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Bekker, Anne; Verlinden, Jouke

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LIFE CYCLE ASSESSMENT OF WIRE + ARC ADDITIVE MANUFACTURING COMPARED TO GREEN SAND CASTING AND CNC MILLING IN STAINLESS STEEL

Anne C.M. Bekker, Jouke C. Verlinden

Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands

Abstract

Wire and Arc Additive Manufacturing (WAAM) is a metal 3D printing technique based on robotic welding. This technique yields potential in decreasing material consumption due to its high material efficiency and freedom of shape. Empirical measurements of WAAM, using a deposition rate of 1kg/h, were performed on site of MX3D. The measured power consumption per kg stainless steel is 2.72 kW, of which 1.74 is consumed by the welder, 0.44 by the robotic arm, and 0.54 by the ventilation. The material loss was 1.1%. A 98% argon 2% CO2 welding gas was used with a flow of 12 l/min.

A cradle-to-gate Life Cycle Assessment (LCA) was performed. To give this assessment context, green sand casting and CNC milling were additionally assessed, through literature and databases. The purpose of this study is to develop insight into the environmental impact of WAAM. Results indicate that, in terms of total ReCiPe endpoints, the environmental impact of producing a kg of stainless steel 308l product using WAAM is comparable to green sand casting. It equals CNC milling with a material utilization fraction of 0.75. Stainless steel is the main cause of environmental damage in all three techniques, emphasizing the importance of WAAM's mass reduction potential. When environmentally comparing the three techniques for fulfilling a certain function, optimized designs should be introduced for each manufacturing technique. Results can vary significantly based on product shape, function, materials, and process settings.

Keywords: LCA; additive manufacturing; wire + arc additive manufacturing; metal 3D printing; environmental impact

1 INTRODUCTION

The fabrication of metal parts and products is a significant contributor to multiple aspects of environmental damage (Norgate et al. 2007). The impact of the metal industry is especially high in the aircraft sector due to high buy to fly ratios that result in high waste volumes. Furthermore, the requirement of spare parts in automotive and aerospace industries implies a large volume of unused stock that cannot be repurposed (Rossetti & Choi 2005). Such requirements also lead to a conservative innovation strategy. In the last decades, additive manufacturing (AM) or 3D printing techniques have been developed. AM is a means of building up a 3D shape by 'printing' (depositing, solidifying, or fusing), layer on top of layer (Gibson et al. 2010). Although AM is typically slower than conventional manufacturing technologies, it enables one-off products, customization, makes the supply chain redundant and lead times shorter. AM is often seen as a disruptive technology, which does not only offer production flexibility and customization, but also material and resource efficiency (Huang et al. 2013).

It is important to assess the full environmental impact of new manufacturing techniques, to enable others to make a well-informed choice environmentally-wise. At this moment, there is limited research on the environmental impact of AM techniques, specifically for metal production (Bekker et al. 2016). While such techniques may be more efficient in material consumption, its energy use per produced part is considerable (Baumers et al. 2016). (Huang et al. 2016) on the other hand, highlights the energy savings potential in the case of lightweight aircraft components.

One promising technique is Wire and Arc Additive Manufacturing (WAAM). WAAM is a technique in which a shape is fabricated by welding layer upon layer with a robotic arm, until a desired three-dimensional shape has been formed (Ding et al. 2015). It can span larger areas than other additive manufacturing techniques for metals (Frazier 2014); while other AM techniques are bound to a predefined bounding box, WAAM can theoretically print objects of any size, as demonstrated by the six-metre 3D spar structure at Cranfield University[1] and the proposed 3D printed bridge by MX3D[2]. Furthermore, investigations into mechanical properties show promising results. In the case of titanium WAAM, the strength is only approximately 10% less on average than extruded titanium, with a similar ductility (Wang et al. 2013). Furthermore, fatigue life exceeded extruded titanium in most tested specimen. Measurements of WAAM printed stainless steel samples are still in development.

The WAAM process in this case is based on gas metal arc welding (GMAW, also known as MIG). As depicted in Figure 1, this technique is based on depositing metal as an electrode wire by creating an arc with DC power, while an inert gas is added to shield oxygen and pollutants from the weld pool. The workflow starts with a CAD model, which is converted to robot paths by a deposition strategy (Busachi et al. 2015). Challenges of WAAM involve improving deposition strategies and recovery of deposition failures (Mehnen et al. 2010).

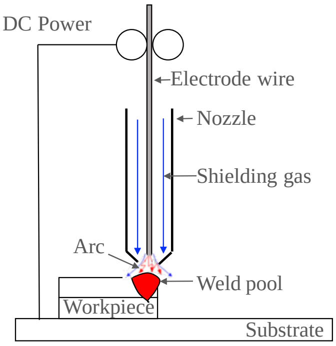

FIGURE 1. Schematic of gas metal arc welding.

While currently in its infancy, a number of academic and commercial institutes are actively working on WAAM applications, e.g. for aerospace, marine, and construction domains (Busachi et al. 2015). One of the benefits of AM and WAAM is the ability to create lightweight, optimized structures. The sofa in Figure 2 shows an example of a lightweight structure made with WAAM. Such shapes and constructive features could or would not be made with casting, CNC milling, or other conventional manufacturing technologies. This implies that a benchmark with new manufacturing techniques should include designs fulfilling the same function, optimized for the specific manufacturing technique, compared to a conventionally produced product (Tang et al. 2016).

FIGURE 2. Dragon Bench sofa, made in stainless steel by WAAM, measuring 2x4x2 meters[3].

This article assesses the environmental impact of WAAM compared to traditional manufacturing means of stainless steel components: green sand casting and CNC milling. The next section describes the methodology of this assessment, including the material and energy flows. This is followed by the results, discussion and conclusion.

2 METHODOLOGY

A life cycle approach is taken for assessing the environmental impact. Life cycle assessment (LCA) is a method for analysing the complete life cycle of a product, process or system, from raw material acquisition to end-of-life treatment, in terms of environmental effects (The International Standards Organisation 2006). An LCA consists of four steps: setting the goal and scope of the study; inventorying the material and energy flows of the system; assessing the impact of the material and energy flows; and interpreting the results. This LCA is performed in line with the ISO framework (The International Standards Organisation 2006).

2.1 GOAL AND SCOPE DEFINITION

The main objective of this study is to assess the environmental impact of WAAM, with the intent to enable further research and development on cleaner production systems through digital production. To give this assessment context, WAAM is compared to green sand casting and CNC milling. Both techniques are well-known, widely used, and suitable for one-off products and small series. In addition, both possess the ability to make relatively complex shapes, making them viable manufacturing alternatives.

