The International Journal of Advanced Manufacturing Technology
https://doi.org/10.1007/s00170-018-2264-7

ORIGINAL ARTICLE

A life cycle assessment-based approach for evaluating the influence of total build height and batch size on the environmental performance of electron beam melting

Van Thao Le[1] · Henri Paris[2]

Received: 19 November 2017 / Accepted: 31 May 2018

Abstract

Electron beam melting (EBM) is emerged as a promising metal-based additive manufacturing technology. The technique allows the build of complex and fully dense metallic parts by using an electron beam to melt metallic powder layer by layer. This technique has been applied efficiently in aeronautic and automobile sectors, as well as biomedical engineering. However, the environmental performance of EBM is still an open question. This paper aims to offer a more comprehensive understanding on environmental impacts related to EBM process. A methodology based on life cycle assessment (LCA) method is proposed to evaluate environmental impacts related to EBM. In particular, the influence of different parameters, such as total build height, batch size (i.e., number of parts per build), and material waste due to support structures on the environmental performance of EBM is discussed. By comparing environmental impacts between (EBM + finishing machining) and conventional approach (i.e., machining) approaches, which are used to manufacture a same mechanical part, the environmentally friendly area of each manufacturing approach is also determined. The results show that the (EBM + finishing machining) approach becomes the best option on the environmental point of view when the total build height decreases and the batch size is close to a full build configuration. On the other hand, the amount of material waste due to support structures in EBM does not significantly influence on the environmental performance of the EBM process.

Keywords Additive manufacturing · Electron beam melting · CNC machining · Life cycle assessment

Nomenclature

AM	Additive manufacturing
CLAD	Construction laser additive deposition
CM	Conventional machining
DMD	Direct material deposition
EBM	Electron beam melting
FM	Finishing machining
LCA	Life cycle assessment
LCI	Life cycle inventory
SLM	Selective laser melting
SLS	Selective laser sintering
SEC, kJ/cm^3	Specific energy consumption
MRR, cm^3	Material removal rate
M_p, kg	Mass of the final part
M_{rm}, kg	Mass of raw material (Ti-6Al-4V) required for the manufacture of the final part
M_{rc}, kg	Mass of chips in roughing machining operations
M_{fc}, kg	Mass of chips in finishing machining operations
M_{ignt}, kg	Mass of ingot obtained from the material recycling phase in the CM approach
M_{wkp}, kg	Mass of the workpiece in the CM approach

✉ Van Thao Le
thaomta@gmail.com

Henri Paris
henri.paris@g-scop.fr

[1] Advanced Technology Center, Le Quy Don Technical University, Hanoi, Vietnam

[2] University Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, F-38000 Grenoble, France

Published online: 09 June 2018

M_{EBM}, kg	Mass of the EBM-built part in the (EBM + FM) approach
M_s, kg	Mass of support structures for building a part in EBM
M_{pd}, kg	Mass of powder required to build a part
M_{wst}, kg	Mass of material waste in the atomization process
M'_{ignt}, kg	Mass of the ingot obtained from the material recycling phase in the (EBM + FM) approach
$H_{total\ build}$, mm	Total height of build in EBM
$M_{built\ parts}$, kg	Total mass of built parts (including support structures) in EBM
E_{vacuum}, kWh	Energy consumed in the vacuum step of EBM machine
$E_{heating}$, kWh	Energy consumed in the heating step of EBM machine
$E_{melting}$, kWh	Energy consumed in the melting step of EBM machine
$E_{cooling}$, kWh	Energy consumed in the cooling step of EBM machine
$E_{total\ EBM}$, kWh	Total energy consumption of EBM machine
$E_{EBM/part}$, kWh/part	Energy required to build a part in EBM

1 Introduction

Additive manufacturing (AM) has increasing attention and application in both academic and industrial sectors. Due to layer manufacturing principle, this technique can build complex parts that are normally difficult or impossible to be released in machining [1]. Particularly, electron beam melting (EBM) is emerged as a promising metal-based AM technique, which uses the energy of an electron beam to melt metal powder layer-by-layer and builds fully dense parts [2]. Nowadays, EBM and other metal-based AM techniques (e.g., SLM and DMD) are widely applied in automobile and aeronautic sectors, as well as biomedical engineering [3].

Compared to conventional manufacturing (CM) processes (such as casting, forging, and machining), AM is considered as a cleaner production technique. AM technique can produce parts with minimum material waste and does not require additional resources, for example cooling fluid as in machining. In the context of sustainability, this technique presents at least three following advantages:

- Firstly, AM allows using raw materials efficiently by building parts layer by layer. As a result, material waste in AM is minimized in comparison with machining processes [4]. The design freeform offered by AM also enables producing innovative products and lightweight components. Thus, a saving of raw material can be achieved and contributing to reducing the product cost [5].
- Secondly, AM techniques have potential to extend product life through different approaches, such as repairing, remanufacturing of components, and rapid manufacturing of spare components [6]. These techniques also have potential for giving a new life to existing and end-of-life components [7–10].
- Lastly, AM does not require additional resources as in machining (e.g., jigs, fixtures, cutting tools, and coolants). The parts can be produced by small manufacturers that are close to customers. Hence, shorter supply chains and more localized production can be released with AM [11, 12]. This also allows reducing associated transportation and inventory of waste.

However, AM techniques have some limitations, for example a limited range of materials appropriate for use in AM, low process productivity, rough surface finish, and low dimensional accuracy [3]. Thus, a post-processing stage of AM-built parts (e.g., finishing machining or grinding) is normally required to achieve the expected quality of functional surfaces [13]. In addition, if necessary, a heat treatment process is performed to improve the interior quality of as-AM-built parts (e.g., density, microstructures and mechanical properties).

Although technological advantages of AM in comparison with machining have been demonstrated, it is essential to release an assessment of the entire production cycle of parts in terms of environmental impacts (resource consumption and emissions such as greenhouse gases, and toxic substances). This assessment will help designers and manufacturers to select the best strategy between AM and conventional processes (e.g., forging and machining). In fact, the manufacture of parts by AM techniques requires raw material in powder or fill shape. In particular, for powder-based AM techniques, the production of metal powder consumes a significant amount of energy and other resources such as water and argon gas. Thus, environmental impacts of the entire manufacturing process of parts using AM techniques should be well investigated.

Recently, many researchers have turned their attention on the environmental impact assessment of both machining and AM processes. Much research has evaluated energy consumption and environmental impacts related to machining processes. Kara and Li [14] proposed an empirical model for estimating energy consumption of milling and turning machines. This model describes the specific energy consumption (SEC) in a function of the material removal rate (MRR) in machining operations. SEC (kJ/cm^3) is an amount of energy consumed by machine tools for removing 1 cm^3 of materials. Thus, the total energy consumption of the machine tool in a machining operation can be estimated in a function of SEC and volume of chips. Kellens et al. [15, 16] developed a methodology based on life cycle assessment (LCA) for systematic inventory analysis of manufacturing processes. Their method allows obtaining the life cycle inventory data more completely, accurately, and in a relatively rapid manner.

Concerning AM techniques, Gebler et al. [17] presented an assessment of AM from a global sustainability perspective. The authors estimated by 2025 that the total life cycle primary energy supply and avoided carbon dioxide (CO_2) emissions related to AM are 2.54–9.30 exajoules (EJ) and 130.5 to 525.5 million tons (Mt), respectively. A number of studies have also assessed energy consumption and environmental impacts of AM processes. Le Bourhis et al. [18] presented a LCA-based method for evaluating the environmental performance of additive laser manufacturing process. For this purpose, all associated elements, such as energy, fluid, and raw material consumption in both AM and powder production (i.e., gas atomization) processes are taken into account. In their work, materials, fluid, and energy consumed were calculated separately and converted to environmental impact factors. Kellens et al. [19] presented parametric models, which allow an estimation of the environmental footprint of SLS process and covering energy and resource consumptions into process emissions. Faludi et al. [20] also proposed a method for evaluating environmental impacts of SLM process and determined what element causes most impacts: machine and supporting hardware, powder material used, or electricity used to print. The authors showed that the energy consumption dominated environmental impacts. More recently, Kellens et al. [21] summarized the available life cycle inventory data from previously published works and compared environmental impacts relative to some AM processes, such as SLM, SLS, and EBM.

