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Advantages of Additive Manufacturing based on Life Cycle Assessment

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Abstract. Life cycle assessment was used to compare two pump variants, one implementing a binder jetting manufactured component, and the other an equivalent part made by conventional techniques. The assessment confirmed that for production the additively manufactured (AM) part was significantly more climate intensive, although the picture was not the same for all impact categories, where some could favour AM. However, the advantage of AM became apparent in its improved functionality which resulted in energy savings during use. Over the whole lifetime of the pump, the variant implementing the AM component, displayed significant emissions savings, in all impact categories.

1. Introduction

The manufacturing sector as a whole is responsible for large shares of global environmental pressures through its demand of resources extraction and materials production, coupled with large energy needs. The carbon footprint of materials production covers around 25% of global annual emissions, of which iron and steel alone account for around 10% [1, 2].

Additive Manufacturing (AM) or 3D Printing has been recently recognized as one of technologies crucial towards a resilient and climate-neutral economy in Europe [3]. Certain characteristics of AM have the potential to improve the sustainability of manufacturing and products in several industries [4, 5]. Market studies project rapid growth globally, of this still novel manufacturing approach, from the roughly $10B in 2020 to perhaps as much as $350B or 1.5% of total manufacturing in 2035.

AM encompasses a broad variety of manufacturing technologies, distinguished by processes that "successively join material to create physical objects as specified by 3D model data" (ISO/ASTM 52900:2021). Today AM covers a broad range of materials, from polymers, metals, ceramics, and composites. Its particular advantages stand in possibilities to realize very complex shapes, topology optimization and lightweight designs that can translate in functional improvements[6]. It is widely recognised that AM offers significant advantages in terms of design freedoms, mass customisation, co-creation and innovative business models [7].

The sustainability and in particular environmental sustainability of AM has been studied, however many gaps in this area remain [8, 9]. The literature generally indicates that the impacts of manufacturing with AM compared to conventional techniques (CM) incurs larger impact, which in many cases is related to low batch numbers and much higher energy consumption of AM. However, shape complexity and topology optimization can potentially improve functionality and even result in increased product lifetime. Unfortunately, many life cycle assessments (LCA) are still performed cradle-to-gate, meaning that potential differences or impact savings during use and end-of-life are in many cases not considered[6, 8]. Moreover, recent reviews found that the a large share of existing LCA studies also suffer from methodological inconsistencies [8]. The benefits of AM in terms of energy savings/efficiency over that lifetime of products has been shown in a few studies such as for molds with conformal cooling[10] and aircraft components [11].

The study presented here compared two water pump variants that have the same function, with the difference consisting of a operational component implemented in the pump, which was either manufactured by AM, specifically Metal Binder Jetting (MBJ) or by CM consisting primarily of metal forming and welding processes. The study was conducted cradle-to-grave, to reflect differences during the use and end-of-life phases. It should be mentioned that there are at least a couple of examples where similar parts produced by metal AM compared to CM processes were assessed by LCA [12, 13]. In both cases referred, the scope was not cradle-to-grave and potential functionality differences were not considered. Metal Binder Jetting (MBJ) is also one of the AM techniques less present in research literature.

2. Materials and method

The method most recognized and used in decision-making to quantify the environmental impact of products is Life Cycle Assessment (LCA). Within LCA there are two main modelling frameworks, which can be chosen depending on the decision-making context [14]. An attributional framework is generally recommended for micro-scale decision context, while the consequential framework for meso- or macro-scale. Notwithstanding the lack of consensus in the LCA community on these recommendations, we used here both modelling approaches, which enhances the overall assessment and reduces sensitivity and uncertainty that could be introduced by model choices[15]. The main modelling difference between the two frameworks is the use of average data (attributional) vs. marginal data (consequential). Average data (e.g. the electricity market mix in a year) denotes a static, accounting perspective, while marginal data, which involves identifying market players that will react to the decision taken, denotes a more future oriented perspective.

The assessment was performed with Activity Browser (version 2.9.5), using the database ecoinvent 3.9.1 cut-off version for attributional modelling and the consequential version. The Activity Browser (AB) is an open source software for LCA that provides a graphical user interface (GUI) to Brightway2 [16]. In both modelling frameworks, crediting was applied when materials are recycled, or energy is recovered from waste generated in production and the product end-of-life.

