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Environmental assessment of additive manufacturing in the automotive industry

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ABSTRACT

3D-printing, also known as Additive Manufacturing (AM), is an emerging technology with suggested potential to decrease environmental impacts in the manufacturing industry. Potential benefits from implementing the technology include reduced product weight, transportation and material losses, as well as improved functionality and possibility for printing of spare parts. Possible drawbacks are increased energy use in production and the slow printing process. As the technology is expected to grow significantly, it is important to assess potential environmental effects of implementation. In this study a Life Cycle Assessment (LCA) is used in the case of Powder Bed Fusion (PBF) of the metal parts of an engine in a light distribution truck. Conventional manufacturing is compared to scenarios with 3D-printing, one representing the present state of development of 3D-printing technology and one representing a possible future state. The results show that, in the future case, PBF potentially improves life cycle environmental performance by redesigning components for weight reduction. However, a clean electricity source was required as well as technological development allowing for printing of large components, with low-impact raw materials. When instead assessing AM in its present state of development, results showed only moderate or negligible environmental improvements. To achieve the future potential environmental benefits from AM it is important to use clean electricity and to develop the technology to be able to use low-impact feedstock materials such as low-alloy steel (avoiding materials based on e.g. nickel). Industries implementing AM should seek to exploit the benefits of the technology, such as weight reduction and functionality improvements as well as the potential offered for printing spare parts for remanufacturing and repairing.

1. Introduction

Additive Manufacturing (AM), or 3D-printing,[1] is an emerging technology believed to have a large potential for disrupting or revolutionising many different industries (Walachowicz et al., 2017). Many techniques fall under the umbrella term of AM, such as powder bed fusion, binder jetting and material extrusion (ASTM International, 2012). They are all different techniques for constructing three-dimensional objects by binding material together until a desired shape and size is achieved based on 3D model data (ASTM International, 2012; Rombouts et al., 2006). Each one uses a different method to bind the material together and each can use different feedstock materials, such as plastic or metal. When it comes to metal AM, one of the most ubiquitous techniques is Powder Bed Fusion[2] (PBF) (Wohler's Associates, 2016). There are many areas of application for PBF, and particularly the automotive and aerospace industries have shown interest in the technology (Volvo Group, 2017). The potential to use PBF in automotive and aerospace applications has been demonstrated in tests under high-stress conditions, such as high-speed aerospace turbines (Clarke, 2017), structural components or hydraulic valves in aeroplanes (Jackson, 2017a, 2017b), turbine nozzles for helicopter engines (Haria, 2017) and rocket engine components (Jackson, 2017c).

The technology is in an early stage of adoption and brings with it several potential benefits, many of which are still uncertain, both in

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[1] The terms “Additive Manufacturing” and “3D-printing” will be used interchangeably throughout this paper.

[2] Other names for Powder Bed Fusion include e.g. Selective Laser Melting, Laser Beam Melting and Laser Sintering.

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terms of environmental consequences and resource use (McAlister, 2014). Of the potential benefits and drawbacks identified, some features could enable improved resource efficiency or environmental performance, while others could hinder that potential (Holmström and Gutowski, 2017; Jamshidinia et al., 2015). AM allows for redesigns of components, e.g. for lower weight, which would reduce fuel consumption in vehicles (Lifset, 2017; Mami et al., 2017). Through redesign, several parts may also be integrated into one, thus reducing the total number of components and potentially facilitating assembly and dismantling (Kellens et al., 2017). The more complex a product is, the more advantageous it is to 3D-print, since the cost and energy for printing is not dependent on component complexity (Quinlan et al., 2017). Components can consequently be redesigned to provide additional functionality, for example improved cooling by integration of cooling channels into the structure to enhance energy efficiency and performance of the entire product (Ford and Despeisse, 2016).

Specialised parts can be produced quickly and on demand, benefitting prototyping and repairing (Jamshidinia et al., 2015). Printing of spare parts on demand can lower costs for producing and storing sufficient quantities of spare parts. Furthermore, the additive, rather than subtractive, nature of AM technology means that more of the input material ends up in the final component, thereby reducing material losses (Nyamekye, 2015; Priarone et al., 2017).

There are also several inherent disadvantages of AM, e.g. high energy consumption, a slow printing process and limitation regarding what materials and sizes can be 3D-printed (Gutowski et al., 2017). The slow printing process is especially problematic for any prospects of potential mass production (Kellens et al., 2017).

Considering these effects, and the expected development and diffusion of AM it is important to assess the potential environmental and resource consequences of implementing metal AM in general and PBF in particular. However, such assessments are challenging because of the inherent uncertainties associated with emerging technologies (Arvidsson et al., 2017). Furthermore, there are only a handful of previous papers that have quantitatively assessed the environmental effects of metal AM. Most studies consider only energy consumption or only the printing process itself (Lifset, 2017). Additionally, the fast technological development of AM is rarely considered (Huang et al., 2017). One Life Cycle Assessment (LCA) on PBF was performed by Faludi et al. (2017), focussing on impacts from construction and operation of an AM machine as well as powder production. They carried out a detailed assessment of different build orientations and machine cycles, but excluded the application and use of the component. By using lab-scale data, they did not consider technological development of AM. Another study was conducted by Liu et al. (2018), who compared the environmental impacts of Directed Energy Deposition to conventional manufacturing of high-speed gears for wind turbines. Like Faludi et al. (2017) they excluded application and use, as well as technological development. In contrast, Huang et al. (2017) have investigated and compared the environmental and economic consequences of PBF for injection moulding, including the cradle-to-grave impacts considering future technological development in several scenarios. Similarly, Mami et al. (2017) calculated the life cycle impact and cost of manufacturing airplane components with PBF from cradle-to-grave. Their model represented optimised manufacturing, which can be said to correspond to a future scenario.