In order to identify the environmental performance area of AM processes, a number of studies have compared environmental impacts related to the manufacture of parts by either AM or conventional manufacturing (CM) approaches (Table 1).

The first research, which compares AM and machining processes from the environmental point of view, was released by Morrow et al. [22]. The authors compared the specific energy consumption and air emissions between traditional processes (e.g., casting and machining) and DMD process in cases of steel mold production. The authors found that DMD is more environmentally friendly and more energy-efficient to manufacture complex molds, which present a significant amount of material to be removed by machining. In other cases, machining process is still a good option in terms of environmental impacts. Serres et al. [23] also compared CLAD (construction laser additive deposition) and machining processes for the manufacture of a mechanical part on the environmental dimension based on LCA method. These authors found that approximately 90% of the environmental impacts were due to the powder production in the case of CLAD and the ingot production in the case of machining. Based on the manufacture of the mechanical part, they concluded that the CLAD enables reducing resource consumption and human

Table 1 Related works on environmental comparison between AM and CM processes

Paper reference	AM process	Criteria of the comparison between AM and CM processes	Element used to observer the evolution of comparison results
Morrow et al. [22]	DMD	Energy consumption and air emissions associated with the production of molds	Shape of molds: production of simple mold and complex mold
Serres et al. [23]	CLAD	Damages to human health, impact on ecosystems, and resource consumption associated with the production of a specific Ti-6Al-4V part	Quantity of consumed powder in CLAD: building totally the part and building partially the part (adding features on the machined part) by CLAD
Tang et al. [24]	Binder Jetting	Energy consumption and CO_2 emissions associated with the manufacture of the aircraft engine bracket	Part geometry: production of parts without and with topologically optimized geometry
Peng et al. [25]	Laser cladding	Resource consumption, water, and atmospheric emissions associated with the impeller production	Quantity of consumed powder in laser cladding: building totally impeller and remanufacturing impeller by laser cladding
Paris et al. [26]	EBM	Ratio between the environmental impact of EBM and the environmental impact of CM associated with the manufacture of a titanium turbine	Shape factor: varying values of the shape factor (i.e., varying amount of material removed by machining (chips) to obtain the final part)
Priarone et al. [27]	EBM	Energy demand and CO_2 emissions associated with the manufacture of parts	Part geometry: manufacture of three parts having similar envelop dimensions but they have different shapes

health damage by approximately 70%. However, when the mechanical part size is larger, the environmental impacts related to CLAD process will be higher and could be more comparable with conventional machining. Huang et al. [28] estimated the primary energy demand and the greenhouse gas emission of AM for manufacturing lightweight aircraft components. These authors also identified environmental benefits provided by shifting from CM to AM approach. Their results showed that AM presents energy and material saving because of its ability to manufacture lightweight parts. Tang et al. [24] also presented a framework for environmental impact analysis of AM process (binder jetting), and compared it with CNC machining. They proved that the binder jetting process consumes less energy and generates less CO_2 emissions to produce a topologically optimized part than CNC milling for the same product. Recently, Peng et al. [25] also proposed a LCA method to compare the environmental impacts between three manufacturing approaches of impeller: CM (milling), AM (laser cladding) combined with machining and additive remanufacturing. Their results showed that the additive remanufacturing approach is the most environmentally friendly option, followed by AM and CM, in terms of global warming potential, water eutrophication potential, and acidification potential. However, AM approach is not always more environmentally friendly than CM.

Concerning EBM process, Baumers et al. [29, 30] estimated that, in a full-build configuration, the specific energy consumption of EBM for building a specified Ti-6Al-4V part was about 17 (kWh/kg). However, this estimated value may not be proper to calculate the energy consumption for other parts. As a matter of fact, the energy consumed in EBM depends not only on the part volume, but also on the total build height, and so on. Paris et al. [26] recently compared environmental impacts between EBM followed by machining and machining, based on the manufacture of a titanium turbine. The authors suggested that EBM is preferable in the environmental aspect when the material volume (chips) to be removed in CNC machining is important. Priarone et al. [27] also evaluated the influence of material-related aspects of EBM and CNC machining on energy demand and CO_2 emissions. However, in their work, material and energy consumption in each process were collected and converted into embodied energy and CO_2 footprint for primary production. These elements are then used as the metrics to compare two manufacturing approaches. The authors also adopted the specific energy consumption of EBM estimated by Baumers et al. [29, 30] to calculate energy consumption in their case study. In addition, in the works of Paris et al. [26] and Priarone et al. [27], the authors only focused on investigating the influence of the material removal ratio in machining (i.e., the chip quantity to be removed from the workpiece to obtain the final part) on environmental trade-offs between EBM + finishing machining (FM) and conventional manufacturing (CM). Moreover, these authors only considered the single part build configuration of EBM in their environmental comparison. The influence of other factors, such as total build height, batch size (i.e., number of built parts per build), and material waste due to support structures on environmental performance of EBM, is not yet taken into account. In fact, the total build height in EBM is also a factor that has a significant influence on the energy consumption of EBM. Moreover, EBM allows building multiple parts per build. The energy consumption per part in the full build configuration is normally lower than that in the simple build configuration [29, 30]. Thus, it is necessary to consider these factors in the environmental assessment of EBM process.

The current study aims at filling the aforementioned knowledge gap and giving a more comprehensive understanding about environmental impacts of EBM. Thus, the influence of total build height, batch size, and material waste in EBM on its environmental performance is particularly investigated. The environmental comparison between (EBM + FM) and CM approaches for the manufacture of parts is also released. This comparison enables determining the environmental performance area of each manufacturing approach.

This paper is organized as follows. In Section 2, the case study and system boundaries of the assessment method are presented. Section 3 focuses on describing the life cycle inventory (LCI) related to both (EBM + FM) and CM approaches. The method to calculate environmental impacts and different scenarios for environmental comparison are addressed in Section 4. Section 5 discusses on the results obtained from different comparison scenarios and determines the environmental performance domain of each manufacturing approach. Finally, Section 6 summarizes conclusions of the current work.

2 Methodology

In order to calculate environmental impacts related to the manufacture of parts by (EBM + FM) and CM approaches, a LCA-based method is proposed in the current work. All analyses are carried out with SimaPro software (*version 8.0.4.30*) in conjunction with the "Ecoinvent"database (*version 3.1*).

The environmental impact comparison between (EBM + FM) and CM (i.e., machining) approaches is performed based on the manufacture of a lightweight part made of Ti-6Al-4V alloy (Fig. 1). The mass of the lightweight part is $M_p = 0.18$ (kg) and its envelope dimensions are 150 (mm) of length, 50 (mm) of width, and 30 (mm) of height. This part is selected because it presents a high value of the ratio (K) between the mass of the workpiece (M_{wkp}) and the mass of the final part (M_p) in machining, $K = M_{wkp}/M_p = 6$. In this case, the quantity of removed chips in machining is very important, five times bigger than the mass of final part.

