Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

CHALLENGES IN ASSESSING THE SUSTAINABILITY OF WIRE + ARC ADDITIVE MANUFACTURING FOR LARGE STRUCTURES

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Abstract

Additive manufacturing is known as a disruptive technology, in enabling freedom in shape and on-demand production with little human intervention. At present, large-scale digital manufacturing means are being developed, such as Wire & Arc Additive Manufacturing (WAAM). These could be beneficial in aerospace, automotive and construction industries. However, while the technology is rapidly developing, little is known on the sustainability aspects. This article explores how such environmental effects could be assessed for a novel technology, and the production of large-scale products by means of a Life Cycle Assessment (LCA). Forerunning results show possible gains in material usage when compared to traditional manufacturing technologies, and in power consumption when compared to different additive manufacturing technologies. Future research will focus benchmarking WAAM against alternative manufacturing techniques, including green sand casting and CNC milling.

Introduction

Additive manufacturing (AM) or 3D printing is often seen as a disruptive technology (Geraedts, Doubrovski, Verlinden, & Stellingwerff, 2012), which does not only offer production flexibility and customization, but also material and resource efficiency (Huang, Liu, Mokasdar, & Hou, 2013). Larger-scale products (also called mega-scale rapid manufacturing machines) have been considered since the past decade (Buswell, Thorpe, Soar, & Gibb, 2008), in particular for concrete (Lim et al., 2012) and plastics (Love, 2015). Wire and Arc Additive Manufacturing (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, Pan, Cuiuri, & Li, 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. 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, Erkoyuncu, Colegrove, Martina, & Ding, 2015). One such example is the attempt to print an eight meters long metal footbridge, depicted in Figure 1 (MX3D, 2015).

Due to the early stage of the additive manufacturing, little is known on its sustainability aspects. This article explores how environmental effects could be assessed for the production of large-scale products by means of a Life Cycle Assessment (LCA). It will start by introducing the background of the WAAM process and by

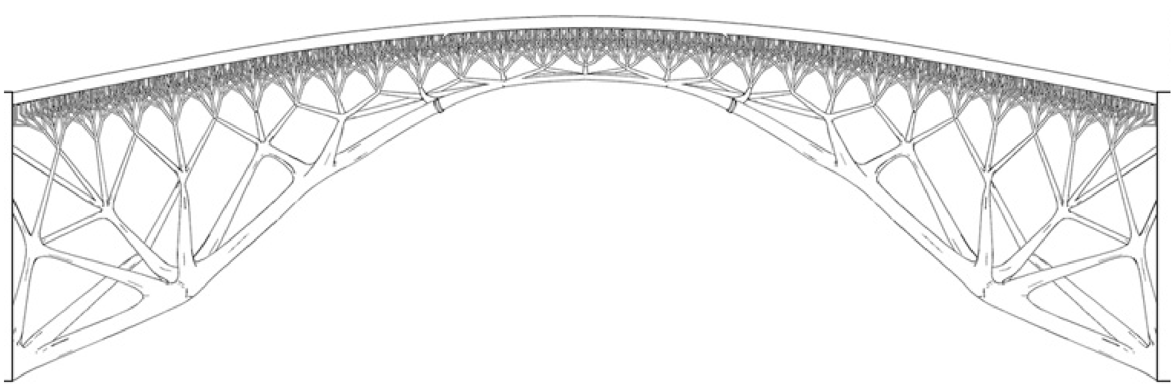

Figure 1. Artist impression of 3d printed bridge (source: MX3D).

exposing the process boundaries. In a subsequent section, the known (life cycle) assessment methodologies are considered. Before conclusions, forerunning results will be reported, in which the object of study is the aforementioned (to be) 3D printed bridge.

Background

The WAAM process

The WAAM process in this case is based on gas metal arc welding (GMAW), also known as MIG, depicted in Figure 2. This enables metal deposition 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). Investigations into mechanical properties show promising results. When porosities are avoided, mechanical properties are good. In the case of titanium WAAM, the strength is only approximately 10% less on average than extruded titanium, with a similar ductility (Wang, Williams, Colegrove, & Antonysamy, 2013). Furthermore, fatigue life exceeded extruded titanium in most tested specimen. Measurements of WAAM printed stainless steel are still in development. Current challenges of WAAM involve improving deposition strategies, to prevent peak development at crosslines, and deposition failures (Mehnen, Ding, Lockett, & Kazanas, 2010).

