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Development of a Comparative Assessment Method For Additive and Conventional Manufacturing With Regard to Global Warming Potential

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Abstract

Additive Manufacturing (AM) opens new possibilities for producing complex parts while achieving high material efficiency. Besides the technological advantages, AM is considered a key technology for sustainable production. A widely used approach to measure the sustainability of a product is the Life Cycle Assessment (LCA) by using the impact category of the Global Warming Potential (GWP). The setup of LCA is complex and requires a deep understanding of the process. LCAs carried out so far for AM mainly focused on energy consumption and the printing process itself. GWP caused by other up and downstream manufacturing steps, such as material preparation, has received little attention so far. This requires more comprehensive LCAs, increasing the complexity and effort. Therefore, the GWP is often not considered when deciding whether to use AM or Conventional Manufacturing (CM) for producing a part in the industry. This work presents a simplified method (GWP-method) for comparing AM and CM regarding the GWP by identifying so-called hotspots (the most significant production steps in terms of GWP). Based on the identified hotspots, the assessment scope was narrowed down, and an Assessment Equation (GWPAE) was developed. The GWPAE can then be used for the analysis of produced GWP for other product families and production scenarios for the defined process route. The method is demonstrated for an aerospace part as a case study. Finally, the deviation of the derived GWPAE is checked by directly comparing the results of the GWP of an LCA for another production scenario and lies at 5,9%.

Keywords

Life Cycle Assessment; Additive Manufacturing; Global Warming Potential; Hotspots; Sustainability

1. Introduction

In the past, the manufacturing industry focused mainly on economic mass production. Today, the major challenge is to create production systems and supply chains that are not only economically but also ecologically sustainable. This leads several industries to focus their efforts on reducing the Global Warming Potential (GWP) of production and their products. This already starts with the planning and selection of the process route. For the quantification of the GWP of the process route, a Life Cycle Assessment (LCA) is a common procedure used in science [1]. However, carrying out an LCA requires detailed information along the entire process route and demands high costs and expertise. Hence, it is often not applied in industry, leading to decisions regarding manufacturing technology without considering ecological impact [2].

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One decision being made in the planning process of production is the decision between Additive Manufacturing (AM) and Conventional Manufacturing (CM). Compared to subtractive or forming manufacturing of CM, AM builds up the parts by iterative addition of layers [3]. As a result, more complex geometries and reduced material use in production can be achieved. Therefore the advantage of AM regarding ecological sustainability often lies in material efficiency and its application in the production of lightweight parts [4,5]. One of the most widely used AM technologies is the Powder Bed Fusion of metals using a laser-based system (PBF-LB/M). In this process, metal powder is melted layer by layer using a controlled laser beam movement [6,7]. Since AM is still a young manufacturing method compared to CM (the first patents for AM were filed in 1984 [7]), the preparation of an LCA is a particularly complex task due to the lack of process knowledge and data [8,4,9]. The process route for PBF-LB/M requires several pre- and post-processing steps, such as powder production and separation of the part from the supporting metal plate (with the associated loss of material). Those steps and their impacts are often neglected in an assessment [10,4]. So, it is not certain for which parts the AM process route is an option with lower GWP compared to CM. This work aims to facilitate the selection of parts with less GWP in production through AM. A method is presented to derive an assessment equation that facilitates this selection for product families and different process scenarios of a defined process route.

2. State of the Art

The reduction of effort when carrying out an LCA is already a widely discussed topic (see reviews of [11,12]). For example, Beemsterboer et al. alone summarized 166 sources in their literature review. For that, they used the database of ‘Scopus’ and ‘Web of Science’ and conducted different ways of spelling ‘LCA’ with ‘simplification’, ’streamlining’, ’scoping’, and ‘screening’ for the search. Due to the high amounts of hits (2653 hits), they decided to exclude abstracts and keywords from the keyword search [11]. Based on these sources 5 simplifying logics for LCA were defined. However, these logics still present generic solutions for the LCA of products and processes, which apply to a wide range of contexts. The approaches for specific production decisions in industry are very broad and still represent a very complex and time-consuming method.