The impact assessment method used was Environmental Footprint (EF) v.3.1, which is also the method recommended in product environmental footprint (PEF) studies. The method was updated in 2022 and comprises 16 midpoint indicators.

2.1 Goal and Scope definition

The goal of the present study was to assess and compare the environmental sustainability of an industrial pump in two variants, one containing a component manufactured by MBJ and the other containing the equivalent manufactured by conventional techniques (CM).

The assessment covers the whole life cycle of the pump, but not any potential remanufacturing or reuse. The functional unit used in the comparison of the pump variants was: "the provision of steady and reliable operation within specific parameters, for 5000h/year and a lifetime of 15 years". Figure 1 illustrates the process steps and life cycle stages included in the assessment, with more details on the AM process route.

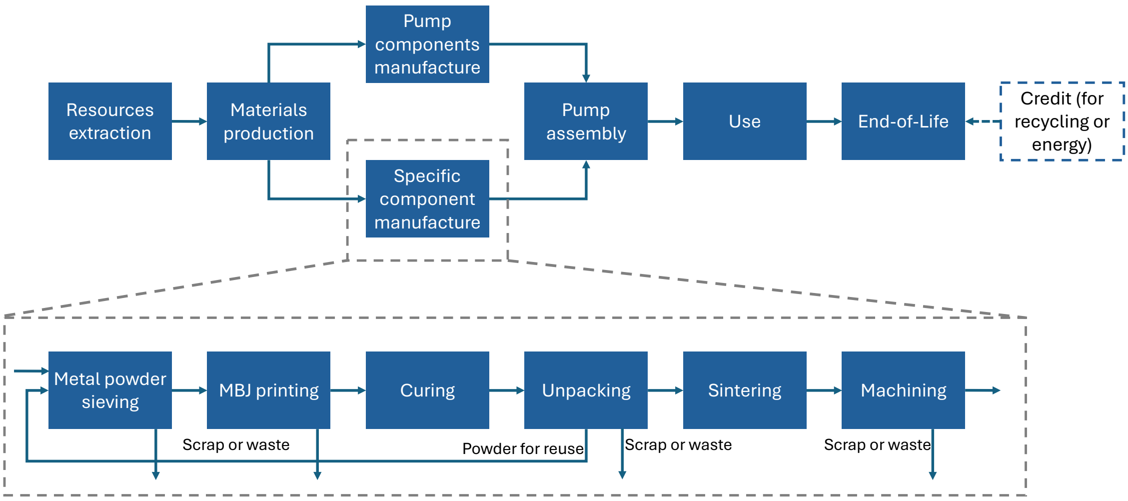

Figure 1. System diagram illustrating the simplified cradle-to-grave life cycle for the assessed pump. Additionally, more detail is presented on the manufacturing steps for the AM component.

2.2 Life Cycle Inventory

The specific pump components produced by both manufacturing setups were extensively tested, revealing differences in robustness and in energy consumption favouring the variant manufactured by AM. Nevertheless, an increase in the functional lifetime of the pump is not yet confirmed and was not included in this assessment.

The weight of the entire pump is around 80 kg, while the specific components is around 350 g. The life cycle inventory (LCI) for the pump manufacturing was based on its bill of materials. However, most of LCI data cannot be made public here due to novelty and confidentiality aspects. A general description is given below.

The foreground system of the LCA is site and case specific to the locations of Grundfos A/S and the pump studied, which results in limited usability and transferability of the LCA results for other cases, e.g. different pumps or even a similar pump from a different manufacturer. Further limitations come from the use of secondary data in the LCI, which was necessary in cases, where no primary data was available.

Resource extraction and materials manufacturing was taken directly from background database (ecoinvent). The AM route included additionally 316 steel powder manufacturing. All relevant manufacturing steps (figure 1) were modelled individually, including mass flows of materials or parts, inputs of consumables (e.g. binder or different gasses) and energy, as well as waste and emissions. The latter included losses of powder or part breakage, and emissions of, for example products of oxidation processes during sintering. Air collection, purification, and conditioning systems were included for the AM line. In most cases, capital goods, or the use of machinery, was also accounted for. Lastly, transport between all manufacturing stages was included.

The use phase primarily reflected the difference in electricy consumption of the pump, which was based on extensive testing data. The tests demonstrated 15-20% energy consumption improvement during use in similar conditions for the pump with the AM component.