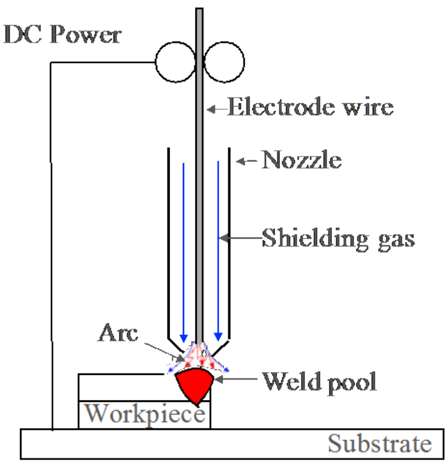

Figure 2. Schematic of gas metal arc welding.

Life Cycle Assessment

Life Cycle Assessment (LCA) is a method for analyzing 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).

In accordance to ISO standards, there are four phases in an LCA study:

a. Goal and scope definition
b. Inventory analysis (LCI): an overview of the in- and outputs of the system
c. Impact assessment (LCIA): the LCI flows are converted into simpler indicators, to provide more understanding. Steps in this process, depending on the method used, include classification, characterization, normalization and weighting.
d. Interpretation phase: understanding, discussion and processing of the data collected in the previous steps. This phase is performed in parallel to the rest. Ideally this step includes an uncertainty and sensitivity analysis, to indicate the reliability of the results.

Goal and scope definition

Goal

The level of detail and the scope of an inventory analysis depend on the goal of the study (The International Standards Organisation, 2006). In the case of MX3D, the main goal is to benchmark WAAM against similar