The evaluation of the GWP of AM and CM process routes have also been discussed in several papers, such as [13–16], and is done by establishing LCAs for both process routes. For PBF-LB/M in particular, the results of the comparative LCA analyses deviate strongly [14,17–19,10,20,21]. The reason can be found in the difference between the considered process steps, industry sector, and material of a part and defined LCA system. Table 1 gives an overview of all comparative LCA analyses for PBF-LB/M with information on their modeling and key results. The fact that the results change depending on the industry and the part illustrates the complexity of the issue. None of these studies have addressed the question of how to identify parts where AM leads to a reduced GWP using a less complex method besides LCA.

Table 1 Literature review for comparative LCA between CM and AM (using PBF-LB/M).

Reference	Compared process steps with process route of	Material	System boundary	Part/ industry sector	Key finding
[14]	casting, forging, assembly	system of aluminum, cast iron, low-alloy steel, stainless steel	cradle-to-gate	automotive part: whole engine	• in the future, AM printing will be favorable for GWP reduction. • electricity mix is significant whether AM is worthwhile
[17]	Electron Direct Melting (EDM)	aluminum alloy	cradle-to-gate	compressor wheel	• EDM needs less energy than PBF-LB/M • higher packed build jobs produce less GWP

[18]	milling, cutting, turning, casting	aluminum alloy	cradle-to-gate	aircraft: seat buckle, fork fitting	• AM parts may use as little as 1/3 to 1/2 of the energy needed to produce CM parts
[19]	forming, turning	aluminum alloy	cradle-to-grave	four tubes	• PBF-LB/M does not appear to be a green solution without weight reduction
[10]	turning, milling, hobbing, casting, rolling, annealing, sawing, melting	steel, aluminum alloy	cradle-to-gate	gear	• Material losses and energy consumption for PBF-LB/M are important parameters for making it more sustainable. Energy consumption outweighs the ecological impact caused by material losses.
[20]	casting, aging, milling, drilling	stainless steel	cradle-to-gate	hydraulic valve	• PBF-LB/M is more environmentally sustainable than CM • powder preparation stage has the largest ecological impact through the life cycles
[21]	casting	nickel alloys	cradle-to-gate	aircraft: engine turbine blade	• reduction of the GWP and ecological impact in the use of AM is approximately 4% in comparison to CM for the given part.

3. GWP-method

The method developed here is used to derive an assessment equation that comparatively quantifies the ecological impacts between AM and CM for fixed production routes. On the one hand, the method is intended to simplify the production decision between AM and CM regarding the ecological impacts, and on the other hand, the derived assessment equation can be used to analyze the process route for different production scenarios. Global Warming Potential (GWP) is chosen as the quantified impact category for the assessment, which is expressed in units of CO_2 equivalent (kg CO_2 eq.), so the method is referred to as the GWP-method in this paper. The method identifies the hotspots, and the scope is reasonably narrowed without significantly weakening the informative value for decision-making. Hotspots are in this work the most significant production steps in terms of GWP. To establish an assessment equation that relatively compares the GWP of the AM and CM process routes, the hotspots of GWP first be identified for both process routes. The assessment equation is called the Global warming Potential Assessment Equation (GWPAE) in this work. For the hotspot identification, a reduced approach of an LCA analysis is carried out which performs both a horizontal and vertical reduction of the inventory model according to the definition of [11]. Therefore, the LCA includes the modules of extraction and production and includes the process steps that differ between the production route of AM and CM. So, **step 1** is the analysis of the use case and determination of the production routes for AM and CM together with the needed input and output sources like electric energy, materials, wastes, etc. Afterward, **step 2** identifies the different process steps of both process routes. **Step 3** includes the creation of the LCA models for the different process steps for AM and CM. Based on the LCA results the GWP hotspots HS were identified in **step 4**. The last step (**step 5**) is the establishment of the GWPAE that follows the form as shown in equations (1) and (2).