When comparing these technologies, the structural component is important. This is determined by a combination of shape and material properties (e.g. tensile strength and isotropy). Material properties of manufactured metal differ per technology, as well as tolerances and the geometries possible to manufacture. As mentioned in the introduction, this should be addressed when comparing technologies; however, this is outside the scope of this study. Aside the resources required for design optimization, the structural properties of WAAM produced materials are not yet certain. The results of this study should, however, be easily applicable to such case studies. For these reasons, the *functional unit* is mass-based. This enables potential future research to easily apply the environmental data resulting from this assessment to case studies and other comparisons. For future research, it is recommended to perform a case study in which the impact of design optimized products for each of the three manufacturing methods, fulfilling the same function, are compared. Note that this impact will vary with the type of metal. The functional unit has been defined as the impact per kilo of manufactured 308l in a one-off (batch size of one) production. For WAAM, the size of the batch is irrelevant for its impact. For casting, due to the mould making, it is relevant however. As no specific product is assessed in this study, a cradle to (factory) gate analysis is executed.

System boundaries represent the borders between what is, and what is not taken into account in an LCA. There are two main reasons for determining the boundary of the system: time (and money) available, and significance (influence on the total environmental impact). The more in detail and depth the assessment is, the more accurate its results will be. However, every step further down the tree takes an exponentially larger amount of time. At a certain point, there is not much value in going down deeper for the assessment due to its low influence on the complete impact. Assessing the tools, materials, energy, and emissions used for producing the tools that made the welder used for WAAM will not only take an immense amount of time and data, but will also likely have a near zero effect on the total impact of the system.

In this analysis, the machinery itself is not assessed. In addition to the substantial amount of time and effort it would take to assess it, with many unknowns within its (sub)systems, the machinery is assumed to have little influence on the total impact per stated functional unit. This assumption is based on the following logic. Imagine a robot is printing stainless steel for 8 hours a day, 260 days a year, for a minimum duration of 5 years. Stainless steel is known to have a high environmental impact, as can also be seen in the results of this study. Depending on the parameters, at this point in time, a robot prints on average between half a kilo and a kilo of 308l per hour. Adding this up over 5 years, it does not seem farfetched to neglect the manufacturing of the robot, as well as other used machinery in either WAAM, green sand casting, and CNC milling. Minor maintenance and consumables for WAAM, CNC milling and green sand casting are neglected as well. The electricity the machinery consumes however, is assessed.

Figure 3 shows the assumed logical processing steps from raw material to factory gate for WAAM, CNC milling, and green sand casting. Note that the block of stainless steel includes all flows up until the material, including mining. Transport between these individual steps has been neglected due to its low significance (<1%). A smooth process is assumed for all manufacturing techniques.

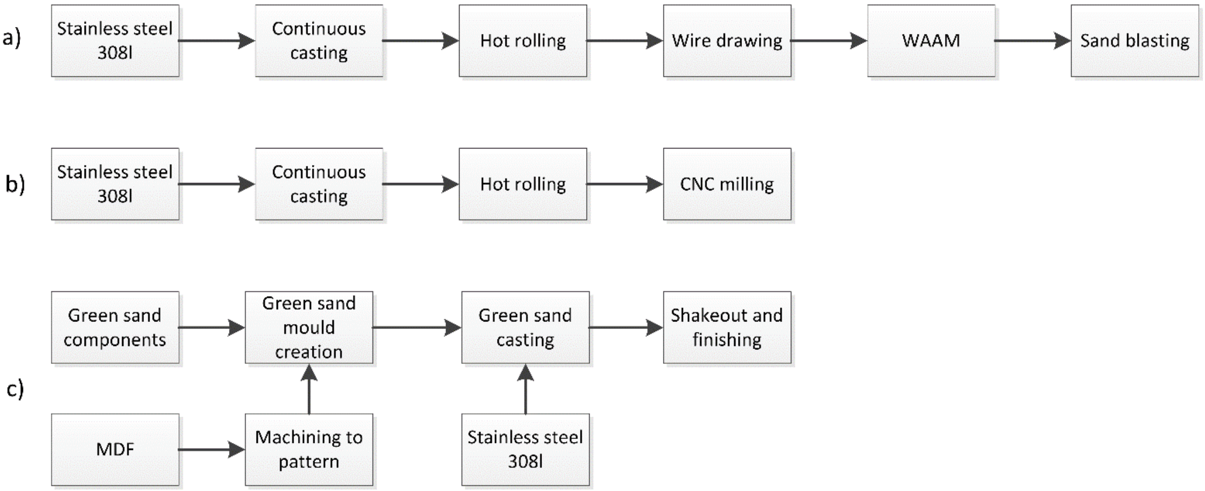

FIGURE 3. Processing steps of a) WAAM, b) CNC milling, and c) green sand casting, from raw material to factory gate. Note that stainless steel 308l includes all flows up to mining.

2.2 MEASUREMENTS ON WAAM

Empirical measurements on WAAM were executed on site of MX3D. Power consumption, gas flow, welding wire and waste were measured. The final used measurements are performed while printing three tubes simultaneously, to avoid waiting for previous layers to cool down. The welding base plate and the spindle of welding wire were weighed before and after printing, to measure the weight of the print and the consumed welding wire respectively. The difference of these two masses indicates the metal waste, induced by welding spatter. The power consumption was measured with this same principle: a kWh meter was read out before and after the print. The power consumption of the robot, the welder, and the ventilation were measured separately. The test print took one hour and 17 minutes. Mass of the print was 1.286 kg. Total welding wire consumed was 1.300 kg. The deposition rate, or printing speed, was approximately 1kg/h. Gas flow was set to 12 l/min. In the next section, the material flows resulting from this test are explained.

2.3 INVENTORY ANALYSIS

2.3.1 WAAM

Inputs of wire and arc additive manufacturing (WAAM) consist of welding wire, shielding gas, and electricity. Outputs are emissions to air, the printed object, and welding spatter (waste). Measurements on WAAM have been performed on site of MX3D, as explained in 2.2. This section shows the material flows from cradle to gate, based on these measurements, plus a brief elaboration on the performed measurements. Emissions could not be measured due to the absence of specialized equipment.

Required input material for producing a kg of printed 308l increases by the accumulating effect of material loss during all steps up to the final manufacturing process. Table 1 shows the assumed material utilization fractions concerning the proceeding steps of WAAM, and thereby the mass over which each impact should be calculated. The material utilization fraction indicates the fraction of input material that will be left after the process (different format of buy-to-fly ratio). Table 1 shows that 1.298 kg of stainless steel 308l is needed for manufacturing 1 kg of stainless steel 308l product.

TABLE 1

WAAM utilization fractions and resulting quantities.