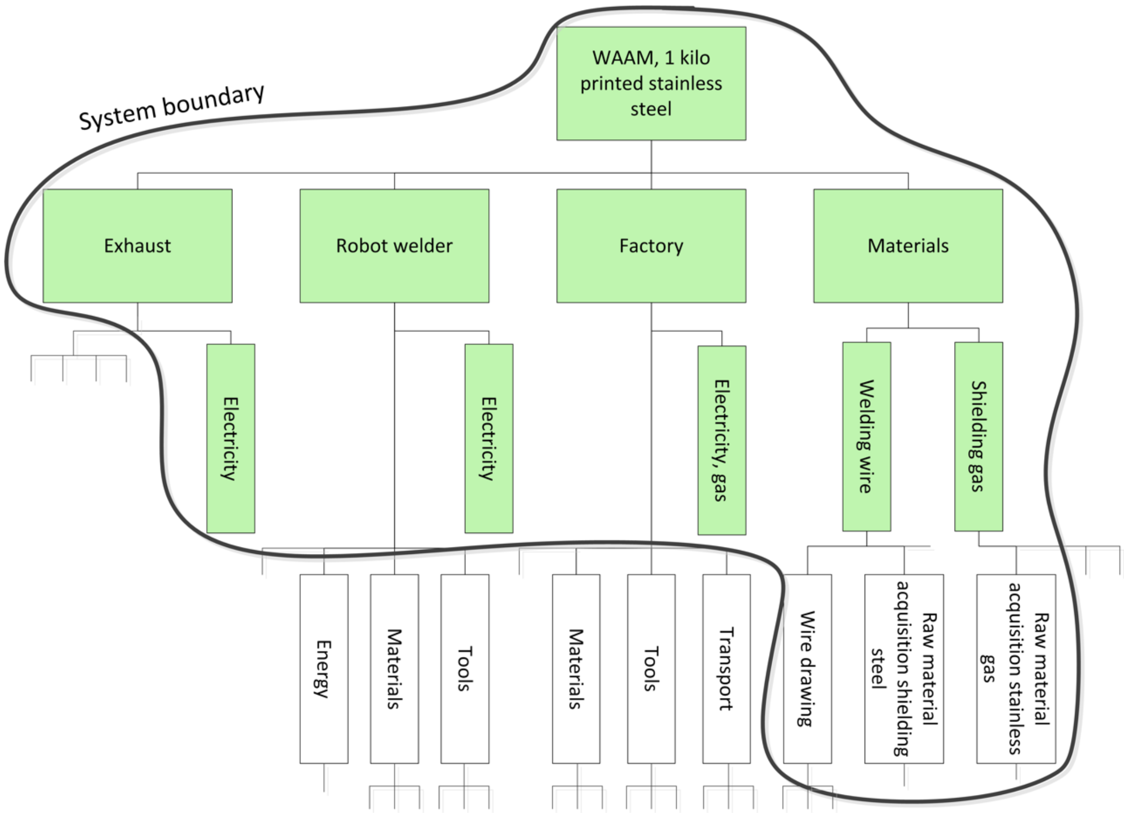

Figure 3. System Boundary of the WAAM process.

techniques (metal additive manufacturing) and/or conventional techniques, and to find out whether it could have environmental benefits in certain areas versus other manufacturing techniques. Besides the comparison of manufacturing technologies, the goal of the assessment is to compare the environmental impact of the (future) 3D printed bridge to another metal bridge with the same *Functional Unit* (FU). The FU defines what exactly is being studied and quantifies the function of the system (The International Standards Organisation, 2006). It serves as reference system for inputs and outputs of the system, and enables comparability between alternate systems. The functional unit of the MX3D bridge is defined as: a metal, 3 meters wide bridge spanning 8 meters, with the capacity to support a load of x Newton, following safety requirements, with a lifetime of 20 years. The mentioned numbers in this FU can be subject to change. Of course, this is a limited definition of the intended product, as it also entails aesthetics (Wallsgrove, 1995), safety (Crespo-Minguillón & Casas, 1997), and ergonomics (Nagamachi, 1997). However, in order to make an assessment as objectively as possible, in line with the ISO14040 standard, these aspects will not be taken into account.

System boundaries

The system boundaries represent the borders between what is, and what is not taken into account in an LCA. Figure 3 displays the system boundaries of the inputs as defined for WAAM in this study. The green blocks represent aspects that can be measured at the WAAM factory. Examples are the power consumption of the exhaust ventilation, and the consumption of welding wire. Other blocks, such as wire drawing, represent data that needs to be obtained by means of databases, scientific papers, and/or suppliers. The system boundary defines the boundary between what will, and will not be taken into account in the assessment. For instance, take the ‘factory’ branch. The power and gas consumption to keep the factory running (for heating and light mainly), is measurable. However, without setting a boundary it will not stop there. The energy, materials, transport and tools necessary for building the factory itself also indirectly contribute to the environmental impact of the factory and therefore to that of WAAM. Consecutively, the tools for creating the materials and the tools themselves also contribute to its impact. As you might start to see, this chain goes on practically infinitely.

There are two main reasons for determining the boundary of the system: time (and money) available, and significance (influence on the total impact). The more in detail and depth the assessment is, the more accurate its results will be. However, every step further down the tree (as in Figure 3) takes an exponentially larger amount of time. At a certain point, there is not much value in going deeper down the tree for the assessment due to its low significance on the complete impact.

For instance, when focusing on the robot welder, its electricity consumption is taken into account. However, the assessment of the manufacturing of the robot itself is disregarded, considering that determining its indicators would take substantially more effort with many unknowns. In addition, we assumed that the production of the robot itself would not have a significant effect (<2%) on the assessment, due to which it can be ignored in the equation (Vogtlander, 2014). This claim is based on the following reasoning: assume the robot is printing stainless steel for 8 hours a day, 260 days a year, for a duration of 5 years. Stainless steel is known to have a large eco-impact, while depending on the parameters, a robot prints on average between half a kilo and a kilo per hour. In addition, welding is also known to have quite a high eco-impact. Adding this up over 5 years, it does not seem farfetched to neglect the manufacturing of the robot.