$$\Delta\mathrm{GWP}(GWP_{AM}, GWP_{CM}) \ = GWP_{AM}(HS_{AM,i}) - GWP_{CM}(HS_{CM,i}) \tag{1}$$

$$GWP_{PR} = \sum_{PR,i=1}^{PR,N} EF_{PR,i} \times HS_{PR,i} \tag{2}$$

Parameter	Explanation
ΔGWP	difference of GWP between AM and CM [kg CO_2 eq.]
GWP_{PR}	Amount of GWP of the process route PR
PR	type of process route with $PR \epsilon [AM, CM]$
$HS_{PR,i}$	hotspot i of process route PR [unit]
$EF_{PR,i}$	emission factor of the hotspot i in the process route PR [kg CO_2 eq. per unit]
i	index
PR, N	amount of identified hotspots N in the process route PR

So ΔGWP can be interpreted accordingly:

- $\Delta GWP < 0$: GWP of the CM is higher than of the AM process route
- $\Delta GWP > 0$: GWP of the AM is higher than of the CM process route

Emission Factors EF indicates how much GWP is released when a defined quantity of an energy source or material is used and can be looked up in different sources like databases such as Ecoinvent [22] etc. The application of the GWP-method through the five described steps is also schematically shown in Figure 1.

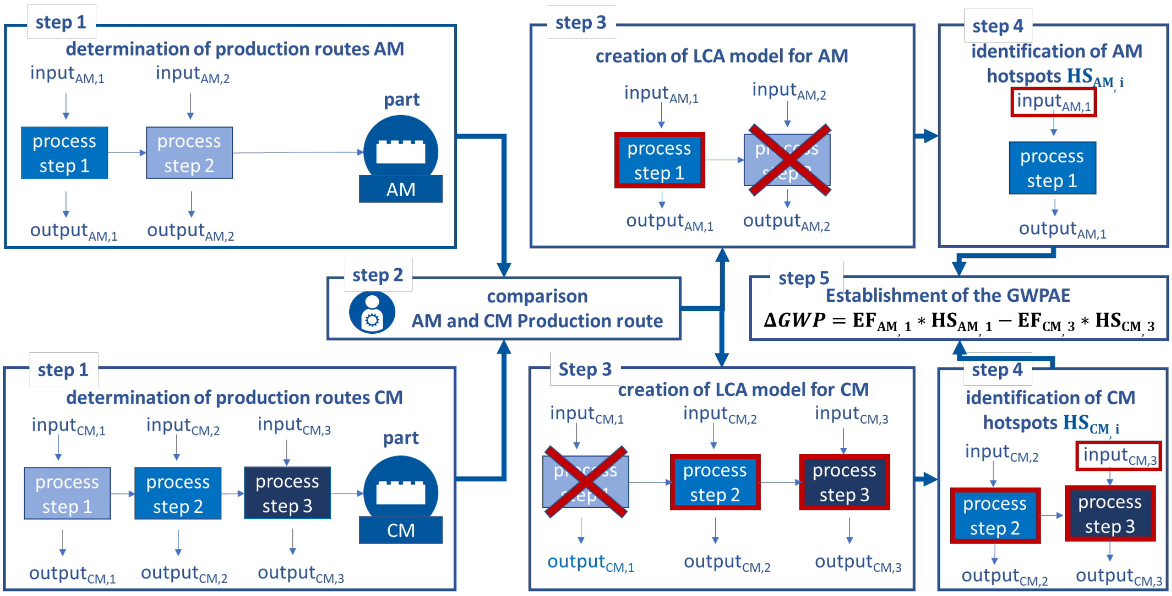


Figure 1: Schematic illustration of the GWP-method in the five steps.

4. Case study

In this work, the GWP-method is presented for an aircraft turbine bearing ring with cooling channels (material: M50NiL). The design of the bearing ring differs for the two process routes. The CM design is an assembly of two rings for the integration of the cooling system. The AM design can be printed directly as one part therefore the AM design allows placing the cooling system closer to the heat generation of the turbine. In addition, a weight reduction of 1 kg of the metal alloy can be achieved. More information about the use case can be found in [23].