Material or process	Material utilization fraction	Mass (kg)
Stainless steel 308l	1	1.298
Continuous casting	0.9	1.298
Hot rolling	0.95	1.169
Wire drawing	0.92	1.110
WAAM	0.989	1.021
Sand blasting	0.99	1.010

Continuous casting creates billets from the input bits of 308l. Material utilization fractions of this manufacturing technique were not found. (BCS Incorporated, 2005) and (Jost 2011) show a melt loss of 5-8% for steel in a direct arc furnace, or 2-3% for an induction furnace; the furnaces best suitable for stainless steel. The continuous casting process after melting is efficient and has little material loss. A material loss of 10% is assumed for continuous casting, giving it a material utilization fraction of 0.9.

Hot rolling improves the material properties of the billets and brings them closer to the desired shape; in this case, metal rod. It is not uncommon for a hot rolling setup to be placed directly after a continuous casting machine, to take advantage of its heated state. In this study however, it is assumed that hot rolling occurs at a different moment. CES EduPack (Granta Design 2016), an interactive materials and processes data tool, shows a material utilization fraction of 0.9-1 for hot rolling. SimaPro (PRé Consultants 2016), which will be described in section 2.4, shows an utilization fraction of ca. 0.95 (50g extra input material is required for 1 kg processed steel according to its model). A material loss of 5% is assumed for hot rolling.

Wire drawing transforms steel rod into welding wire. CES shows a material utilization fraction of 0.85-0.9; SimaPro ca. 0.96 (43g per kilo). Averaged between these two, 0.92 has been applied in this assessment.

Empirical measurements on site of MX3D were performed to gain knowledge on power and material consumption of *WAAM*. The printing speed, or deposition rate, was 1 kg/h. The welding type used is MIG (Metal Inert Gas) short-arc welding. The total power consumption is 2.72 kW per kg, of which 1.74 is consumed by the welder, 0.44 by the robotic arm, and 0.54 by the ventilation. The material loss was 1.1%, by welding spatter (and some cut welding wire). Note that this material loss does not consider possible faulty prints; a proper printing process is assumed, as was the case with this test. A 98% argon 2% CO2 shielding gas was used during welding, with a flow of 12 l/min. This translates to 1.172 kg argon/kg 308l and 0.0265 kg CO2/kg 308l. Note that with a different printing speed, the quantity of consumed welding gas will differ. Printing with higher deposition rates will need relatively less welding gas. In addition, due to a shorter printing time per kg, less electricity will be consumed by the ventilation. For welding itself, the energy efficiency per deposited mass can differ with power, though more research is required on this relation as discussed in (Sproesser et al. 2016). In addition, the melting efficiency of welding is determined by the product of arc power and travel speed (DuPont & Marder 1995); a higher product of arc power and travel speed results in a higher melting efficiency.

Sand blasting removes the oxidation layer that forms on the surface during welding. This lightweight layer constitutes of less than 1% by mass. A material loss of 1% is assumed to account for potential local surface smoothing.

2.3.2 CNC MILLING

For CNC milling, the steps up to hot rolling match those of WAAM, with the difference that the hot rolled parts will not be rod, but bar shaped. The material utilization fraction of CNC milling itself depends on the design. Here, by example, 0.5 will be used.

TABLE 2

CNC milling utilization fractions and resulting quantities.

Material or process	Material utilization fraction	Mass (kg)
Stainless steel 308l	1	2.339
Continuous casting	0.90	2.339
Hot rolling	0.95	2.105
CNC milling	0.50	2.000

2.3.3 GREEN SAND CASTING

Green sand casting starts with the creation of a pattern, which has the shape of the to-be-cast product. For a single or couple of castings, this pattern is generally made of wood. The pattern is usually painted or otherwise coated to reduce sticking to the sand mould and for a better surface finish. A green sand mould is created from this pattern, in which the metal is cast.

TABLE 3

Green sand casting utilization fractions and resulting quantities.

Material or process	Material utilization fraction	Mass (kg)
Stainless steel 308l	1	1.538
Green sand casting*	0.65	1.538
Pattern wood (MDF)	1	0.190
MDF machining	0.50	0.190

*green sand is included in this green sand casting process

CES shows green sand casting has a material efficiency ranging between 0.5 and 0.8. The centre, 0.65, was used for all calculations in this study. Table 3 shows that the manufacturing 1kg of 308l product by green sand casting requires 1.538 kg of 308l. The basic green sand casting flows are extracted from (Dalquist 2004).

Measurements on green sand casting in the United States by the government and industry groups show a power consumption of 2.96 kWh per kilo of metal (Dalquist 2004). This energy includes heating of the metal, mould preparation, casting, and finishing. It does not consider the type of metal input, which consists mainly of iron (72%), aluminium (13%), and steel (10%). The heat input required to melt stainless steel is similar to that of iron. Due to the absence of more specific data, this number will be used as is.

Table 4 displays on-site emissions for an electric arc furnace (EAF) and for shakeout. Shakeout is the process where the cast shape is removed from the green sand mould. This process destroys the green sand mould. A new mould would be required for a second casting.

TABLE 4

Emissions of green sand casting (Dalquist 2004).

EAF emission	Emission (kg)/kg cast metal
Particulate matter	0.0063
Carbon monoxide	0.00925
VOC (volatile organic compounds)	0.00009
Shakeout emission	
Benzene	0.000003765
Formaldehyde	0.000001769

0.5 kg green sand is landfilled per kg of cast metal in the US (Dalquist 2004). Green sand is composed of sand, clay (as binder), water, and optionally carbonaceous additives (e.g. bituminous seacoal, anthracite, or ground coke). Proportions vary depending on required or preferred properties. The sand assumed in this study consists of 89% silica sand (by mass), 7% bentonite clay, and 4% water. Additives, which can for instance cause a better surface finish, are a very small component by mass (Dalquist 2004). Due to the absence of impact data on these additives in addition to its low presence, they are neglected in this this assessment. It is also assumed that no (more polluting) cores are required for the process, and that the process runs smoothly and without failed castings.

Since this assessment concerns a one-off product, the pattern creation should be considered in the assessment. Medium density fibreboard (MDF) is assumed as pattern wood over the more normally used mahogany, for its low cost and easy manipulability. Although the pattern will likely be coated, this coating is not included in this assessment. For creating a pattern of a shape of a kg of steel, assuming double the volume of wood is required to make the pattern, 0.19 kg of MDF is needed.

2.4 IMPACT ASSESSMENT

In this study, SimaPro 8.1.1.16 (PRé Consultants 2016) and ecoinvent 3.3 (Wernet et al. 2016) were used as main data sources. Ecoinvent is a life cycle inventory (LCI) database. SimaPro is an LCA tool which allows one to see, create and adjust the detailed LCI flows of materials and processes, and calculate their impact assessments by a method of choice. SimaPro includes LCI datasets such as ecoinvent. The used libraries within SimaPro are Ecoinvent 3 (allocation, recycled content – unit) and Idemat 2014 v3 (Delft University of Technology 2014).