Life Cycle Inventory

The basic in- and outputs of the WAAM system are depicted in Figure 4. The quantity of these inputs, particularly that of welding wire, shielding gas and electricity, can be measured easily. The output of welding spatter, or metal waste, is also straightforward. This quantity can be obtained by determining the difference in the weight of the printed part and that of the input material (mass of input welding wire). Measuring the output emissions is complex; specialized equipment is necessary for acquiring this data. Without the availability of this equipment, this data can only be approximated by deriving the emissions from existing measurements of welding. Note that this is a basic diagram for the initial assessment of WAAM itself. When assessing products, depending on the goal of a potential comparison, aspects such as finishing, maintenance and recycling should also be taken into account. The result of the Life Cycle Inventory is a list of the material and energy flows in the system, including raw resources and emissions to air. The welding wire for instance is built up from all materials that are inside the alloy, such as silicon and phosphor, plus all components used for and emitted by processing the material into welding wire. One can imagine that an LCI is usually a long list which provides little understanding. A life cycle impact assessment (LCIA) aids in making sense of all this data.

Life Cycle Impact Assessment and its challenges

Figure 4. Basic inputs and outputs of the WAAM process.

An LCIA converts the input and output flows of a Life Cycle Inventory (LCI) into simpler indicators that are easier to understand. Although there are different methodologies, an LCIA entails of up to four steps as depicted in Figure 5.

1. An assessment starts by *classifying* all inventory flows into their areas of impact. Commonly used categories are climate change (carbon footprint), natural resource depletion, stratospheric ozone depletion, acidification, photochemical ozone creation, eutrophication, human toxicity, and aquatic toxicity (Healy, Lorek, & Rodríguez-Labajos, 2013).
2. This classification step is followed by *characterization*: all substances are multiplied by a factor relative to its impact within its category. The result is a list with impact categories, expressed with a single indicator each. For instance, climate change is expressed in kg CO2 equivalent (kg CO2eq). If CH4 has a characterization factor of 21, the respective impact of 3 kg CH4 would be 63 kg CO2eq.
3. Consequently, these results are *normalized*. This means the characterized data will be compared to (divided by) a reference value. An example of a reference value is the average environmental impact of a European citizen in a year on the respective impact category.

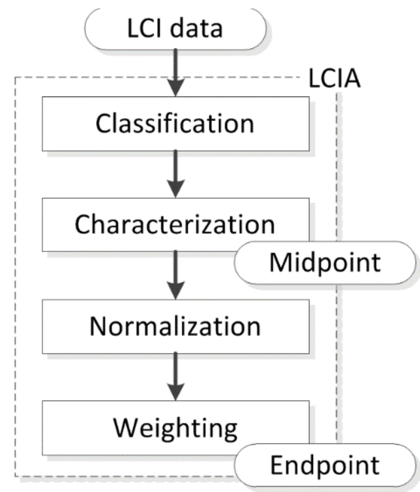

Figure 5: Steps of an LCIA.

4. The last step is *weighting*. In weighting, each normalized category indicator is multiplied by a weighing factor, which are determined by value choices, and added to its damage area of effect. The international standard (The International Standards Organisation, 2006) disproves of this step since no scientific base exists for this weighting, enabling subjectivity and manipulation of results. In case the choice for weighting is made, it is advised to use the default weighting determined by the used methodology to avoid as much subjectivity as possible.

Midpoints and Endpoints

Midpoints and endpoints represent impact categories at different stages in the LCIA process.

Midpoints are problem-oriented. They are the result of the characterization step. Midpoints express the impact onto the different environmental categories, such as acidification and climate change (the problems). True midpoint data is not normalized. Due to midpoint data having a scientific base, it has a relatively low uncertainty.

Endpoints are damage-oriented. They model the environmental impacts in terms of damage to certain areas. For example, in case of ReCiPe[1], these categories are human health, ecosystem health, and damage to resources. Where midpoints stop after the characterization phase, endpoints continue with normalization and (non-scientific) weighting. In addition, how exactly midpoints affect the areas of damage is estimated by complex models, containing many assumptions. This causes a relatively high uncertainty for endpoints. A total endpoint score, being the sum of all endpoints, is often used for comparing products.