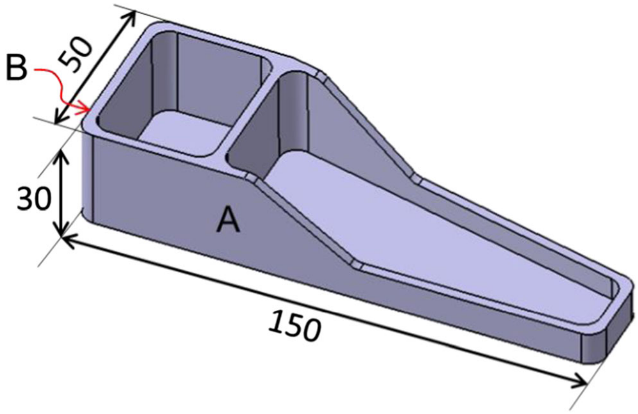


Fig. 1 The lightweight part used in the case study

Hence, it is reasonable to manufacture this part by AM processes to minimize material waste.

In this study, the geometry of final parts manufactured by (EBM + FM) and CM approaches is identical and they have the same technical specifications. In addition, the mechanical properties of titanium parts built by EBM are comparable with those of titanium parts manufactured by convention processes (e.g., forging and machining) [2]. Hence, it is assumed that the in-use performance and the lifetime of parts obtained by both manufacturing approaches are identical (i.e., there is no influence of environmental impact related to the use stage of parts on environmental impact comparison between two manufacturing approaches). Thus, this study particularly focuses on the comparison of environmental impacts related to manufacturing processes and associated transportation during the manufacture of parts. The environmental impacts involved with the use phase and end-of-life stages of the part are not taken into the comparison. Moreover, the material waste (e.g., chips in machining operations and support structures in EBM) in both manufacturing approaches is recycled into raw material that will be used in the next manufacturing cycle of the part. Thus, the material recycling is considered as a unit process.

The system boundaries for environmental impact assessment are presented in Fig. 2. According to the CM approach (Fig. 2a), the lightweight part is achieved by CNC machining from a titanium block (workpiece) with a mass $M_{\mathrm{wkp}} = 1.08$ (kg). The workpiece is obtained from the ingot by the rolling process. We assumed that 100% of the ingot mass (M_{ingt}) is transformed into the workpiece, i.e., $M_{\mathrm{ingt}} = M_{\mathrm{wkp}} = 1.08$ (kg). In fact, the rolling process allows obtaining a bar with desired cross section and great length. The workpiece is a small part of the bar. Hence, the percentage of material waste produced in this process is very low and can be neglected. In this case, to obtain the final part, a significant amount of chips (or material waste) in machining has to be removed, including 0.87 (kg) of chips in roughing machining operations (M_{rc}) and 0.03 (kg) of chips in finishing machining operations (M_{fc}). The second value ($M_{\mathrm{fc}} = 0.03$ kg) is estimated from the depth of cut a_{p} (Table 3) and total area of the final part surfaces. The ingot is produced from the chips of roughing and finishing machining operations in the previous manufacturing cycle and an amount of raw Ti-6Al-4V (M_{rm}, kg) through the material recycling phase. In this study, the

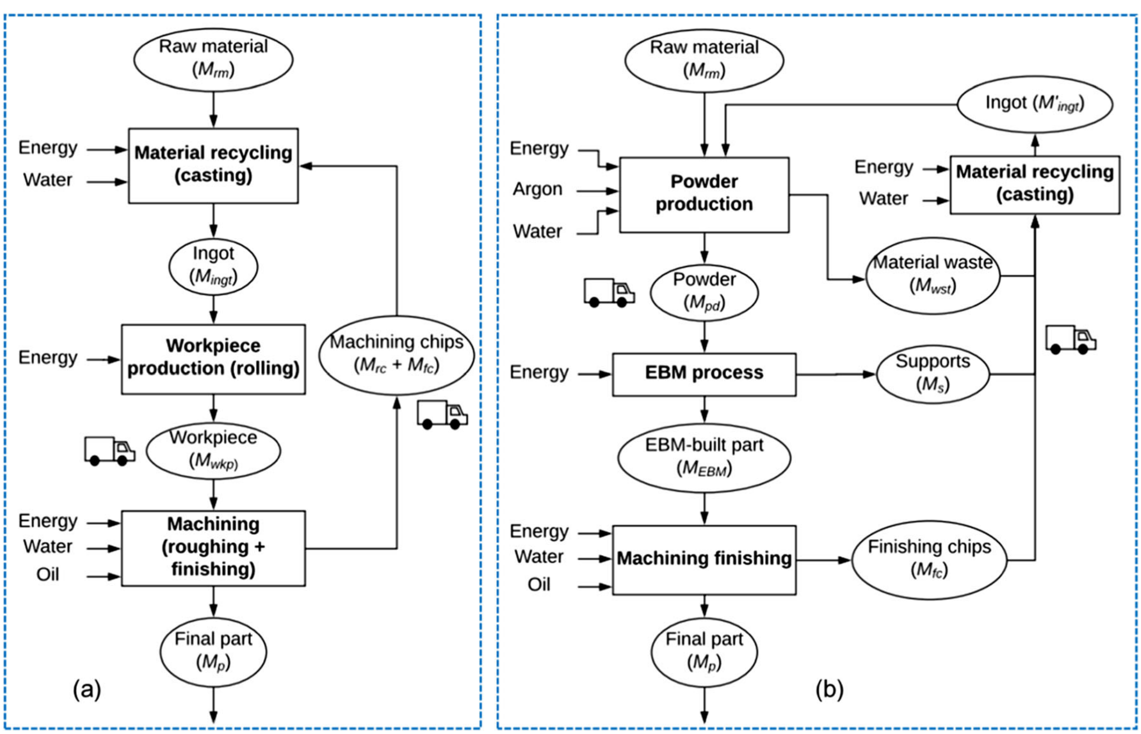


Fig. 2 System boundaries for the comparative analysis: **a** CM and **b** (EBM + FM)

technique "4C process"—Cold Crucible Continuous Casting process [31]—is used to recycle titanium chips. This process allows 100% of chips to be recycled into the ingot. The transportation of workpieces and chips in CM approach is performed by a same type of lorry.

According to (EBM + FM) approach (Fig. 2b), the part is manufactured in two principal phases: a "semi" part (M_{EBM}, kg) with geometry close to that of the final part is firstly built by EBM from the Ti-6Al-4 V powder. The final part is then obtained by finishing all surfaces of the semi part in machining. The mass of titanium powder required in EBM is M_{pd} (kg). Normally, a thickness of 0.25 (mm) is added into functional surfaces of titanium parts built by EBM for finishing machining operations. In this study, all surfaces of the part (Fig. 1) with a total area of 270 (cm^2) have to be finished. Thus, the total quantity of chips in finishing operations for EBM-built part is approximately equal to 0.03 (kg). This value is identical to that in the CM approach, $M_{fc} = 0.03$ (kg). The powder unused in EBM will be reused for the next build cycle. The material waste in EBM process (M_s, kg) is due to the generation of support structures. In the current work, the Ti-6Al-4V powder is produced by gas atomization process [32]. In the (EBM + FM) approach, the material waste in powder production and in EBM (i.e., M_{wst} and M_s, respectively) and the chips in finishing operations (M_{fc}) are also recycled into the ingot (M'_{ingt}, kg) by 4C process as in the CM approach. This ingot and an amount of raw Ti-6Al-4V (M_{rm}) are used to produce the Ti-6Al-4V powder in the next manufacturing cycle. The transportation of powder from the titanium powder production site to the manufacturing location (i.e., EBM machine) and the shipment of material waste and chips to the material recycling site are also performed by the same type of lorry as in the CM pathway.

3 Life cycle inventory

3.1 Material recycling and workpiece production

As aforementioned, the technique "4C process" is used to recycle chips and waste in both manufacturing approaches. This process is performed in a copper crucible under high vacuum and cooled by water that circulates within the crucible wall. According to data presented in the work of Paris et al. [26], in order to recycle 1 kg of Ti-6Al-4V, 155 (l) of water and 4.08 (kWh) of electricity are required.

In the CM pathway (Fig. 2a), the total quantity of material to be recycled is the sum of M_{rc}, M_{fc}, and M_{rm}, and equal to 1.08 (kg). The water and energy consumption for material recycling phase in the CM approach are shown in Table 2.