For expressing the environmental impact, the ReCiPe endpoints method v1.12 is used (Goedkoop et al. 2009). The default and recommended settings are applied: hierarchist perspective, with European normalisation and average weighting[4] (PRé Consultants 2016). Endpoints and midpoints represent impact categories at different stages in the LCIA process. Midpoints express the impact of a system by a series of categories (which can vary per method) such as climate change and acidification. Non-normalized midpoints cannot be added up or compared to midpoints from different categories since most have different units. Endpoints model the environmental impacts in terms of damage to certain areas. ReCiPe's endpoint categories are damage to human health, ecosystem health, and resources. Endpoints have the same unit, and can be added up and compared to each other. For the purpose of easy comparison and communication, results in this study will be expressed in endpoints. To provide more depth, and insight into the affected areas of impact, non-normalized midpoint data is provided additionally at the end of the results section. The ReCiPe midpoint method v1.12 is used, with hierarchist perspective (Goedkoop et al. 2009).

Manufacturing locations for used SimaPro and ecoinvent instances were chosen with the following order of preference: Dutch, European, World. Where data was missing, new instances were created in SimaPro. Data for these instances was extracted from scientific papers, CES EduPack (v16.1.22), and/or adjusted from other instances found in SimaPro. The next section explains how the LCIA is performed and explains the sources of impact data.

2.4.1 WAAM

Table 5 shows the sources of the impact (LCIA) data for all steps of the process tree of WAAM. This table is followed by further information on the data gathering of the impact assessment.

TABLE 5.
WAAM impact data sources.

Material or process	Source
Stainless steel 308l	SimaPro, derived from stainless steel 316l, Idemat 2014 dataset
Continuous casting	Ecoinvent v3.3
Hot rolling	SimaPro, ecoinvent 3 dataset, without steel
Wire drawing	SimaPro, ecoinvent 3 dataset, without steel
WAAM	SimaPro, derived from welding, arc, steel, ecoinvent 3 dataset
Sand blasting	CES (energy based, fine machining)

Stainless steel 308l is not included in any of the accessible databases. It was created in SimaPro by adapting the existing Idemat 2014 instance stainless steel 316l based on the composition of 308l. The 308l used for printing at MX3D is branded Oerlikon[5]. The details of its composition are shown in table 6. A market mix of 40% recycled steel, which is applied in the 316l instance, is maintained, complying with (Vogtlander 2014).

TABLE 6
Stainless steel 308l alloy materials composition (%); manufacturer Oerlikon[5].

C	MN	SI	P	S	CR	NI
0.02	1.8	0.45	<0.025	<0.020	20	10

Continuous casting

LCI data of continuous casting is only available as the continuous casting of aluminium. Due to the introduction of this data only since ecoinvent v3.2, it cannot be found or adjusted within (the used version of) SimaPro itself. The instance of continuously casting stainless steel has been approximated by subtracting the input materials, which mainly consists of the (ecoinvent) instance liquid aluminium, from that of continuously cast aluminium, and substituting it with the energy required to liquefy the same quantity of 308l. This energy is assumed to be 0.5 kWh/kg, based on (Margolis et al. 1999; Biswas et al. 2012).

Hot rolling and *wire drawing* were taken directly from SimaPro, after removing the input steel.

WAAM has been derived from the ecoinvent instance Welding, arc, steel. Emissions of WAAM were not measured due to the absence of specialized equipment. The emissions of the welding instance, which concerns low-alloyed steel, are used as replacement. It is difficult to estimate the significance of the welding fumes. A lower alloyed steel is likely to emit a lower quantity of harmful emissions compared to a stainless steel such as 308l. Normal welding on the other hand tends to consume more power per unit weight of metal deposited, because it needs to heat up more base material and starts at a lower temperature. Due to WAAM's layered approach, previous layers are still hot when the next layer is printed. From (Sproesser et al., 2015) it can be derived that the quantity of emissions is correlated to power consumption. Less power equals less emissions. In the current configuration of WAAM in SimaPro, welding fumes account for 7.4% of its impact.

Argon, the main component of the shielding gas, is included in the WAAM process in SimaPro. However, it could only be found in liquid form in the databases, while compressed argon is used at MX3D. Within SimaPro, the ecoinvent 3 instance Argon, liquid (market for) has been used. This exists of liquid argon production and transport, where transport causes only a small fraction of the impact (<1%). The production of argon occurs through the fractional distillation of liquefied air. It is therefore assumed that this instance should be sufficiently similar to apply to this assessment.

Nothing similar to *sand blasting* could be found in any of the used databases. The energy required to remove the material by fine machining is used instead. Fine machining of 308l in CES costs 3.1 MJ (0.86 kWh) per kg removed. Though this impact likely deviates significantly from the actual impact of sand blasting, it concerns only a very small part of the assessment.

2.4.2 CNC MILLING

Table 7 shows the sources of the impact (LCIA) data for all steps of the process tree of CNC milling. All steps up to CNC milling are the same as the corresponding ones in WAAM.

TABLE 7

CNC milling impact data sources.

Material or process	Source
308l	SimaPro, derived from stainless steel 316L, Idemat2014 dataset
Continuous casting	Ecoinvent v3.3
Hot rolling	SimaPro, ecoinvent 3 dataset, without steel
CNC milling	SimaPro, ecoinvent 3 dataset, chromium steel removed by milling, average, input 'hot rolled chromium steel' removed

The instance of *CNC milling* itself is taken directly from SimaPro. As its CNC variation (computer numerically controlled) is not available, the CNC aspect is not considered. It is expected to be of relatively low significance, and is neglected in this assessment. The impact of conventional drilling is 2.9% lower compared to that its CNC variant. This difference is 7.6% for turning.

Milling is available for three sizes in SimaPro: small, average, and large. Milling smaller sizes has a higher environmental impact compared to average sizes (168% of the average variant); milling larger sizes has a lower impact (90% of the average variant). The average milling size is used for this assessment.

2.4.3 GREEN SAND CASTING

Table 8 shows the sources of the impact data for all steps of the process tree of green sand casting. No assessment of sand casting was found in any accessible databases or datasets. Instead, data from literature, as mentioned in the LCI section, was used to simulate the process of green sand casting in SimaPro.

TABLE 8

Green sand casting impact data sources.

Material or process	Source
308l	SimaPro, derived from stainless steel 316L, Idemat2014 dataset
Green sand casting	(Dalquist 2004; Margolis et al. 1999), SimaPro
MDF	SimaPro, ecoinvent 3 dataset, medium density fibreboard
MDF machining	CES (energy based, 80% coarse 20% fine machining)

The instance of *green sand casting*, including the green sand, was composed in SimaPro with the inventory flows shown in 2.3.3. All applied flows originate from ecoinvent 3.