Challenge #1: Diversity in methodologies

Figure 6 shows the evolution of significant LCIA methodologies through time. They in particular differ in their procedural steps, yielding fluctuating LCIA results for equivalent LCI (Pizzol et al., 2011).. Furthermore, classification and characterization is different for each method. While one method might have 18 midpoint categories (ReCiPe) into which LCI data can be classified, another might have 11 (LUCAS) (Budavari et al., 2011). Differences in characterization can occur due to different interpretations of the impact of certain materials.

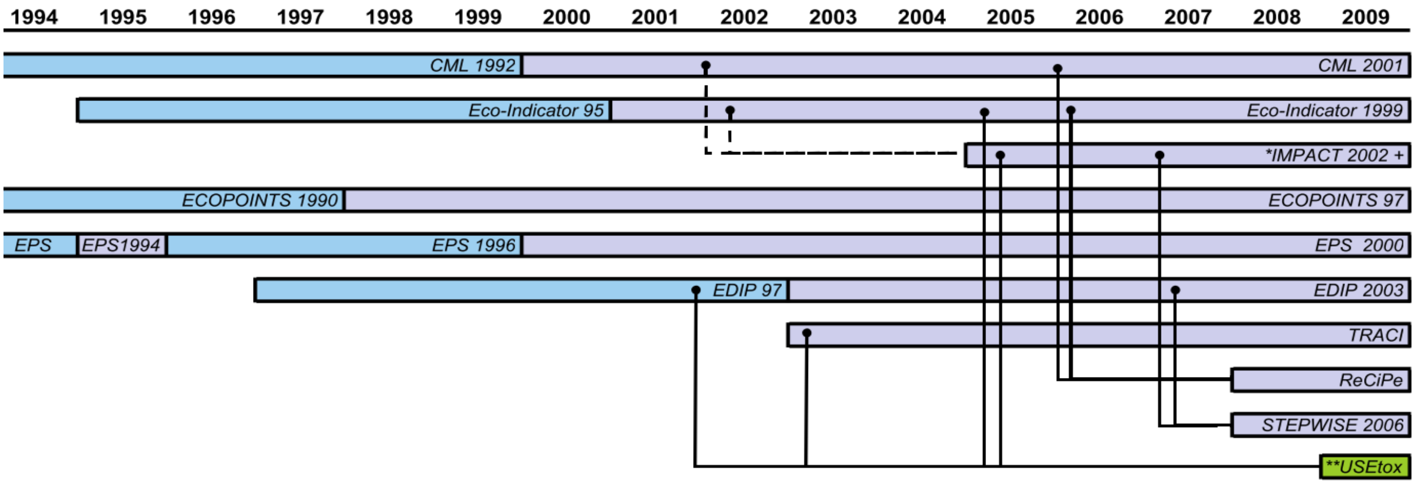

Figure 6. Development over time of LCA methodologies (Pizzol et al., 2011).

In addition, characterization factors of a number of materials are missing in certain methodologies due to lack of knowledge. Some methodologies have much more substances in their characterization list than others.

Variations in normalization occur as well. One methodology might have more outdated reference data than others for instance. Differences in weighting occur mainly due to varying takes on relative importance, and can cause large deviations.

Challenge #2: Specifying LCIA results

Results can be specified in several ways called indicators; varying in depth, communication ease, and uncertainty. There are multiple categories for expressing the Life Cycle Inventory. They can be prevention-based (eco-costs), problem-oriented (midpoint), or damaged oriented (endpoint), of which the latter two are much more well-known.

Prevention-based assessments

(Vogtlander, 2014) created a prevention-based impact model, entitled *eco-costs*. Eco-costs express the environmental burden of a product on basis of the cost of prevention of that burden. It is a relatively new system, and is not widely used at this point in time. This indicator is expressed in euros.