On the other hand, in the (EBM + FM) approach, the total mass of material waste to be recycled is the sum of chip quantity in finishing machining operations (M_{fc}), material waste in EBM and in atomization (M_s and M_{wst}, respectively).

Table 2 Energy and water consumption of the material recycling in the CM approach

Mass of titanium to be recycled (kg)	Water consumption (l)	Electric energy consumption (kWh)
1.08	167.4	4.41

The workpiece in the CM pathway is achieved from the ingot by rolling process. According to Priarone et al. [27], the specific energy consumption of the rolling process is 14.5 (MJ/kg). Thus, the energy required to obtain 1.08 (kg) of the workpiece is 15.66 (MJ).

3.2 CNC machining

In this study, a 3-axis CNC machine (Fadal VMC 4020) is used to perform roughing and finishing operations in both CM and (EBM + FM) approaches. In order to estimate energy consumption in machining, the empirical model proposed by Kara and Li [14] is adopted, as shown in Eq. (1). This model can predict the total energy consumption of a machine tool with the accuracy more than 90%.

$$\text{SEC} = C_0 + \frac{C_1}{\text{MRR}} \tag{1}$$

In Eq. (1), SEC (kJ/cm^3) presents the total energy consumption of machine tools for removing 1 (cm^3) of materials; C_0 and C_1 are the specific coefficients of machine tools. For the 3-axis CNC machine (Fadal VMC 4020) and in a cutting wet condition, $C_0 = 3.082$ (kJ/cm^3) and $C_1 = 1.396$ (kW) [14]. MRR (cm^3/s) presents the material removal rate in machining operations, which can be calculated from cutting parameters by Eq. (2):

$$\text{MRR} = \frac{a_e{}^* a_p{}^* V_c{}^* f_z{}^* z}{60^* \pi^* D} \tag{2}$$

where a_p (mm)—axial depth of cut; a_e (mm)—radial depth of cut; V_c (m/min)—cutting speed; f_z (mm/tooth)—feed per tooth; z—number of teeth; and D (mm)—diameter of the cutting tool.

In this study, a 15-mm-diameter flat end mill and an 8-mm-diameter flat end mill are used for roughing and finishing operations, respectively. The values of MRR, SEC, and energy consumed in machining operations are given in Table 3.

In addition, cutting fluid (70–90% of water and oil) is lost during machining operations. This loss can be considered as cutting fluid (water and oil) consumption. According to Kellens et al. [16], the rate of oil and water losses are about 0.042 and 0.238 (g/s), respectively. From this data, energy,

Table 3 Calculation of energy, water, and oil consumption in machining of Ti-6Al-4V parts

Element	Roughing operation	Finishing operation
a_p (mm)	2.5	0.25
a_e (mm)	11.25	6
V_c (m/min)	40	60
f_z (mm/tooth)	0.075	0.07
z	4	4
MRR (cm^3/s)	0.119	0.017
SEC (kJ/cm^3)	14.77	86.58
Mass of chips (kg)	$M_{rc} = 0.87$	$M_{fc} = 0.03$
Energy consumption (kWh)	0.806	0.163
Water consumption (kg)	0.391	0.096
Oil consumption (kg)	0.069	0.017

water, and oil consumption in machining operations can be calculated, as given in Table 3.

3.3 Powder production

As mentioned above, the titanium powder is produced by gas atomization process. In this process, the melted raw material is flowed through a nozzle under the gravity effect, then spitted into fine droplets by argon jets. The droplets are solidified thanks to a convective exchange during their displacement in the atomization room [18]. For titanium-based alloys, this process allows the powder production with a high efficiency. Baumers et al. [30] estimated that the total energy requirement to produce Ti-6Al-4V powder can be approximated at 560.6 (MJ/kg). According to Serres et al. [23], the efficiency for production of Ti-6Al-4V powder by gas atomization process is about 93%. To produce 1 (kg) of titanium powder, 1.95 (kWh) of electricity and 0.32 (kg) of argon are required. In the work of Le Bourhis et al. [18], the authors investigated the electricity, water, and gas (argon) consumption for metallic glass atomization. They showed that for producing 1 kg of metallic glass powder, the gas atomization process consumed 7 (m^3) of argon, 14.4 (MJ) of electricity, and 155 (l) of water. In this work, the data presented in the works of Serres et al. [23] and Le Bourhis et al. [18] is used. Concretely, to obtain 1 (kg) of Ti-6Al-4V powder, we need 1.075 (kg) of raw Ti-6Al-4V (including 7% of material waste), 1.95 (kWh) of electricity, 0.32 (kg) of argon, and 155 (l) of water.

3.4 Electron beam melting

In this study, an EBM machine model A1 of Arcam® is used to build the part. The quantity of powder (M_{pd}) required to build the part is equal to the sum of final part mass (M_p = 0.18 kg), chip mass in finishing machining operations (M_{fc} = 0.03 kg), and mass of support structures (M_s). The unused powder in EBM process will be reused for the next manufacturing cycle.

The detailed information and the work principle of EBM machines have been presented in previous works [2, 33]. Normally, the build of parts in EBM is performed through four steps, i.e., vacuum, heating, melting, and cooling. These steps are briefly described as follows:

- Firstly, a 316-L stainless steel plate (with 210 mm × 210 mm × 10 mm of dimensions) is placed on the build table of the machine. Titanium powder is loaded in two powder hoppers and dispersed onto the build plate by the powder rake. Thereafter, the vacuum is released until the build environment pressure reaches 10^{-5} (mbar).
- Following the vacuum step, the heating step is performed. The build plate and powder are heated by electron beam until temperature at the top surface of the common part reaches initial build temperature (e.g., 740 °C in the case of Ti-6Al-4V alloy). At that time, the build of first layer is started. Once the current layer is fully built, the build table is lowered an increment of 50 μm for building the next layer. In this way, the part is built layer by layer until the total build is complete.
- Once the parts are completely built, the slow cooling step taking under vacuum is executed until temperature at the bottom surface of the build plate reaches 100 °C. From this moment, the powder block including built parts can be taken out from the machine. The built parts are then treated in the post-processing stage.

In order to estimate energy consumption in EBM process, we have released three cases of part build. This has been described in our recently published work [34]. The energy consumption in four steps of EBM is summarized in Table 4.

It is found that the energy consumption in the vacuum and heating steps generally do not depend on the built parts: E_{vacuum} = 1.78 (kWh) and $E_{heating}$ = 2.02 (kWh). On the other hand, the energy consumption in the melting step ($E_{melting}$, kWh) depends on the quantity of melt powder ($M_{required}$

Table 4 Energy consumption of EBM in three cases of part build

Elements	Build (1)	Build (2)	Build (3)
Mass of required powder ($M_{required\ powder}$, kg)	0.23	0.44	0.34
Total build height ($H_{total\ build}$, mm)	10	35	59
Build steps in EBM	Measuring energy consumption (kWh)		
Vacuum	1.78	1.78	1.78
Heating	2.02	2.02	2.02
Melting	7.10	19.2	31.51
Cooling	0.49	1.60	2.42

Table 5 Impact categories in IMPACT 2002+ method

	Midpoint categories	Damage categories
LCA results	1. Carcinogens	Human health
	2. Non-carcinogens	
	3. Respiratory inorganics	
	4. Ionizing radiation	
	5. Ozone layer depletion	
	6. Respiratory organics	
	7. Aquatic ecotoxicity	Ecosystem quality
	8. Terrestrial ecotoxicity	
	9. Terrestrial acid/nutri	
	10. Land occupation	
	11. Aquatic acidification	
	12. Aquatic eutrophication	
	13. Global warming	Climate change
	14. Non-renewable energy	Resources issues
	15. Mineral extraction	

powder, kg) and the total build height ($H_{\text{total build}}$, mm). After the entire melting step, the cooling is performed to decrease the temperature of consolidated powder block (including built parts) from 740 to 100 °C [34]. The energy consumed in this step depends on the volume of this consolidated powder block. However, the surface of workspace in EBM is not changed because we want to build a maximum number of parts. Therefore, the energy consumed in the cooling step (E_{cooling}, kWh) only depends on the total height of the build. From the measured data in Table 4, the energy consumption in the melting and cooling steps are estimated by Eqs. (3) and (4), respectively.