The End-of-Life (EoL) stage for the pump after decommisioning, was based on likely waste handling routes, but did not include primary data. Processes included pre-treatment of metal scrap by shredding and sorting, metals recycling and waste incineration for non-metal pump materials. Recycling losses were accounted and primary materials production was credited for recycling outputs.

2.2 Sensitivity and uncertainty

A number of sensitivity checks were made, however, not all will be presented here. A data quality check was performed with the commonly used pedigree matrix by Weidema and Wesnæs [17].

Sensitivity checks included electricity: consumption during use, pump lifetime, which was tested as a theoretical potential due to higher robustenes of the AM component, and lastly, the influence of manufacturing batch sizes. In regard to electricity consumption during use, we further tested the influence of different use locations, as the pump is sold on a global market. As baseline, use location is assigned in Denmark, and as sensitivity we test average Europe and China.

3. Results and interpretation

The results comparing the pump variants in the two LCA modelling framework are illustrated for the impact category climate change in figure 2. As can be observed the use phase of the pump lifecycle is responsible for 99% and 95% of total emissions in the attributional and consequential results. The large difference between the results in the two frameworks are due to the type of energy consumed. The attributional results reflect the still significant emissions profile of the current Danish electricity mix (around 0.25 kg CO2e per kWh) vs. the consequential which reflects the growing shares of wind, solar and biomass of the future. Also clear is the advantage of using the pump with the AM component, which has around 8 tons CO2e less emissions overall.

The right side of figure 2 shows the same results but without the use phase, revealing that in fact the production of the pump has slightly higher overall impact in the consequential framework. As the pump is mostly made up of different metals, a large share of the production impacts is offset by recycling and ensuing credits.

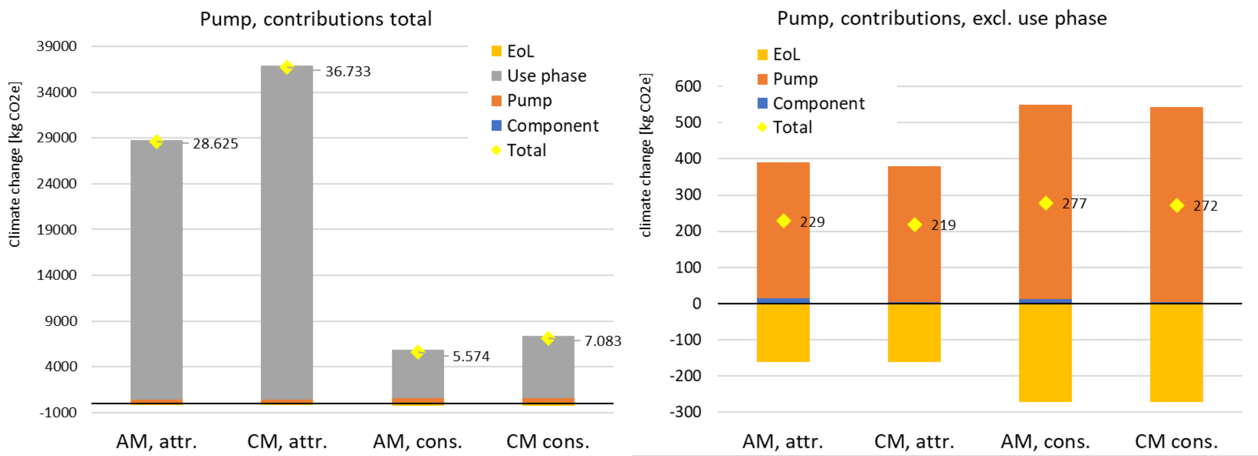

Figure 2. Results showing the contributions to the climate change impact (kg CO2e GWP100), for the entire lifecycle (cradle-to-grave) of the pump, and without the use phase. Bars above the 0 line denote burdens while below the line denote savings (credits); attr. and cons. denote the attributional and the consequential LCA modelling frameworks; EoL denotes end-of-life.

Figure 3 showcases further how the use stage emissions (in attributional) would look if the location of the pump use is moved to average EU settings or China (CN). Both new locations have electricity mixes today with higher emission factors, especially China with electricity dominated by coal. In these conditions, the improved energy efficiency of the pump with the AM component can result in much larger emission savings over the lifetime of the pump.