MDF was taken directly from SimaPro, ecoinvent. *MDF machining*, or anything similar, was not found in SimaPro. The energy required to remove the material by coarse (80%) and fine (20%) machining is used instead. Coarse machining of MDF takes 0.58 MJ; fine machining 1.28 MJ per kg removed. This equates to 0.72MJ per kg removed MDF.

3 RESULTS

This section communicates the impact of WAAM, CNC milling, and green sand casting, per kilo of 308l product. These impacts, including those of all processing steps from raw materials to factory gate as communicated in figure 3, are expressed in ReCiPe endpoints (Pts). Table 9-11 show their damage (impact) to human health, ecosystems, and resources. The impacts of all steps are already multiplied by their respective quantities.

Figure 4 presents a graphical overview of the impacts of the processing steps. In this graph, it can clearly be seen that in either WAAM, green sand casting, or CNC milling, the largest percentage of environmental damage originates from the stainless steel itself. This is a point of opportunity for WAAM, which aims to decrease material consumption with its freedom of shape, enabling the application of topology optimization in addition to producing little waste. The environmental impact is linearly related to the mass of the product. If WAAM would reduce material requirements of a product by 20%, its impact would be reduced with 20%.
45.8% of the impact of 308l is caused by chromium, 23.4% by nickel, and 9.03% by manganese. Most of the impact of stainless steel 308l is caused by alloy components. A lower grade steel would harm the environment significantly less.

The main sources of impact aside the material originate from WAAM, CNC milling, and green sand casting itself. When disregarding the material loss, most of the impact of green sand casting is caused by energy input. With the current assessment, 98.2% of the impact of green sand casting is caused by energy. This number is, however, highly uncertain due to lack of specific data. The material flows of green sand were implemented in the green sand casting instance. These flows account only for a very small percentage of the impact: 1.4%.

For WAAM, 44% of the impact is caused by energy input. 48% is caused by the shielding gas [no liquid argon?]. This shows the significance of WAAMs printing speed mentioned in 2.3.1, since a higher deposition rate needs less shielding gas per unit weight deposited.

The environmental impact of CNC milling is attributed for 18% to electricity, and 53% to energy and auxiliary inputs. These auxiliary inputs exist mainly of energy and (hazardous) waste streams. 22% of the impact is caused by ‘metal working factory’, which is mostly related to land occupation and transformation.

Table 12 and figure 5 compare the endpoint impacts of the three techniques. WAAM and green sand casting have nearly the same total impact, with that of WAAM 3.3% lower. CNC milling with a material utilization fraction of 0.5 has a considerable larger impact. CNC milling is a subtractive fabrication technique, in contrast to the additive nature of WAAM and casting. For better insight on its impact, figure 6 shows the impacts of a range of material utilization fractions of CNC milling next to WAAM. The break-even point between the two lies at a material utilization fraction of 0.75. WAAM causes slightly more damage to human health and less to resources relative to CNC milling and green sand casting.

TABLE 9
Environmental impact of a kg of WAAM manufactured stainless steel 308l, in ReCiPe endpoints (Pt).

Material or process	Material utilization fraction	Mass	Mass removed	Unit	Human Health (Pt)	Eco-systems (Pt)	Resources (Pt)	Total (Pt)
308l	1	1.298		kg	0.483	0.145	0.722	1.349
Continuous casting	0.90	1.298		kg	0.034	0.018	0.031	0.083
Hot rolling	0.95	1.169		kg	0.008	0.004	0.008	0.020
Wire drawing	0.92	1.110		kg	0.013	0.008	0.006	0.027
WAAM	0.989	1.021		kg	0.166	0.072	0.116	0.353
Sand blasting*	0.99	1.010	0.010	kg	0.000	0.000	0.000	0.000
Total					0.704	0.247	0.882	1.832

*The impact for sand blasting is too small to see with the used number of decimals (total of 0.0004885)

TABLE 10

Environmental impact of CNC milling manufactured stainless steel 308l, in ReCiPe endpoints (Pt).

Material or process	Material utilization fraction	Mass	Mass removed	Unit	Human Health (Pt)	Ecosystems (Pt)	Resources (Pt)	Total (Pt)
308l	1	2.339		kg	0.870	0.261	1.300	2.431
Continuous casting	0.90	2.339		kg	0.061	0.032	0.056	0.149
Hot rolling	0.95	2.105		kg	0.025	0.011	0.026	0.062
CNC milling	0.50	2.000	1.000	kg	0.083	0.050	0.051	0.183
Total					1.039	0.354	1.433	2.825

TABLE 11

Environmental impact of green sand casting manufactured stainless steel 308l, in ReCiPe endpoints (Pt).

Material or process	Material utilization fraction	Mass/ volume	Mass removed	Unit	Human Health (Pt)	Ecosystems (Pt)	Resources (Pt)	Total (Pt)
308l	1	1.538		kg	0.572	0.172	0.855	1.599
Green sand casting	0.65	1.538		kg	0.098	0.059	0.103	0.260
MDF	1	0.253		l	0.009	0.014	0.009	0.032
MDF machining	0.50	0.253	0.095	l-kg	0.000	0.000	0.000	0.001
Total					0.680	0.245	0.967	1.892

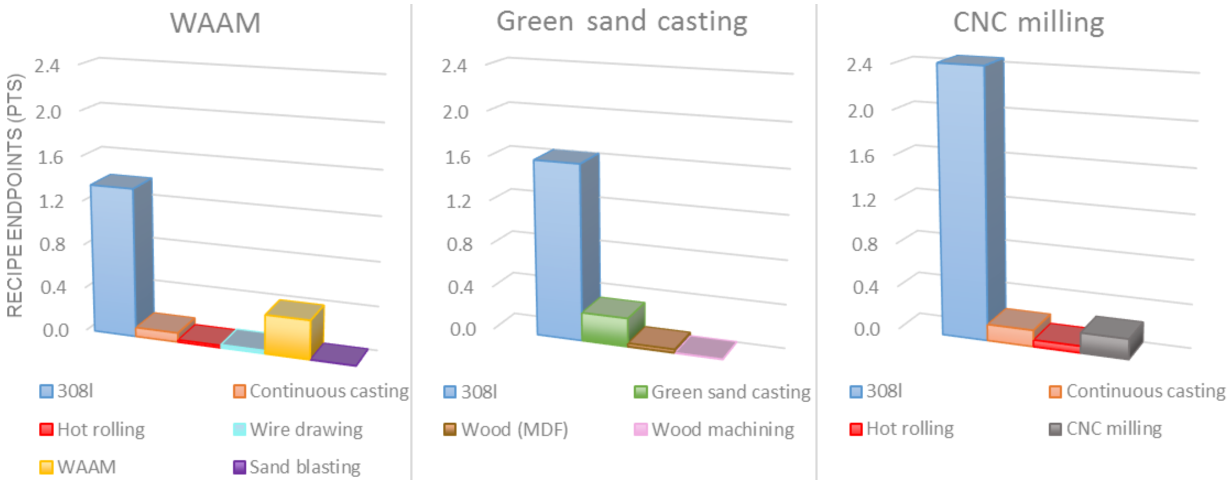

FIGURE 4. Environmental impacts of the processing steps of WAAM, green sand casting, and CNC milling respectively, in ReCiPe endpoints (Pts), per kg of manufactured 308l product.