$$E_{\text{melting}} = 5.23^{*} M_{\text{required powder}} + 0.5^{*} H_{\text{total build}} \quad (3)$$

$$E_{\text{cooling}} = 0.039^{*} H_{\text{total build}} + 0.145 \quad (4)$$

The mass of powder consumed to build a part is M_{pd}. Thus, the powder required to build N parts, $M_{\text{required powder}}$, is equal to $N^{*}M_{\text{pd}}$. Finally, the total energy consumption in EBM is calculated by Eq. (5), and the energy consumed to build a part in EBM is determined by Eq. (6).

$$\begin{aligned} E_{\text{EBMtotal}} &= E_{\text{vacuum}} + E_{\text{heating}} + E_{\text{melting}} + E_{\text{cooling}} \\ &= 3.95 + 5.23^{*} N^{*} M_{\text{pd}} + 0.539^{*} H_{\text{total build}} (\text{kWh}) \end{aligned} \quad (5)$$

$$E_{\text{EBM/part}} = 5.23^{*} M_{\text{pd}} + \frac{0.539^{*} H_{\text{total build}} + 3.95}{N} \ (\text{kWh/part}) \quad (6)$$

In EBM process, the quantity of material waste (M_{s}, kg) is calculated from the material loss attributed to support structures. Generally, the support structures are required for the build of complexly designed components.

4 Environmental impact calculation and comparison

To calculate the environmental impacts, the IMPACT 2002+ method [35] available in SimaPro software is used. This method proposes a feasible implementation of a combined midpoint/damage approach that links all types of life cycle inventory results via 15 midpoint categories to four damage categories: human health, ecosystem quality, climate change, and resources (Table 5). In this study, four damage categories are particularly used to analyze the results and compare two manufacturing approaches (i.e., EBM + FM and CM) in terms of environmental impacts.

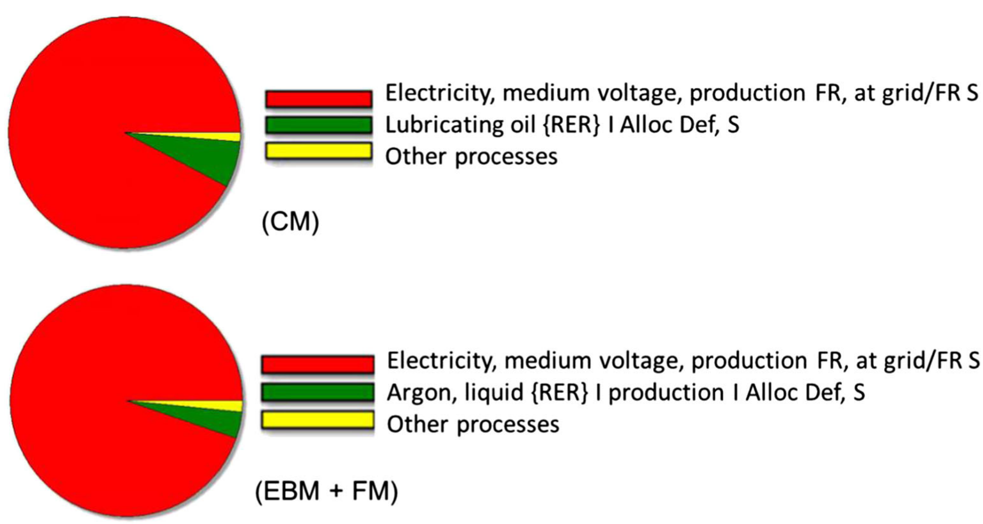


Fig. 3 Contribution of inventory elements to environmental impacts related to CM and (EBM + FM) strategies in the case of $N = 3$; $H_{\text{total build}} = 30$ (mm) and $M_{\text{s}} = 10\%^{*}(M_{\text{p}} + M_{\text{fc}})$

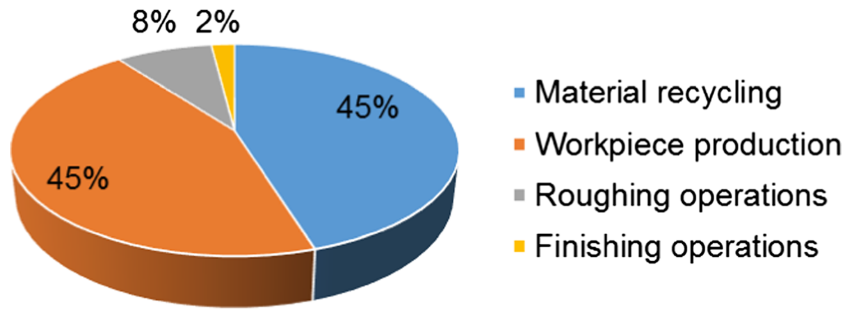


Fig. 4 Energy consumption of processes in the CM approach

In this work, we also define a dimensionless ratio for each damage impact category as Eq. (7). This ratio enables comparing two manufacturing approaches according to the selected impact category.

$$R = \frac{\text{Environmental impact related to } (\text{EBM} + \text{FM})}{\text{Environmental impact related to CM}} \quad (7)$$

If the value of R is inferior to 1, the (EBM + FM) approach is more environmentally friendly. In contrary, R is superior to 1, the CM is more pertinent to manufacture parts in the environmental point of view. In the case of R equal to 1, both manufacturing approaches are similar in terms of environmental impacts.

In order to observe the influence of the total build height and batch size (i.e., number of parts per build) and material waste in EBM on environmental trade-offs between two manufacturing approaches, three scenarios are proposed as follows:

- In the first scenario, the total build height is fixed, $H_{\text{total build}} = 50$ (mm), i.e., the side surface (A) of the part (Fig. 1), is used to position the part on the build plate of EBM. The material waste in EBM is negligible, $M_s \approx 0$. On the other hand, the number of parts per build in EBM is varied: $N = \{1; 3; 4; 5; 7\}$.
- In the second scenario, the number of parts per build is fixed ($N = 4$) and the material waste in EBM is also negligible, $M_s \approx 0$, while the total build height in EBM is varied, $H_{\text{total build}} = \{30; 50; 150\}$ (mm). These values of the total build height in this scenario are selected as follows:
  - $H_{\text{total build}} = 30$ (mm) when the part is positioned on the build plate of EBM using the bottom surface (as shown in Fig. 1).
  - $H_{\text{total build}} = 50$ (mm) when the side surface (A) is used to position the part on the build plate.
  - $H_{\text{total build}} = 150$ (mm) when the side surface (B) is used to position the part.
- In the third scenario, the number of parts per build and the total build height in EBM are fixed: $N = 6$ and $H_{\text{total build}} = 50$ (mm), whereas the amount of material loss due to the support structures—that are calculated as percentage value of the mass of EBM-built part ($M_p + M_{fc}$), varies in range of {0; 10; 20; 30; 40; and 50%} of ($M_p + M_{fc}$).

5 Results and discussion

From the results obtained in SimaPro, we firstly observe the contribution of inventory elements to environmental impacts generated in (EBM + FM) and CM approaches (Fig. 3).