Application of the GWP-method for the case study

Steps 1-3

First, the LCA is set up for the process route. Thus, the LCA aimed to quantify the GWP for the fabrication of one bearing ring by AM and CM [25]. Together with the bearing ring manufacturer, the different process steps between AM and CM are identified. This includes the process steps for CM forging, piercing, and ring milling. For AM the steps of PBF-LB/M, powder atomization, and Hot Isostatic Pressure (HIP) were included in the LCA (see Figure 2). Transport by lorry between the location of the bearing ring manufacturer and the company that used the bearing ring in the turbine was also considered due to the different part weights for AM and CM production. The distance between the companies is 189 km. [26]. Also, a green production (argon production with eco-electricity) of the argon is assumed. The bearing ring production took place in Germany, so the average energy mix of Germany is set as the energy source. The AM and CM process routes were detailed about input and output materials and a system was created for both process routes with primary and secondary data. The data used are presented in Table 2 for AM and Table 3 for CM.

The LCA follows ISO 14.044 recommendations with the exception that no external critical review of the results was carried out by third parties [24]. The impact assessment used the European CML-IA baseline from Ecoinvent v3 and the Global Warming Potential (GWP100) is set as the relevant impact category regarding the goal and scope of this study [24,22]. To perform the LCA, the data utilized for the AM processes were collected from the industrial partner of the manufacture of the bearing ring, and CM data was gathered from secondary sources from the literature. The simulations were done with SimaPro software, version classroom v.9.1.0.8, and the integrated database Ecoinvent v3 [22].

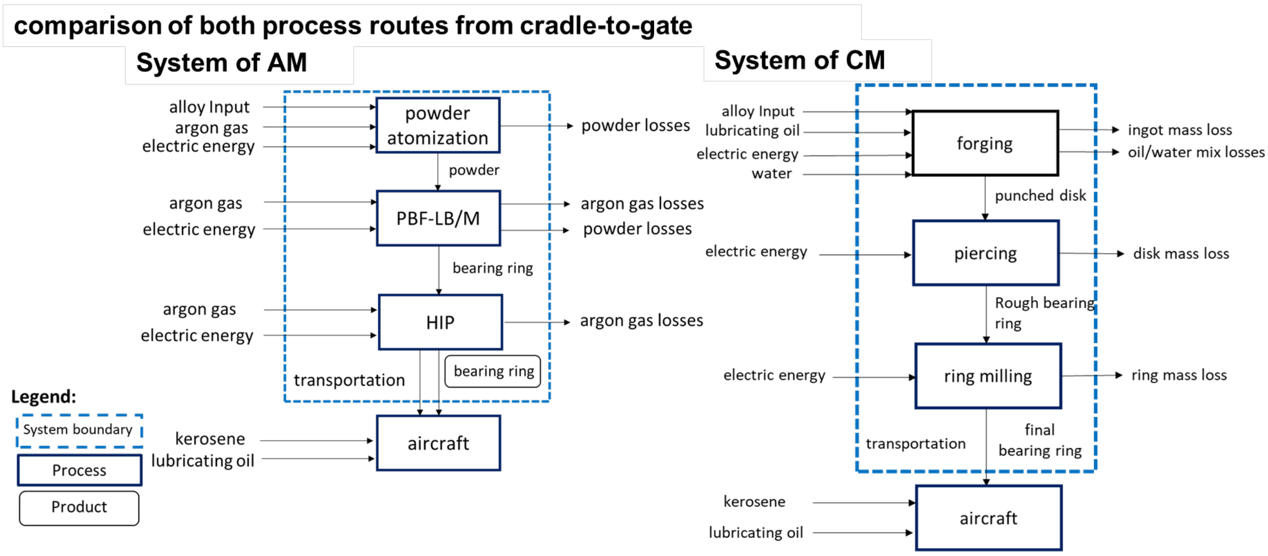


Figure 2: LCA model of the AM and CM process route from cradle-to-gate.