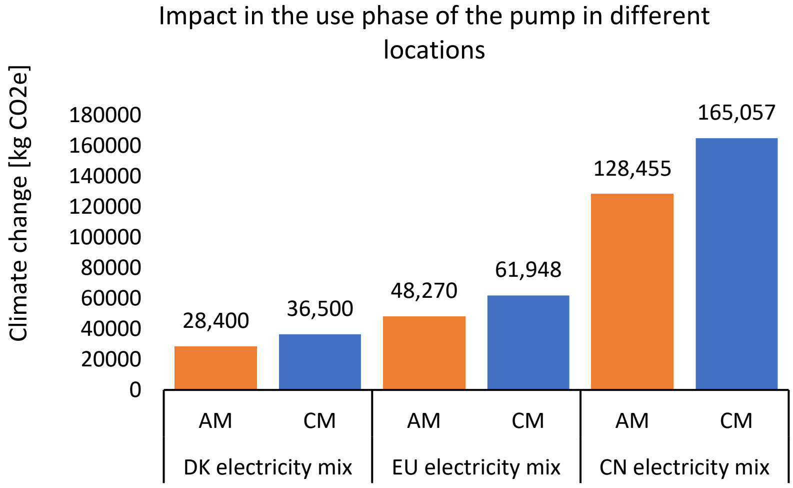

Figure 3. Results for the use stage in different locations.

Next, let us have a look at the cradle-to-gate, or production, environmental impact results for the specific component manufactured by AM or CM. Figure 4 illustrates the results in the two LCA modelling frameworks. Fist, the results point to the AM component being around 3 times more climate impact intensive that the CM equivalent. This is not unexpected and in line with literature. The AM results stand out for steel feedstock and the sintering process, while the 3D printing itself is not as significant. Powder manufacturing entails typically additional metal remelting steps, while sintering has significant energy requirements.

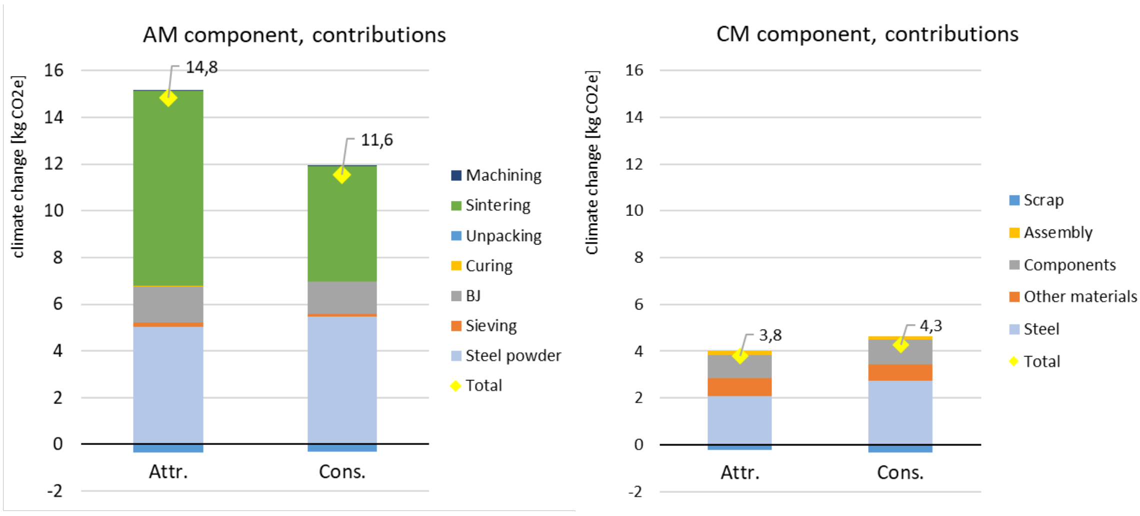

Figure 4. Contribution analysis results for the manufacturing of the specific pump component. Attr. and cons. denote the attributional and the consequential LCA modelling frameworks.

Interestingly, figure 4 also shows that in the consequential framework, the climate impact of the AM component decreased, compared to the CM component where it slightly increased. This is explained in the first case by the different energy consumed in sintering (with less emissions), and in the second case, it is explained primarily by the higher emissions of 316 steel manufacturing in the consequential framework.