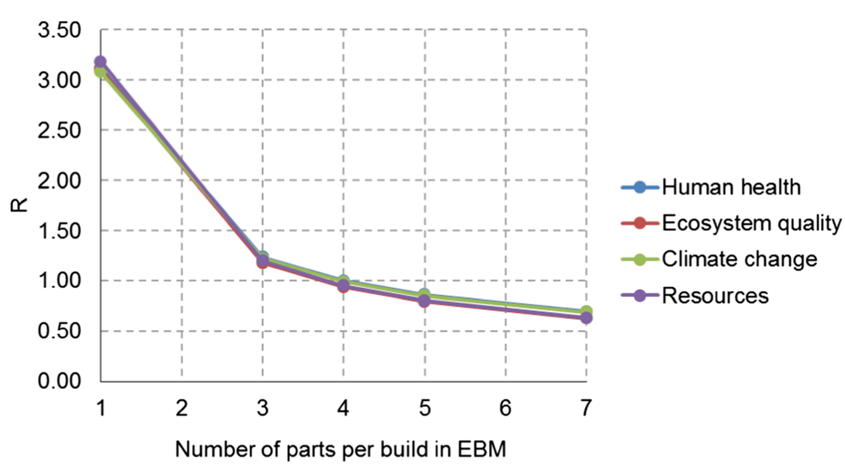
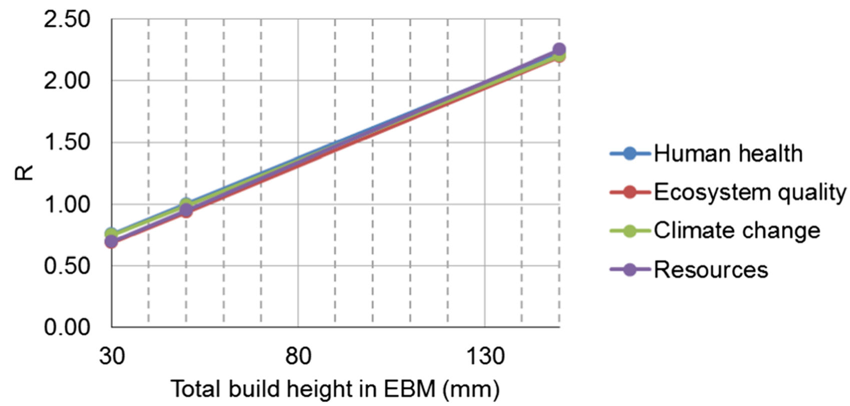


Fig. 5 Evolution of R as function of N according to damage categories in scenario 1

Fig. 6 Evolution of R as function of $H_{total\ build}$ according to damage categories in scenario 2



It shows that energy and cutting fluid consumption are two main elements that cause environmental impacts in the CM approach; whereas energy and argon consumption mainly cause environmental impacts in the (EBM + FM) pathway. Other processes contribute to a very small percentage of the total environmental impacts.

In the CM approach, the material recycling and workpiece production phases present a major percentage (about 45% for each process) of total energy consumption. The energy consumed in roughing and finishing machining operations take only 10% of the total energy consumption in the CM approach (Fig. 4). On the other hand, the energy consumed in EBM and atomization processes has the highest proportion of total energy consumed in the (EBM + FM) approach.

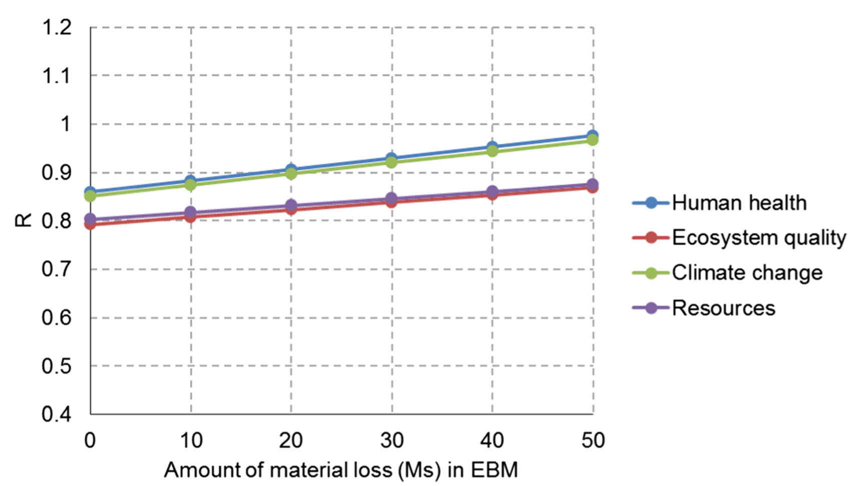
Figure 5 shows the evolution of the comparative ratio (R) according to four damage categories in the first scenario. It is found that the value of R is superior to 1 for all selected damage categories when N is equal to 1, 2, and 3. This means the CM approach is much more environmentally friendly to manufacture the part than the (EBM + FM) in these cases ($N = 1, 2,$ or 3). The (EBM + FM) becomes more interesting in the environmental aspect when the number of built parts in EBM increases because R decreases according to the increase of N. Particularly (EBM + FM) is the best option for manufacturing part in the environmental point of view when the number of parts per build in EBM is superior or equal to 5.

These can be explained by the following reasons: the energy consumption in EBM to build the parts, in the case $N = 1$ or 3, is much higher than total energy required in the CM (e.g., 32 (kWh) or 11.4 (kWh) in compared with 9.79 (kWh)).

When the number of parts per build in EBM is equal to 4, the comparative ratio R starts being inferior to 1 for all selected damage categories. However, the values of R are very close to 1, between 0.94 and 1. Thus, we can consider that both manufacturing approaches are similar in the environmental dimension. At higher values of N, $N \geq 5$, the energy required to build per part in EBM is significantly inferior to that consumed in the CM pathway. (EBM + FM) is much more environmentally friendly than the CM. In this case ($N \geq 5$), the advantage of EBM in terms of energy efficacy versus in a single part build configuration is also demonstrated.

Figure 6 shows the trend of the comparative ratio (R) as function of the total build height ($H_{total\ build}$) in the second scenario. It is found that the environmental impacts related to (EBM + FM) approach linearly increase with the total build

Fig. 7 Evolution of R as function of M_s in scenario 3



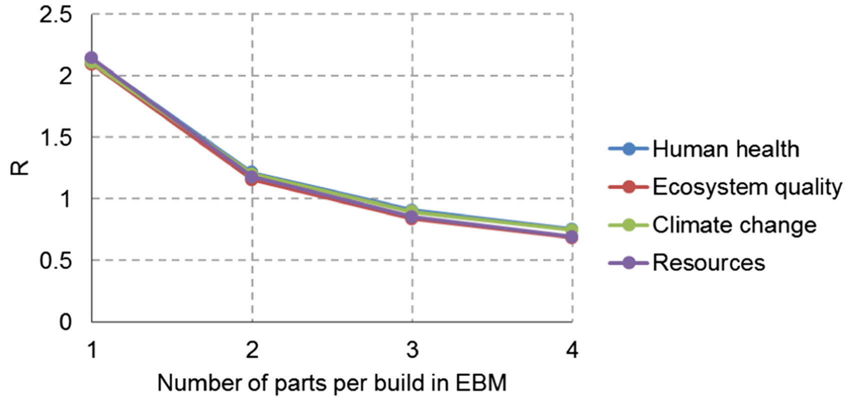


Fig. 8 Evolution of environmental comparison ratio *R* as function of *N* in the first option

height ($H_{total\ build}$) in EBM. Particularly, the (EBM + FM) approach generates much more environmental impacts when $H_{total\ build}$ is superior to 50 (mm). The main reason is that the energy required in EBM per part in these cases is much higher than energy required to produce the part in the CM approach. For example, with $H_{total\ build} = 150$ (mm), the energy consumed in EBM is 22.3 (kWh) in compared with 9.79 (kWh) of total energy consumption in the CM approach. In addition to impacts relative to energy consumed in EBM, energy and argon consumed in atomization process contribute an important impact on the environment. Hence, at high value of the total build height, e.g., $H_{total\ build} > 50$ (mm), the (EBM + FM) approach generates much more environmental impacts. When $H_{total\ build} = 50$ mm, we observe the same result of environmental comparison, as shown in Figs. 5 and 6.