Table 2: Parameter for the AM process route.

Additive Manufacturing				
Unit process	**Parameters**	**Value**	**Unit**	**References**
powder atomization	alloy input	6,45	kg	primary source of manufacturer
	powder losses	1,45	kg	primary source of manufacturer
	electric energy	18,97	MJ	calculated based on [14]
	argon gas (green production)	9,70	kg	calculated based on [17]
PBF-LB/M	powder	5	kg	primary source of manufacturer
	powder losses	3	kg	primary source of manufacturer
	electric energy	195,84	MJ	calculated based on [27] and [28]
	argon gas (green production)	35	kg	calculated based on [29]
	argon gas losses	6,75	kg	measured in DAP labs
Hot Isostatic Pressing (HIP)	material input (bearing ring)	2	kg	primary source of manufacturer
	ring output (final bearing ring)	2	kg	primary source of manufacturer
	electric energy	3	MJ	calculated based on [30]
	argon	3,07	kg	calculated based on data from the manufacturer
	argon losses	0,15	kg	calculated based on data from the manufacturer

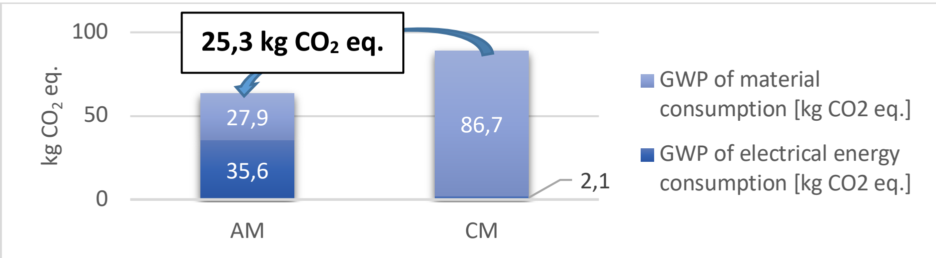
Table 3: Parameter for the CM process route.

Conventional Manufacturing				
Unit process	**Parameters**	**Value**	**Unit**	**References**
forging	alloy input	20	kg	primary source of manufacturer
	ingot mass loss	6	kg	calculated based on [31]
	electric energy	10	MJ	calculated based on [32] and [33]
	lubricating oil	0,338	kg	calculated based on [33]
	oil/water mix losses	1,64	kg	calculated based on [33]
piercing	punched disk input	14	kg	calculated based on [31]

	disk mass loss	0,7	kg	calculated based on [31]
	electric energy	0,18	MJ	calculated based on [32] and [34]
ring milling	rough bearing ring	13,3	kg	redundant
	final bearing ring	3	kg	primary source of manufacturer
	ring mass loss	10,3	kg	redundant
	electric energy	0,21	kJ	calculated based on [35] and [36]

Step 4

The results from the LCA show that 63,6 kg CO_2 eq. are emitted to produce the bearing ring by AM and 88,8 kg CO_2 eq. for the production process by CM. Therefore, the AM bearing ring from cradle-to-gate emits 25,3 kg CO_2 eq. (28,5%) less than the bearing ring produced by means of CM. In the CM route, the influence of the extraction of the metal alloy to produce the part is the largest share of the total GWP with 97,9%. GWP of AM is mainly caused by the extraction of the used metal alloy of the bearing ring (here M50NiL) and the energy consumed by the laser beam for the print process. Thereby, 49% of the GWP is caused by the electrical energy consumption for the printing process and 43,9% is prevenient from the material extraction of the metal alloy. 5% of the GWP originates from energy consumption during powder atomization. The results of the LCA calculation together with an overview of the percentage of GWP of the different process steps are shown in Figure 3.