TABLE 12

Environmental damage of WAAM, green sand casting, and CNC milling per kilo 308l to human health, ecosystems, and resources.

	Human Health (Pt)	Ecosystems (Pt)	Resources (Pt)	Total (Pt)
WAAM	0.704	0.247	0.882	1.832
Casting	0.680	0.245	0.967	1.892
Milling (0.5)	1.039	0.354	1.433	2.825

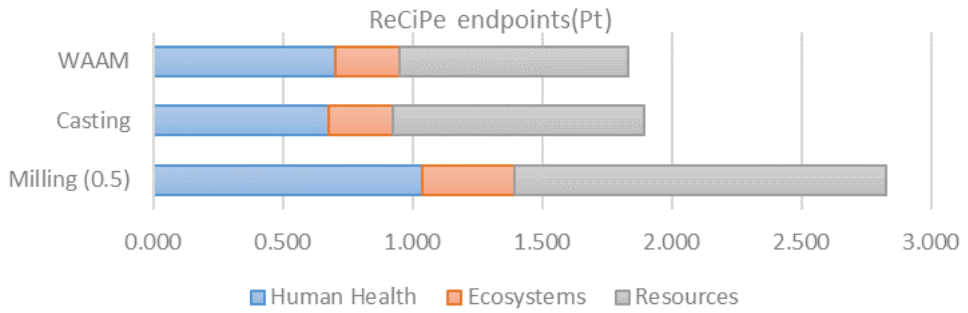

FIGURE 5. Environmental damage of WAAM, green sand casting, and CNC milling, per kg 308l; table 12 visualized.

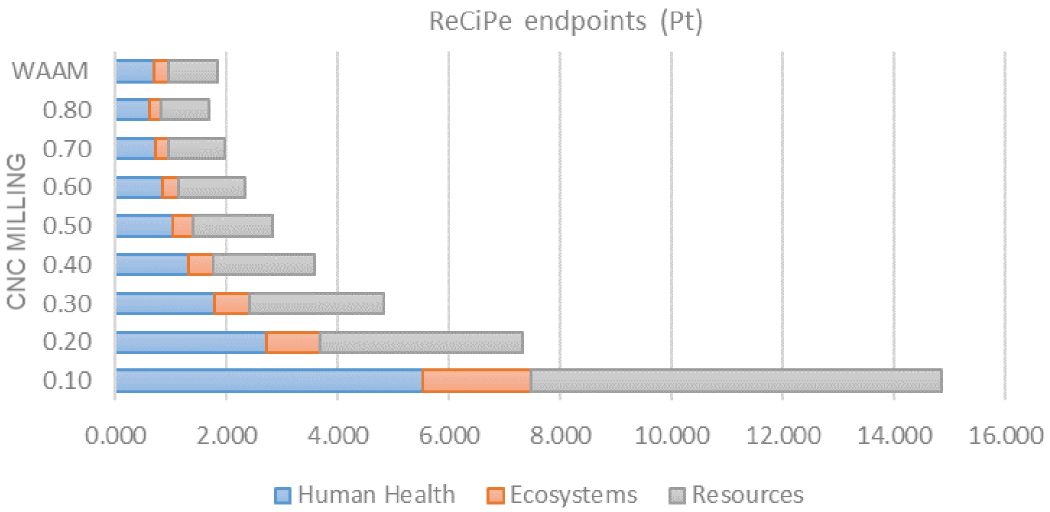

FIGURE 6. CNC milling at different material utilization fractions, next to WAAM.

Midpoint results

Tables 13 to 15 show the impact of WAAM, CNC milling and green sand casting, expressed in non-normalized ReCiPe midpoints. Note that most of these midpoints have different units. These tables are shared for more insight into the environmental impact. They will not be further discussed within this document. For further information on these impact categories, please refer to (Goedkoop et al. 2013).

TABLE 13

Midpoints of WAAM.

Impact category	Unit	Stainless steel 308l	Continuous casting	Hot rolling	Wire drawing	WAAM	Sand blasting	Total
Climate change	kg CO2 eq	7.46E+00	8.73E-01	2.06E-01	3.70E-01	3.69E+00	5.75E-03	1.26E+01
Ozone depletion	kg CFC-11 eq	5.91E-07	5.16E-08	2.43E-08	2.57E-08	2.17E-07	3.04E-10	9.09E-07
Terrestrial acidification	kg SO2 eq	1.07E-01	2.29E-03	6.55E-04	7.40E-04	1.27E-02	5.50E-06	1.24E-01
Freshwater eutrophication	kg P eq	6.61E-03	2.74E-04	7.72E-05	1.26E-04	1.22E-03	1.39E-06	8.31E-03
Marine eutrophication	kg N eq	2.20E-03	4.19E-04	2.73E-05	1.06E-04	5.28E-04	5.42E-07	3.28E-03
Human toxicity	kg 1.4-DB eq	7.38E+00	2.08E-01	7.39E-02	1.12E-01	1.78E+00	1.02E-03	9.56E+00
Photochemical oxidant formation	kg NMVOC	3.15E-02	1.50E-03	7.76E-04	4.46E-04	7.46E-03	6.12E-06	4.17E-02
Particulate matter formation	kg PM10 eq	3.36E-02	1.27E-03	2.57E-04	2.49E-04	7.41E-03	2.02E-06	4.28E-02
Terrestrial ecotoxicity	kg 1.4-DB eq	1.45E-03	6.15E-05	1.13E-05	4.39E-04	1.40E-03	6.34E-08	3.36E-03
Freshwater ecotoxicity	kg 1.4-DB eq	2.11E-01	8.27E-03	5.93E-03	1.03E-02	3.88E-02	5.09E-05	2.74E-01
Marine ecotoxicity	kg 1.4-DB eq	2.13E-01	7.46E-03	5.58E-03	9.88E-03	5.80E-02	4.78E-05	2.93E-01
Ionising radiation	kBq U235 eq	2.39E+00	1.01E-01	5.88E-02	6.04E-02	7.06E-01	7.72E-04	3.32E+00
Agricultural land occupation	m2a	1.78E-01	3.84E-02	4.39E-03	2.63E-02	1.47E-01	2.88E-04	3.95E-01
Urban land occupation	m2a	7.38E-02	8.27E-03	8.34E-04	1.49E-03	1.73E-02	1.75E-05	1.02E-01
Natural land transformation	m2	1.16E-03	2.02E-04	3.69E-05	1.69E-04	5.45E-04	1.06E-06	2.12E-03
Water depletion	m3	-1.92E+00	4.36E-03	1.06E-02	1.76E-02	6.08E-01	1.88E-05	-1.28E+00
Metal depletion	kg Fe eq	1.09E+01	1.01E-02	3.03E-03	9.64E-03	4.71E-02	5.33E-05	1.10E+01
Fossil depletion	kg oil eq	2.01E+00	2.71E-01	7.22E-02	4.89E-02	1.06E+00	1.79E-03	3.46E+00