Midpoint (problem-oriented) indicators

Midpoint indicators communicate the impact on the midpoint categories, e.g. eutrophication, by all substance flows of a system. With every category having a different unit (e.g. kg SO_2eq), comparing different categories does not work. This implies difficulties in comparing products using midpoints. It is becoming more popular to apply weighting factors to midpoint data in order to gain more understanding of relative contribution. This adds a lot of uncertainty to the data however.

Another way midpoints are used is in *single issue assessments*. A single issue LCIA considers just one midpoint category, such as acidification, and only analyses and/or communicates that aspect. A commonly used issue is climate change (midpoint: carbon footprint). In some methodologies, the three most relevant midpoints are selected. An advantage of this type of indicator is that it is easy to use, and relatively easy to understand and compare. The disadvantage is that it ignores all other pollutants caused by a system. In addition, issues, or indicators, can be chosen in such a way that a product, which might in fact be more damaging to the environment, appears eco-friendlier.

Endpoint(damage-oriented) indicators

Endpoint assessments are designed for raising awareness, and can help companies in producing, and potentially people in consuming, less, or in a more environmental friendly way. The disadvantage is that these calculations are often complex, lack transparency, in need of more assumptions compared to midpoints, and contain a higher subjectivity. The reasons endpoints are so often used are ease of communication, decision making, and simplicity for the reader. It is much easier to communicate and compare endpoints in order to make a choice in an eco-comparison of two systems; especially when all endpoints are aggregated into a single (total) score.

Challenge #3: Availability and quality of data

The first main problems with data availability and quality were encountered when setting up the LCIA of WAAM. Information on the eco-impact of manufacturing processes is difficult to find. Some companies make proper LCAs of their products and processes. However, since it is not obligatory to make this data public, it is usually kept confidential. In addition, data on the manufacturing processes within WAAM's system cannot be found in open databases. Commercial databases and software, such as ecoinvent[2] and SimaPro[3], are expensive. Even there the quality of data cannot be guaranteed.

For an initial, draft LCA, data was retrieved from (Vogtländer, 2012). This data is derived from ecoinvent, which is a renowned LCA database. It only provides the final numbers; not what is included and excluded, or basic information such as year of acquirement. With sometimes large unexplained differences between similar techniques, what causes the differences and what values are closest to reality is unknown. Mistakes might also be present in this datasheet. The reason this datasheet was used is that it was the most useful free data available.

Recently, access to SimaPro and ecoinvent was attained. SimaPro, with ecoinvent as its main database, offers many possibilities in creating or adjusting processes. Striking however was that even basic, traditional processes such as green sand casting, were not present in these databases. This means that for benchmarking WAAM, sufficient research needs to be done to, in addition to WAAM, research the comparative techniques.

Challenge #4: LCIA benchmarking a bridge

The final entry to this list of challenges is finding or determining comparative structures for benchmarking an object. For benchmarking MX3D's unique bridge, an impact assessment of a comparative bridge is required. For proper benchmarking, this reference bridge should have the same functional unit. It will be difficult to find an assessment of such a bridge. Therefore, the bridge of MX3D will be compared to a simple theoretical construction with the same FU (as described in section 'Goal and scope definition'). This will keep subjective elements out of the equation as much as possible. This theoretical construction could for instance be a row of I-bars welded together (with an added handrail if required).

Due to the final design of the bridge still being in development combined with the absence of quality data up until recently, the focus of the LCA is currently still on the impact (and price) of printing a kilo of stainless steel with WAAM.

<u>**Forerunning results**</u>

A start has been made on the impact assessment of WAAM. This section will discuss some forerunning results. Some LCIA data could be retrieved of similar techniques, using the datasheets of (Vogtländer, 2012) described in challenge #3.

An initial, draft LCA has been made of printing a kilo of stainless steel with WAAM. Some impact values of aspects of the process might be quite different in this assessment compared to reality. Especially the impact of the printing itself. Values for standard MIG welding have been used for this purpose. However, the energy consumption of WAAM welding is different compared to average welding. This also has an influence on the welding emissions.