Process route	Origin of GWP		Percentage of GWP for AM and CM [%]
CM	GWP of electrical energy consumption	forging	1,90
		other process steps	0,100
	GWP of material consumption	part metal alloy	97,9
		other materials	0,100
AM	GWP of electrical energy consumption	print process	49,0
		powder atomization	5,00
		other process steps	2,00
	GWP of material consumption	part metal alloy	43,9
		other materials	0,100

Figure 3: LCA results of the cradle-to-gate system of the bearing ring for AM and CM process route.

The hotspots of GWP for both process routes are in the extraction of the metal alloy w_{alloy}. For the AM process route, there is the additional hotspot of the electrical energy required for the print e_{print} and powder atomization e_{powder}.

Step 5

Based on the hotspots identified in Step 4 the following GWPAE can be established analog to equations (1) and (2):

$$\Delta \text{GWP}(CF_{AM}, CF_{CM}) = GWP_{AM}(HS_{AM,w_{alloy}}, HS_{AM,e_{print}}, HS_{AM,e_{powder}}) - GWP_{CM}(HS_{CM,w_{alloy}}) \quad (3)$$

$$GWP_{AM} = EF_{AM,w_{alloy}} \times HS_{AM,w_{alloy}} + EF_{AM,e_{print}} \times HS_{AM,e_{print}} + EF_{AM,e_{powder}} \times HS_{AM,e_{powder}} \quad (4)$$

$$GWP_{CM} = EF_{CM,w_{alloy}} \times HS_{CM,w_{alloy}} \quad (5)$$

5. Results

Using the derived equation GWPAE (see equation (3)-(5)) the calculated difference of GWP between AM and CM amounts $\Delta\text{GWP}(CF_{AM}, CF_{CM}) = -24{,}5$ kg CO_2 eq. Table 4 shows the used values for the calculation of the GWPAE. Here is the EF of the metal alloy of AM and CM $EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$ equal because both routes used the same material. Also, the energy mix that was used is equal for the powder atomization and print. Therefore $EF_{AM,e_{print}} = EF_{AM,e_{powder}}$ is also valid. The difference of GWP between AM and CM based on the results of the established LCA amounts $\Delta\text{GWP} = GWP_{AM} - GWP_{CM} = -25{,}3$ kg CO_2 eq. (see step 4 in subsection 4.1). So, the difference between the LCA and GWPAE results is less than 3,2%. Also, the GWPAE predicted that AM's process route causes a lower GWP compared to CM. It can thus be seen that the differences in GWP of AM and CM can already be mapped with little deviation over a few hotspots. In the next section, it is examined whether the derived GWPAE also provides valid results for other production scenarios.

Table 4: Values of the GWPAE for the origin process route of AM and CM.

Name of the parameter	Value	Source
$HS_{AM,w_{alloy}}$	6,45 kg	primary source of manufacturer
$HS_{CM,w_{alloy}}$	20 kg	primary source of manufacturer
$HS_{AM,e_{print}}$	195,84 MJ	calculated based on [27] and [28]
$HS_{AM,e_{powder}}$	18,97 MJ	calculated based on [14]
$EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$	4,33 kg CO_2 eq./kg	EcoinventV3 (for the material M50NiL)
$EF_{AM,e_{print}} = EF_{AM,e_{powder}}$	0,159 kg CO_2 eq./MJ	EcoinventV3 (for the average energy mix of Germany)

6. GWPAE testing for another production scenario

For the study, the production scenario investigated whether AM or CM production led to a lower GWP if the powder in the build chamber of the PBF-LB/M machine is not reused for the next print. This is a real and common scenario in the aerospace industry for some part groups. It is checked if the GWPAE also predicted a valid estimation of the difference of GWP between AM and CM for another scenario. For checking the GWPAE the LCA for AM and CM of chapter 3 in Steps 1-3 were aligned for the new production scenario. So, the GWP of AM and CM are comparable. Therefore, the parameters in Table 2 "Alloy input" in the powder atomization process step are increased from 6,45 kg to 22,5 kg and the “electric energy” from 18,9 MJ to 66,15°MJ. Also, the "Powder losses" in the PBF-LB/M step are increased from 3 kg to 12,5 kg. The LCA was carried out again with the newly set values. Figure 4 shows the GWP [kg CO_2 eq.] calculated by the LCA.