Finally, figure 5 illustrates results for all 16 impact categories, for the two components. Within the attributional approach the results clearly indicate that the AM component has higher environmental impacts in all categories. However, the picture changes in the consequential results. Here, the CM component performs worse that AM in 6 of the 16 impact categories. Moreover, the results would point that AM has net impact savings in three categories: ionizing radiation, material resources, and water use.

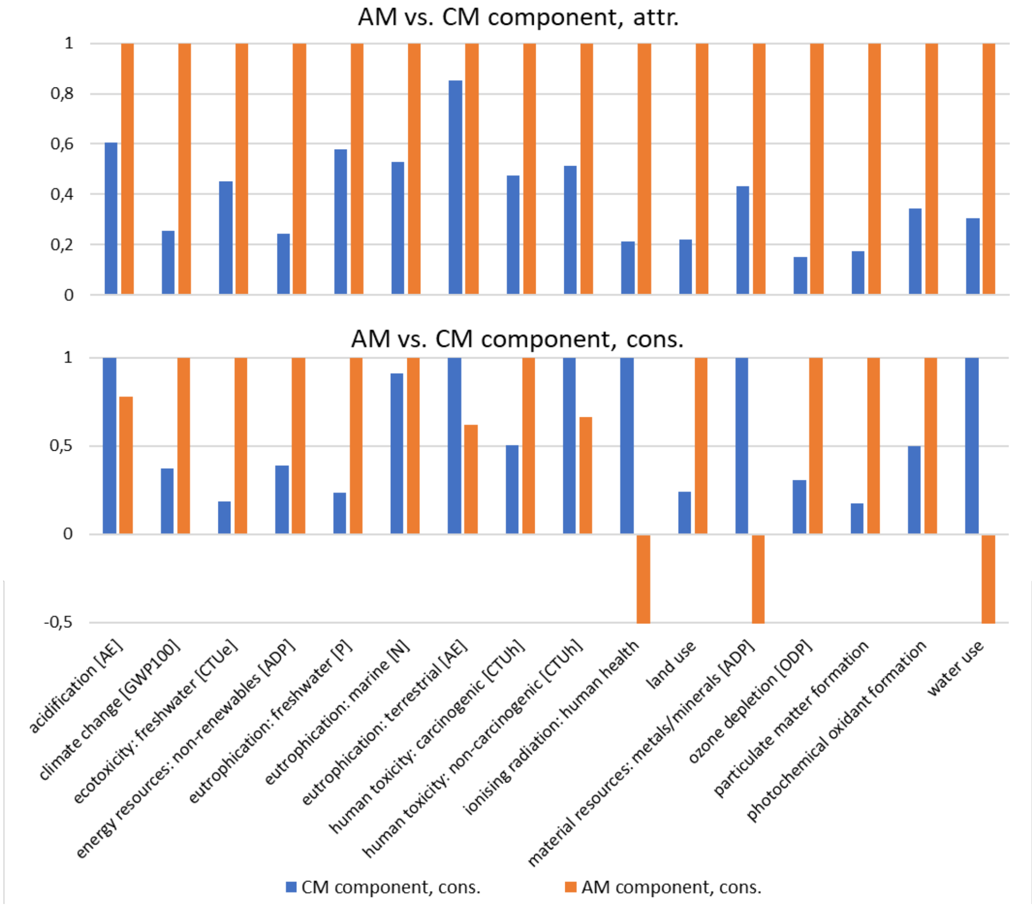

Figure 5. Results (cradle-to-gate) for the comparison in all 16 impact categories. The bars displayed are calculated by internal normalization of the results in each impact category to the option (component) that has the highest impact. Attr. and cons. denote the attributional and the consequential LCA modelling frameworks.

4. Conclusion

This work compared two pump variants, one implementing an MBJ manufactured component, and the other an equivalent one made by conventional techniques, with two LCA frameworks. The assessment confirmed that the AM production of the part was significantly more climate intensive, although the picture was not the same in all impact categories, where some favoured AM. Moreover, the advantage of AM became apparent in its improved functionality which resulted in energy savings during use. Over the whole lifetime of the pump, the variant implementing the MBJ component, displayed significant emissions savings, in all impact categories. Considering their wide use and the global market for pumps, even a slight energy efficiency advantage will result in substantial climate savings.

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