Although the available data at the creation of WAAM's first rough LCA is likely not very accurate, it still provided enough insight to communicate some preliminary results. With relative certainty it can be stated that the main contributor to the environmental impact is stainless steel itself. The second highest impact came from the welding (WAAM). This impact was much higher for instance compared to that of wire drawing: a process for creating the welding wire from billets of stainless steel. Transport had no significant impact. The raw material of stainless steel itself being the largest contributor to the LCA is a promising result, since WAAM aims for a reduction in material usage.

Power requirements

Measurements of WAAM show an average of approximately 1,84 kW (1,4 for the welder plus 0,44 for the robot). This differs significantly from information found on standard Gas Metal Arc Welding (GMAW). A study of (Sproesser, Chang, Pittner, Finkbeiner, & Rethmeier, 2015) compares four different welding techniques by empirical measurements on robot welding apparatus. Energy consumption for gas metal arc welding equals approximately 8 kW.

Table 1: Power of WAAM versus GMAW.

Manufacturing technique	**Power (kWh)**
WAAM	1,84
GMAW	8

This difference might be caused by a combination of factors. First of all, the material deposition by WAAM might be lower per unit of time compared to standard GMAW. Another contributor could be the difference in welding equipment. Newer welding equipment will be more energy efficient. Different metal/gas combinations can also have an impact on how efficient a weld is made and what energy is required. Finally, welding two cold metals parts together (with perhaps a different welding metal) requires more power compared to welding a layer on top of one still warm layer. This difference in energy consumption should result in a lower impact for WAAM compared to standard GMAW.

Power consumption compared to metal AM techniques

Information on power consumption of more traditional metal additive manufacturing techniques, Electron Beam Melting (EBM) of titanium and Direct Metal Laser Sintering (DMLS) of stainless steel, can be found in (Baumers, Dickens, Tuck, & Hague, 2016). Energy consumption for these printing processes is high: 38.4kWh for EBM and 62.9 kWh for DMLS per kilo of printed material. Energy consumption of WAAM is much lower compared to these techniques. When including 0.75 kW for the exhaust ventilation, the process consumes around 5.18 kWh/kg on average, assuming the print parameters are such that the speed of welding is around half a kg per hour (2 * (1.84 + 0.75) = 5.18 kWh)). The resulting comparison is depicted in Figure 7. Note that these measurements only include the power required for the shaping processes themselves.

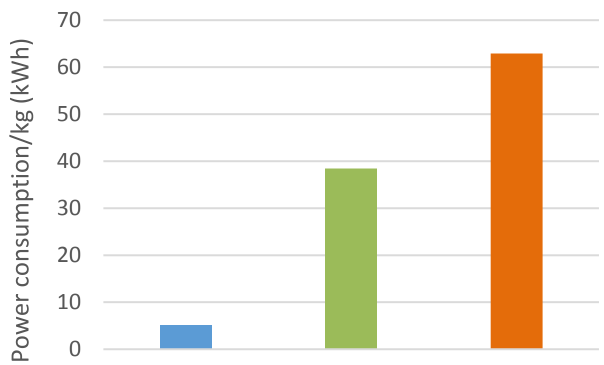

Figure 7: Power consumption per kg of metal by WAAM, EBM, and DMLS.

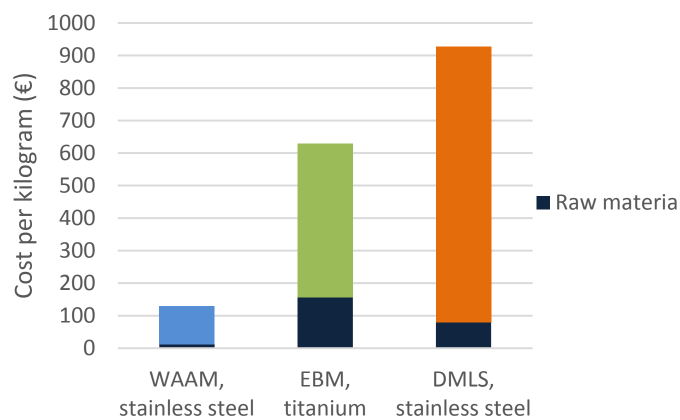

Figure 8: Cost estimation per kg of metal by WAAM, EBM, and DMLS.