TABLE 14

Midpoints of CNC milling.

Impact category	Unit	308l	Continuous casting	Hot rolling	CNC milling	Total
Climate change	kg CO2 eq	1.34E+01	1.57E+00	3.71E-01	2.00E+00	1.74E+01
Ozone depletion	kg CFC-11 eq	1.06E-06	9.29E-08	4.38E-08	1.61E-07	1.36E-06
Terrestrial acidification	kg SO2 eq	1.93E-01	4.12E-03	1.18E-03	8.31E-03	2.07E-01
Freshwater eutrophication	kg P eq	1.19E-02	4.93E-04	1.39E-04	7.34E-04	1.33E-02
Marine eutrophication	kg N eq	3.96E-03	7.55E-04	4.93E-05	3.31E-03	8.08E-03
Human toxicity	kg 1.4-DB eq	1.33E+01	3.74E-01	1.33E-01	8.69E-01	1.47E+01
Photochemical oxidant formation	kg NMVOC	5.68E-02	2.69E-03	1.40E-03	5.27E-03	6.62E-02
Particulate matter formation	kg PM10 eq	6.05E-02	2.29E-03	4.64E-04	2.88E-03	6.62E-02
Terrestrial ecotoxicity	kg 1.4-DB eq	2.61E-03	1.11E-04	2.03E-05	1.19E-04	2.86E-03
Freshwater ecotoxicity	kg 1.4-DB eq	3.80E-01	1.49E-02	1.07E-02	1.57E-01	5.63E-01
Marine ecotoxicity	kg 1.4-DB eq	3.83E-01	1.34E-02	1.01E-02	1.37E-01	5.44E-01
Ionising radiation	kBq U235 eq	4.31E+00	1.82E-01	1.06E-01	3.83E-01	4.98E+00
Agricultural land occupation	m2a	3.21E-01	6.91E-02	7.91E-03	1.86E-01	5.84E-01
Urban land occupation	m2a	1.33E-01	1.49E-02	1.50E-03	1.17E-01	2.67E-01
Natural land transformation	m2	2.10E-03	3.63E-04	6.64E-05	8.90E-04	3.41E-03
Water depletion	m3	-3.45E+00	7.86E-03	1.91E-02	2.31E-02	-3.40E+00
Metal depletion	kg Fe eq	1.97E+01	1.82E-02	5.47E-03	9.82E-02	1.98E+01
Fossil depletion	kg oil eq	3.62E+00	4.88E-01	1.30E-01	4.34E-01	4.68E+00

TABLE 15

Midpoints green sand casting.

Impact category	Unit	308l	Green sand casting	Wood (MDF)	Wood machining	Total
Climate change	kg CO2 eq	8.84E+00	3.04E+00	2.04E-01	1.65E-01	1.23E+01
Ozone depletion	kg CFC-11 eq	7.00E-07	1.62E-07	2.10E-08	9.58E-09	8.92E-07
Terrestrial acidification	kg SO2 eq	1.27E-01	3.09E-03	1.41E-03	2.58E-04	1.32E-01
Freshwater eutrophication	kg P eq	7.83E-03	7.35E-04	5.35E-05	4.03E-05	8.66E-03
Marine eutrophication	kg N eq	2.61E-03	2.91E-04	4.79E+00	3.59E-01	5.15E+00
Human toxicity	kg 1.4-DB eq	8.75E+00	5.40E-01	8.64E-02	3.31E-02	9.41E+00
Photochemical oxidant formation	kg NMVOC	3.73E-02	4.03E-03	1.02E-03	2.75E-04	4.27E-02
Particulate matter formation	kg PM10 eq	3.98E-02	1.14E-03	5.03E-04	9.38E-05	4.15E-02
Terrestrial ecotoxicity	kg 1.4-DB eq	1.72E-03	3.84E-05	3.63E-05	4.62E-06	1.80E-03
Freshwater ecotoxicity	kg 1.4-DB eq	2.50E-01	2.69E-02	6.72E-03	1.83E-03	2.86E-01
Marine ecotoxicity	kg 1.4-DB eq	2.52E-01	2.53E-02	5.94E-03	1.69E-03	2.85E-01
Ionising radiation	kBq U235 eq	2.84E+00	4.06E-01	2.25E-02	2.17E-02	3.29E+00
Agricultural land occupation	m2a	2.11E-01	1.54E-01	3.82E-01	3.62E-02	7.83E-01
Urban land occupation	m2a	8.74E-02	1.05E-02	5.29E-03	9.18E-04	1.04E-01
Natural land transformation	m2	1.38E-03	7.06E-04	5.16E-05	3.87E-05	2.17E-03
Water depletion	m3	-2.27E+00	1.10E-02	4.51E-03	8.79E-04	-2.26E+00
Metal depletion	kg Fe eq	1.29E+01	2.92E-02	1.97E-02	2.92E-03	1.30E+01
Fossil depletion	kg oil eq	2.38E+00	9.45E-01	7.39E-02	5.22E-02	3.46E+00

4 DISCUSSION

This LCA comparison indicates that per kilo of 308l, there is no substantial difference in the environmental impact of WAAM versus green sand casting. For CNC milling, the break-even point lies at a material utilization fraction of 0.75. It is important to keep in mind that these assessment results are estimations. They are not definitive answers. The assessment contains significant uncertainties. Uncertainty and sensitivity analyses are outside of the scope of this study. This section will however briefly discuss these subjects, followed by a segment on LCA implementation.