Figure 7 shows the results obtained according to the third scenario. In this scenario, the amount of material loss (i.e., mass of support structures) in EBM (M_s) has been varied from 0 to 50% of ($M_p + M_{fc}$). It is found that the comparative ratio (*R*) also increases linearly with the percentage of the material waste in EBM. However, the values of (*R*) are always inferior to 1 in the scope of this study. This means the impacts related to the (EBM + FM) approach are always lower than those relative to the CM, based on all damage categories. At higher values of M_s, superior to 60% of ($M_p + M_{fc}$), the CM approach is preferable over the (EBM + FM), considering the four damage categories. However, in general, the amount of material waste (due to the support structures) does not overcome 60% of the built part in EBM. Based on this observation, we can consider that the material waste in EBM does not play an important role on the environmental impacts of (EBM + FM) approach. This observation is also in line with the results obtained in the work of Priarone et al. [27].

In this work, the EBM machine (model A1 of Arcam) is used to build the semi parts. The maximum build dimensions of this machine are 200 (mm) × 200 (mm) in *X* and *Y* axes. As aforementioned, for the part in the case study (Fig. 1), there are three following options that are normally considered to position the part on the build plate of EBM machine:

- The first option consists of placing the part on the build plate using its bottom surface (Fig. 1). This option allows maximum four parts to be built together. In this case, the total build height $H_{total\ build}$ is equal to 30 (mm) and $N_{max} = 4$.
- The second option uses the side surfaces (A) to position the part on the build plate. So the maximum number of parts can be placed on the build plate is seven parts, $N_{max} = 7$, and the total build height is $H_{total\ build} = 50$ (mm).

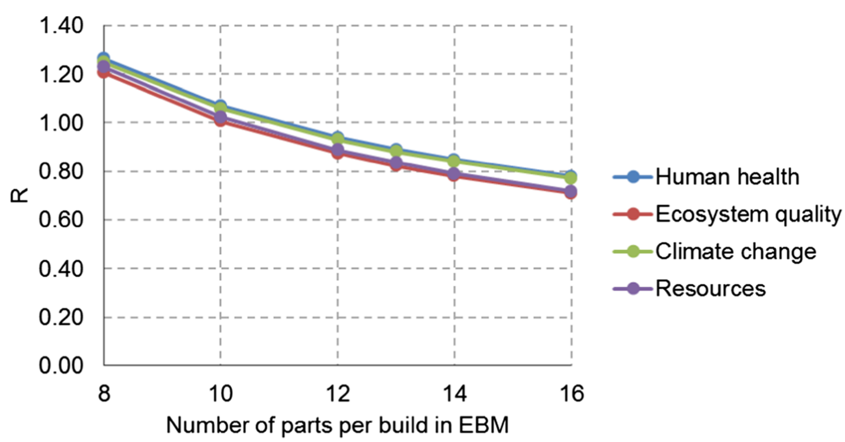
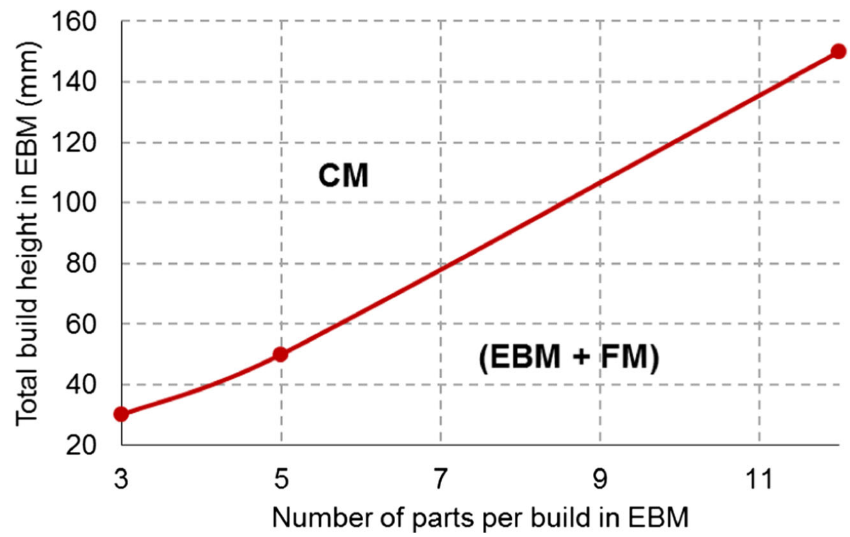


Fig. 9 Evolution of environmental comparison ratio *R* as function of *N* in the third option

Fig. 10 Environmental benefit area of each manufacturing approach



- The last option uses the side surface (B) to position the part. In this case, $N_{max} = 16$ and $H_{total\ build} = 150$ (mm).

As presented in the previous paragraph, in the second option, the (EBM + FM) approach is more interesting in the environmental point of view when $N \geq 5$ (Fig. 5).

In the same way of analysis as in the first scenario (Section 4), Figs. 8 and 9, respectively, show that the (EBM + FM) approach is more environmentally friendly when $N \geq 3$ (for the first option, $H_{total\ build} = 30$ mm) or $N \geq 12$ (for the third option, $H_{total\ build} = 150$ mm), based on all selected damage categories.

From these results, a graph is defined as shown in Fig. 10, which allows identifying the environmental benefit area of each manufacturing approach to manufacture the parts. The underneath the curve contains the variable configurations for which the (EBM + FM) approach is the best solution for the manufacture of parts in terms of environmental impacts. This graph presents an eco-design tool for the specific case study. Once the designers know the number of parts per build and the total build height in EBM, they can easily identify what manufacturing approach that is more interesting in the environmental dimension.

6 Conclusion and future work

This paper aims at giving a more comprehensive understanding on environmental performance of EBM. In particular, the influence of total build height and number of parts per build on the environmental impacts of EBM is identified. The manufacturing of part by the (EBM + FM) approach is compared with the CM in terms of environmental impacts by using a LCA-based method. Through the case study, it is found that the total build height and batch size (i.e., number of parts per build) in EBM are two important factors that significantly influence on the environmental performance of EBM process. On the other hand, the influence of material waste, which is due to the support structures, on the environmental impacts of EBM can be negligible. These results are interesting and can help designers to identify the areas of total build height and batch size in EBM, in which either the (EBM + FM) or the CM approach is the best option to manufacture the parts in the environmental aspect. Overall, the (EBM + FM) approach generates fewer environmental impacts when the batch size close to a full build configuration of EBM is applied because the energy consumption in EBM per part is reduced. However, in the cases where the number of parts per build in EBM is small (e.g., single build), the (EBM + FM) approach does not justify its environmental benefit and the CM approach is still an interesting solution for the manufacture of parts. Finally, the results obtained in this study have been summarized by a graph (Fig. 10), which is considered as an eco-design tool allowing designers and process planners to select the most sustainable manufacturing approach to produce the parts.

However, the environmentally friendly domain of each manufacturing approach (Fig. 10) is still limited by the assumptions and the scope of this study. In future works, we will integrate more constraints of manufacturing processes to obtain more precise results. Moreover, in this study, the final part manufactured by two manufacturing approaches has the same geometry. In fact, the geometry of parts built by EBM can be topologically optimized to reduce the mass. As a result, the quantity of powder required in EBM process is reduced. This would have potential to change environmental comparison results. Hence, it is also interesting to perform the environmental impact comparison between two manufacturing approaches basing on the manufacture of parts, which fulfill the same function but have different geometries.

Acknowledgements The authors would like to thank Auvergne-Rhône-Alpes Region of France for its support.