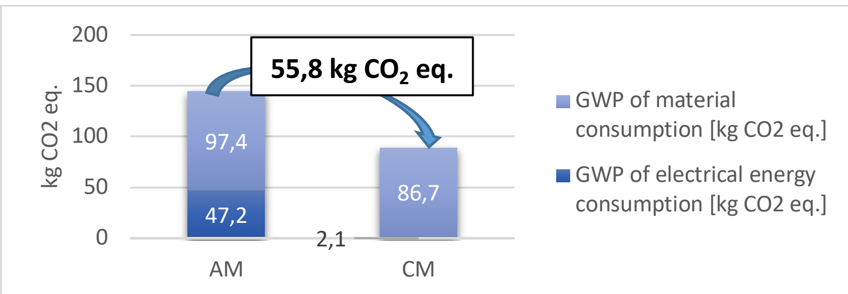


Figure 4: GWP of production scenario without powder recycling.

The difference of GWP through the LCA is 55,8 kg CO_2 eq. Using the derived GWPAE (see equation (3)-(5)) the calculated difference of GWP between AM and CM amounts $\Delta\text{GWP}(CF_{AM}, CF_{CM}) = 52{,}5$ kg CO_2 eq. and predicts that for the production scenario a lower GWP is caused by CM compared to AM. The used values for the calculation through GWPAE are shown in Table 5.

Table 5: Values of the GWPAE for the scenario without powder recycling.

Name of the parameter	Value	Source
$HS_{AM,w_{alloy}}$	22,5 kg	primary source of Manufacturer
$HS_{CM,w_{alloy}}$	20 kg	primary source of Manufacturer
$HS_{AM,e_{print}}$	195,84 MJ	calculated based on [27] and [28]
$HS_{AM,e_{powder}}$	66,15 MJ	calculated based on [14]
$EF_{AM,w_{alloy}} = EF_{CM,w_{alloy}}$	4,33 kg CO_2 eq./kg	EcoinventV3 (for the material M50NiL)
$EF_{AM,e_{print}} = EF_{AM,e_{powder}}$	0,159 kg CO_2 eq./MJ	EcoinventV3 (for the average energy mix of Germany)

So, the deviation between the results is 5,9%. This shows that the GWPAE can be used as a tool to estimate the GWP difference between AM and CM for different production scenarios if the same process route is used. The elaborated GWP-method facilitates the identification of the more favorable manufacturing process for a specific part in terms of emission reduction.

7. Summary and outlook

In this work, a GWP Assessment Equation was introduced via an established GWP-method. The GWP-method assumes that the GWP of a process route can already be reproduced validly enough by analyzing the most relevant steps (hotspots) to make production decisions for parts as of when production led to a lower GWP for AM or CM. The GWP-method was demonstrated with the setup of a part from the aerospace industry. The identified hotspots for CM were the material extraction of the metal alloy of the part. The identified hotspots for AM were the electrical energy consumption for the print and powder atomization and the extraction of the metal alloy. Based on the identified hotspots, the GWPAE was then established and compared with the LCA results. Also, the GWPAE was tested by setting up a different production scenario. It was found that the GWP differences of AM and CM between the LCA calculation results and the GWPAE were only between 3 and 6%. The GWPAE can thus be used to comparatively investigate different production scenarios in terms of GWP between AM and CM.

Since the hotspots can change with different process routes, the GWPAE can only be applied to product families and production scenarios that are manufactured with the same process route. With a different process route, the GWP-method for deriving the new GWPAE would have to be conducted again. In the future, further process routes are investigated using LCAs to obtain more knowledge about the variance of the hotspots with changes in the process route. Furthermore, it is checked if the hotspots for parts made of other materials would be different. The work thus gives a first indication of which GWP-methods can be used to make more sustainable production decisions in the future, but further studies are still needed. In the long run, the method described here could help industries to select manufacturing technologies for their process routes and to predict the inherent GWPs.

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