Shielding gas and emissions

Impacts of the welding gas do not seem to have a large influence on the total (Sproesser et al., 2015). At the current source of LCIA data, the input materials of GMAW are not given, aside from ‘steel’. Stainless steel creates more environmentally unfriendly, toxic fumes, such as chromium VI, compared to lower alloyed steels. However, the significance of these welding emissions is difficult to estimate, as well as the difference with the

GMAW used in the rough LCA. No measurements have yet been performed due to the required specialized equipment. On the other hand, from (Sproesser et al., 2015) it can be derived that the quantity of emissions is directly correlated to the power consumption. The higher the energy consumption, the more emissions. Concluding, the difference in emissions compared to standard GMAW might have either a positive or a negative impact on the current state of the LCIA.

Cost comparison to other AM techniques

A comparison for metal printing costs is presented in Figure 8. A cost and energy benchmark of EBM and DMLS can be found in (Baumers et al., 2016). It highlights the relatively high costs of the Electron Beam Melting of titanium (629 €/kg of which €157 for the raw material) and the Direct Metal Laser Sintering of stainless steel (926 €/kg of which €79 for the raw material), which is largely caused by high machine cost. The cost of WAAM is estimated around 130 €/kg, of which €12 for the raw material (stainless steel), varying with different print parameters. More than half of this share is attributed to labor cost, and can be greatly reduced when the technique is more optimized. Take into account however, that WAAM has a much lower resolution compared to EBM and DMLS, and will need more post-processing. Post-processing is not taken into account into this comparison.

Selection of methodology and indicator

For further processing, ReCiPe[1] was chosen as methodology, a relatively well-known and often-used within the LCA domain. For the selection of indicator, the decision was made that the LCA will be expressed in two manners in successive research: a list of (non-normalized) midpoints, plus ReCiPe endpoints. The goal of the list of midpoints is to give more in-depth information to experts. The endpoints are for ease of communication and decision making. Although the uncertainty of endpoint indicators is higher, they provide people without extensive eco-knowledge with an indication.

Conclusions and future research

WAAM holds promises for mega-scale constructions, bringing the benefits of digital fabrication to a field where traditional manufacturing techniques limit design and deployment. However, for such a new process, it is important to assess its environmental impact. This is difficult to attain, as aforementioned in the four challenges:

- Large differences exist between methodologies and the implied interpretations.
- Results can be specified in several ways, posing a trade-off between assessment depth, communication ease, and uncertainty.
- There is a lack of reliable data of so-called indicators. Even in costly options many significant details are not covered.
- In order to benchmark an object, at least one comparative object with the same functional unit needs to be found or determined, and assessed in addition to the object itself.

Furthermore, we conclude that:

- In accordance with the ISO 14040 standard (The International Standards Organisation, 2006), the aspect of aesthetics and perceived value will not be taken into account in the assessment in order to keep subjectivity to a minimum.
- Forerunning results show that the raw material, stainless steel, seems to be the largest contributor to the LCIA.
- The power consumption of WAAM is lower compared to average GMAW, and to traditional additive manufacturing techniques per kilo of deposited material.

Future research will focus on benchmarking WAAM against alternative manufacturing techniques, including green sand casting and CNC milling. The goal of this comparison is to give guidelines of what technique is the better choice for the environment in a certain scenario. Firstly, with the aid of the newly acquired SimaPro software and ecoinvent database, a higher quality LCIA of WAAM will be made. Results will be expressed in (non-normalized) midpoints, and ReCiPe endpoints. Secondly, alternative manufacturing techniques will be assessed, if not available in ecoinvent by researching LCI input and output flows and applying these in SimaPro.

Acknowledgements

This investigation was executed at the 3D Building FieldLab, funded by the Amsterdam institute of Advanced Metropolitan Solutions (AMS). We thank Tim Geurtjens and all engineering staff at MX3D for the support in performing measurements and constructive discussions.

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[2]www.ecoinvent.org
[3]simapro.com