4.1 UNCERTAINTY

Uncertainty in a life cycle assessment can occur due to various causes: incomplete information, variability, scenario, model, parameter, and data uncertainty, LCI and LCIA model choices, system boundaries, and more. All these mentioned sources of uncertainty apply to this study, and can have a significant effect on the assessment. Empirical measurements of WAAM were done on site, reducing the number of uncertainty sources compared to third party data. However, with different printing parameters, results of WAAM's impact will vary. A higher printing speed will require less shielding gas per kg printed metal and vice versa. Emissions of WAAM are already uncertain due to the absence of measurements, and will also vary with printing parameters. Chosen system boundaries, in addition to LCI and LCIA model choices, also add a layer of uncertainty to the assessment.

For all three process trees (as shown in figure 3), there is an uncertainty element of data availability and quality. The authors of this article relied on existing, external databases. Even within a renowned database such as ecoinvent, large variations can occur for similar techniques, or at different geographical locations. This can for instance be caused by errors, or differences in system boundaries, factory equipment, or process efficiency. In addition, plenty of data is still missing in all databases the authors were aware of and had access to.

Green sand casting has a higher uncertainty (and variability) compared to WAAM and CNC milling. While an often and widely used manufacturing technique, it was not implemented in any of these databases. It had to be constructed by data available in scientific research. Its assessment is based on US data versus the Netherlands, Europe, or global. This data was not based on stainless steel, but on all metals cast in the concerning factories. For the melt phase of stainless steel before casting, an inert (e.g. argon) environment may or may not be required. Emissions emanating from the melting phase of stainless steel are not included, as well as potential emissions to water and ground caused by recycling the green sand. Perhaps most important, there is a large variation between different cast products. CES EduPack indicates a material utilization rate between 0.5 and 0.8. In addition, more complex shapes might require (more polluting) cores or a stronger binder.

4.2 SENSITIVITY

The sensitivity of a model parameter indicates the response a change in this parameter exerts on the results. In this comparison, as shown in the Results section, stainless steel 308l has a large environmental impact compared to all other parameters. This indicates that the response of the model is sensitive to the material utilization fraction of each processing step. The most extreme example within stated boundaries of this study: if the material utilization fraction of green sand casting is reduced from 0.65 to 0.5 or increased to 0.8, its total impact increases by 29.5% or reduces by 18.4% respectively. Between these two extremities, the results can vary by 47.9%. A less extreme example: a decrease of material utilization fraction of wire drawing of 0.92 to 0.90 leads to an increase in impact for WAAM by 2.0%.

4.3 LCA IMPLEMENTATION

As discussed in section 2.1, the functional unit used in this study is mass-based. It does not consider material properties and tolerances. The material properties of WAAM manufactured metal are yet uncertain. In its current state, due to its layered approach, the tolerances of WAAM are not very narrow. Lower precision can translate to higher safety factors in engineering, which might (partially) undo its material efficiency potential. The layered approach also results in a layered surface finish. In cases this is undesirable, more post-processing would be required to flatten this out. Though the layered surface effect is in WAAM's nature, it can diminish in time by the development of better parameters, equipment, and printing strategies. For creating a complex part with a low material utilization fraction and a requirement for low tolerances, a hybrid approach of WAAM and CNC milling is suggested. With WAAM, the outline can be printed with a bit of extra thickness where necessary to account for tolerances (near-net shaping). After a potential heat treatment for improved material properties and reduction of residual stresses, the part can be CNC milled to tolerance.

LCA should be implemented in the design phase of products. Manufacturing constraints of casting, milling and WAAM differ, and appropriate designs should be made for specific comparisons. These design optimizations should include material choice as a parameter, which can also vary with manufacturing technique. Aside a different shape, a different material might be selected for each of the techniques in an optimized situation. WAAM will have a smaller range of materials to choose from compared to casting and milling. Material properties before and after manufacturing should be considered, including the surface finish and tolerances. Note that the environmental impact of manufacturing processes themselves also changes with the material manufactured, e.g. due to different tensile and yield strengths, densities, specific heats and melting points. Variations in the impact of WAAM are likely larger between materials due to the physically more complex nature of welding compared to CNC milling or green sand casting. Printing different materials can require different welding modes or types, power settings, printing strategies, speeds, and types of shielding gas.

Determining the environmental impacts of manufacturing different materials with WAAM would be an important next step. With lower impact materials, other contributors of impact such as electricity will become more significant. The implementation of transport and consumables into the study, such as contact tips, should be reconsidered in the case of low impact materials.

WAAM is a novel technology that is still in development. Changes in the process can be beneficial or disadvantageous concerning its environmental impact.

5 CONCLUSIONS

Wire and Arc Additive Manufacturing (WAAM) is a metal 3D printing technique based on robotic welding. As investigated in this article, this technique yields potential in decreasing material consumption due to its high material efficiency and freedom of shape. In terms of ReCiPe endpoint totals, the environmental impact of WAAM produced stainless steel 308l is comparable to that of green sand casting. It matches that of CNC milling with a material utilization fraction of 0.75. Stainless steel is the main cause of environmental damage in all three techniques. WAAM is more efficient in material use and has the potential to reduce weight by topology optimization. This relation between weight and environmental impact is linear; if topology optimization can reach a 20% reduction in product weight, its impact will be reduced by 20%. The higher the impact of the material, the larger the benefit of WAAM versus green sand casting and CNC milling due to its lower material consumption, and vice versa.

This assessment contains significant sources of uncertainty and is sensitive to changes in material utilization fractions due to the high impact of stainless steel. The results are dependent on external data sources, which can contain errors or have different boundaries or scenarios. Endpoints by themselves have a high uncertainty as is. Especially quality data of green sand casting is lacking. Currently used data of green sand casting is not specific to 308l, and is based on the US, whereas WAAM and CNC milling, including all preceding processing steps, are based on the Netherlands, Europe, or global. Material consumption being the main contributor in this assessment with stainless steel, the uncertainty of the other contributors of the system are less significant.

The comparison is based on manufacturing 1 kilogram of stainless steel 308l, from cradle to gate. However, to benchmark manufacturing techniques for fulfilling a certain function, optimized designs should be introduced for each technique. Results can vary significantly based on product shape, function, materials and their manufactured properties, and process settings.

The main contribution of this article is the initial assessment of WAAM itself, including the empirical measurements, with the intent to enable further research and development on cleaner production systems through digital production. As was the purpose, the comparison with green sand casting and CNC milling served merely as a context. Even with the present uncertainty, it can be stated that the environmental impact of WAAM is in the same order of the impact of traditional manufacturing techniques.

As a novel production technology, further adaptations of the WAAM process will influence its environmental impact. Measurements should be performed on the power consumption and emissions while using different process settings, welding modes, or other materials than stainless steel. When choosing a lower impact metal, the assessment of transport between processing steps, as well as consumables such as contact tips, should be reconsidered. Alternative material selections might encompass other post-processing steps, different process settings, and a different type of shielding gas.

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