References

1. Gibson I, Rosen DW, Stucker B (2010) Additive manufacturing technologies. Springer US, Boston. https://doi.org/10.1007/978-1-4419-1120-9
2. Mandil G, Le VT, Paris H, Suard M (2016) Building new entities from existing titanium part by electron beam melting: microstructures and mechanical properties. Int J Adv Manuf Technol 85: 1835–1846. https://doi.org/10.1007/s00170-015-8049-3
3. Chen L, He Y, Yang Y, Niu S, Ren H (2017) The research status and development trend of additive manufacturing technology. Int J Adv Manuf Technol 89:3651–3660. https://doi.org/10.1007/s00170-016-9335-4
4. Huang S, Liu P, Mokasdar A, Hou L (2013) Additive manufacturing and its societal impact: a literature review. Int J Adv Manuf Technol 67:1191–1203. https://doi.org/10.1007/s00170-012-4558-5
5. Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F (2016) Design for Additive Manufacturing: trends, opportunities, considerations, and constraints. CIRP Ann Manuf Technol 65:737–760. https://doi.org/10.1016/j.cirp.2016.05.004
6. Despeisse M, Yang M, Evans S, Ford S, Minshall T (2017) Sustainable value roadmapping framework for additive manufacturing. Procedia CIRP 61:594–599. https://doi.org/10.1016/j.procir.2016.11.186
7. Le VT, Paris H, Mandil G (2017) Extracting features for manufacture of parts from existing components based on combining additive and subtractive technologies. Int J Interact Des Manuf 12:525–536. https://doi.org/10.1007/s12008-017-0395-y
8. Le VT, Paris H, Mandil G (2017) Process planning for combined additive and subtractive manufacturing technologies in a remanufacturing context. J Manuf Syst 44:243–254. https://doi.org/10.1016/j.jmsy.2017.06.003
9. Le VT, Paris H, Mandil G, Brissaud D (2017) A direct material reuse approach based on additive and subtractive manufacturing technologies for manufacture of parts from existing components. Procedia CIRP 61:229–234. https://doi.org/10.1016/j.procir.2016.11.190
10. Le VT, Paris H, Mandil G (2015) Using additive and subtractive manufacturing technologies in a new remanufacturing strategy to produce new parts from end-of-life parts. 22nd Conf French Mech (CFM2015), 24th–28th August, Lyon, France
11. Durão LFCS, Christ A, Zancul E, Anderl R, Schützer K (2017) Additive manufacturing scenarios for distributed production of spare parts. Int J Adv Manuf Technol 93:1–12. https://doi.org/10.1007/s00170-017-0555-z
12. Ford S, Despeisse M (2016) Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. J Clean Prod 137:1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150
13. Zhu Z, Dhokia V, Newman ST, Nassehi A (2014) Application of a hybrid process for high precision manufacture of difficult to machine prismatic parts. Int J Adv Manuf Technol 74:1115–1132. https://doi.org/10.1007/s00170-014-6053-7
14. Kara S, Li W (2011) Unit process energy consumption models for material removal processes. CIRP Ann Manuf Technol 60:37–40. https://doi.org/10.1016/j.cirp.2011.03.018
15. Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR (2012) Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 1: case studies. Int J Life Cycle Assess 17:242–251. https://doi.org/10.1007/s11367-011-0352-0
16. Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR (2012) Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! Initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies. Int J Life Cycle Assess 17:242–251. https://doi.org/10.1007/s11367-011-0352-0
17. Gebler M, Schoot Uiterkamp AJM, Visser C (2014) A global sustainability perspective on 3D printing technologies. Energy Policy 74:158–167. https://doi.org/10.1016/j.enpol.2014.08.033
18. Le Bourhis F, Kerbrat O, Dembinski L, Hascoet J-Y, Mognol P (2014) Predictive model for environmental assessment in additive manufacturing process. Procedia CIRP 15:26–31. https://doi.org/10.1016/j.procir.2014.06.031
19. Kellens K, Renaldi R, Dewulf W, Kruth J, Duflou JR (2014) Environmental impact modeling of selective laser sintering processes. Rapid Prototyp J 20:459–470. https://doi.org/10.1108/RPJ-02-2013-0018
20. Faludi J, Baumers M, Maskery I, Hague R (2016) Environmental impacts of selective laser melting: do printer, powder, or power dominate? J Ind Ecol 0:S144–S156. https://doi.org/10.1111/jiec.12528
21. Kellens K, Mertens R, Paraskevas D, Dewulf W, Duflou JR (2017) Environmental impact of additive manufacturing processes: does AM contribute to a more sustainable way of part manufacturing? Procedia CIRP 61:582–587. https://doi.org/10.1016/j.procir.2016.11.153
22. Morrow WR, Qi H, Kim I, Mazumder J, Skerlos SJ (2007) Environmental aspects of laser-based and conventional tool and die manufacturing. J Clean Prod 15:932–943. https://doi.org/10.1016/j.jclepro.2005.11.030
23. Serres N, Tidu D, Sankare S, Hlawka F (2011) Environmental comparison of MESO-CLAD process and conventional machining implementing life cycle assessment. J Clean Prod 19:1117–1124. https://doi.org/10.1016/j.jclepro.2010.12.010
24. Tang Y, Mak K, Zhao YF (2016) A framework to reduce product environmental impact through design optimization for additive manufacturing. J Clean Prod 137:1560–1572. https://doi.org/10.1016/j.jclepro.2016.06.037
25. Peng S, Li T, Wang X, Dong M, Liu Z, Shi J et al (2017) Toward a sustainable impeller production: environmental impact comparison of different impeller manufacturing methods. J Ind Ecol. https://doi.org/10.1111/jiec.12628
26. Paris H, Mokhtarian H, Coatanéa E, Museau M, Ituarte IF (2016) Comparative environmental impacts of additive and subtractive manufacturing technologies. CIRP Ann Manuf Technol 65:29–32. https://doi.org/10.1016/j.cirp.2016.04.036
27. Priarone PC, Ingarao G, di Lorenzo R, Settineri L (2016) Influence of material-related aspects of additive and subtractive Ti-6Al-4V manufacturing on energy demand and carbon dioxide emissions. J Ind Ecol 0:1–12. https://doi.org/10.1111/jiec.12523
28. Huang R, Riddle M, Graziano D, Warren J, Das S, Nimbalkar S, Cresko J, Masanet E (2016) Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. J Clean Prod 135:1559–1570. https://doi.org/10.1016/j.jclepro.2015.04.109
29. Baumers M, Tuck C, Hague R, Ashcroft I, Wildman R (2010) A comparative study of metallic additive manufacturing power consumption, 21st Int Solid Free Fabr Symp: 278–88
30. Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R (2016) Shape complexity and process energy consumption in electron beam melting: a case of something for nothing in additive manufacturing? J Ind Ecol 0:1–11. https://doi.org/10.1111/jiec.12397

31. Durand F (2005) The electromagnetic cold crucible as a tool for melt preparation and continuous casting. Int J Cast Met Res 18:93–107. https://doi.org/10.1179/136404605225022883
32. Yolton CF, Froes FH (2015) Conventional titanium powder production. Elsevier Inc. https://doi.org/10.1016/B978-0-12-800054-0.00002-2
33. Béraud N, Vignat F, Villeneuve F, Dendievel R (2017) Improving dimensional accuracy in EBM using beam characterization and trajectory optimization. Addit Manuf 14:1–6. https://doi.org/10.1016/j.addma.2016.12.002
34. Le VT, Paris H, Mandil G (2017) Environmental impact assessment of an innovative strategy based on an additive and subtractive manufacturing combination. J Clean Prod 164:508–523. https://doi.org/10.1016/j.jclepro.2017.06.204
35. Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum R (2003) IMPACT 2002+: a new life cycle impact assessment methodology. Int J Life Cycle Assess 8:324–330. https://doi.org/10.1007/BF02978505