Hence, there is a research gap for studies comparing the life cycle impacts of PBF and conventional manufacturing, considering the entire life cycle and including technological development of AM in the analysis. Furthermore, Kellens et al. (2017) point out some of the most important and likely applications of AM from an environmental perspective. Of the potential benefits they identify, lightweighting for aerospace is considered highly likely to provide potential benefits. Benefits from lightweighting in the automotive industry, on the other hand, is labelled as uncertain, why it is relevant to carry out environmental assessments on AM applied to automotive applications.

The aim of this paper is thus to fill these research gaps by investigating the environmental and resource implications of AM for automotive applications, while searching for the most important factors influencing results. The assessment was done in collaboration with Volvo Group, who utilised PBF technology in previous tests (Volvo Group, 2017), hence PBF is the technology of choice throughout the study. The purpose of the assessment is to compare conventional and additive manufacturing applied to the case of a light truck engine, while considering the future development and adoption of AM. The intended audience for the study is practitioners and researchers in the field of AM, as well as industries looking to implement AM, particularly the automotive industry.

The LCA study examines the future technological development of AM by comparing implementation of AM in its current state of technological development to that of a potential future state. Aspects covered include the size of components that can be 3D-printed and the materials that may be used. Potential future developments not investigated include printing speeds and the effects of localised production and short lead times.

In section 2 follows a description of the method and scope while section 3 details how the life cycle model was built and populated with data. Results and sensitivity analysis are presented in section 4 followed by Discussion and Conclusions in sections 5 and 6.

2. Method and scope

An experimental redesign of a truck engine for 3D-printing by Volvo Group, along with test-prints, made up the starting point for this study to assess the environmental effects of AM (Volvo Group, 2017). The tool used was Life Cycle Assessment (LCA), which enables the assessment of impacts on the environment and human health, as well as resource use, associated with the full life cycle of products or services, including material extraction, production, use and end-of-life (International Organization for Standardization, 2006). GaBi software was used to build a model and generate results, using the add-on DfX, for importing and using a Bill of Materials (Thinkstep, 2017a).

LCA results can be presented as inventory results, as more aggregated impact categories or weighted to a single score. In this study, weighting is used to filter the results and identify key indicators. These are then analysed and presented in depth. Such a procedure was first described by Tillman et al. (1998), who used several distinct weighting methods in a first step to filter the results and thus identify the impacts or emissions that dominate the results in one or more of the employed weighting methods.

Weighting can give an overview for studying relative results between different options, but also entails the loss of nuance and detail in the results. Furthermore, every weighting method is based on different values, assumptions and logic (Hauschild and Potting, 2005). Different methods thus tend to emphasise different aspects of the Life Cycle Inventory. In this study, three different weighting methods are used in conjunction, in order to utilise the strengths and avoid the drawbacks of weighting.

The chosen weighting methods are i) Environmental Development of Industrial Products (2003) (EDIP) (Wenzel et al., 1997), ii) Eco-indicator 99 - Hierarchist approach (EI99) (Goedkoop and Spriensma, 2000) and iii) Environmental Priority Strategies - including indirect effects (EPS), along with corresponding normalisation (Steen, 2015). They were chosen to be distinctly different, as this would increase the probability of each method emphasising different and complementary information in the study. EDIP is a mid-point method that uses a distance-to-target approach to estimate weighting factors, thus expressing impacts in relation to political targets. In the case of EI99 and EPS, weighting factors are instead set for each end-point category (in EI99 by a panel of LCA experts). For EPS, weighting factors are expressed in monetary terms, based on people's willingness to pay for restoring damage to a safeguard subject. Furthermore, EPS takes both present and future generations into account in the valuation of abiotic resources.

Most results in this study are presented quantitatively. However, aspects such as spare part printing and consolidation of components were not explicitly modelled and are instead discussed qualitatively in section 5. Sensitivity analysis is performed for several parameters identified to have inherent uncertainties or to be important for the results.

2.1. Scope and system boundaries

The object of study is an engine in a light distribution truck, assumed to be produced in an engine factory in southern Sweden. The LCA, of attributional type, considers environmental impacts from the whole life cycle of the D5K210 engine (see Fig. 1). This includes manufacturing, where each engine component is either produced conventionally (by material production, casting or forging, assembly etc.) or with AM (by powder production followed by PBF). The manufacture of equipment for production is outside the scope of the study. The finished engine spends the use-phase mounted in a light distribution truck, which includes well-to-wheel fuel production and consumption. When the use-phase is over, the vehicle with its engine is assumed to be sent to a shredder, where materials are cut into pieces and separated and then sent to material recycling. Materials recycled at end-of-life are given credits for avoided primary production but, out of simplicity, no credits are given for scrap resulting from production and assembly going to recycling. The time scale of the study regards Additive Manufacturing and the automotive industry in their present states in one scenario, but also one decade into the future in another, hypothetical, scenario. The assumed scale of adoption of AM is at an industrial scale, with implications mainly for what chamber utilisation rate can be assumed.

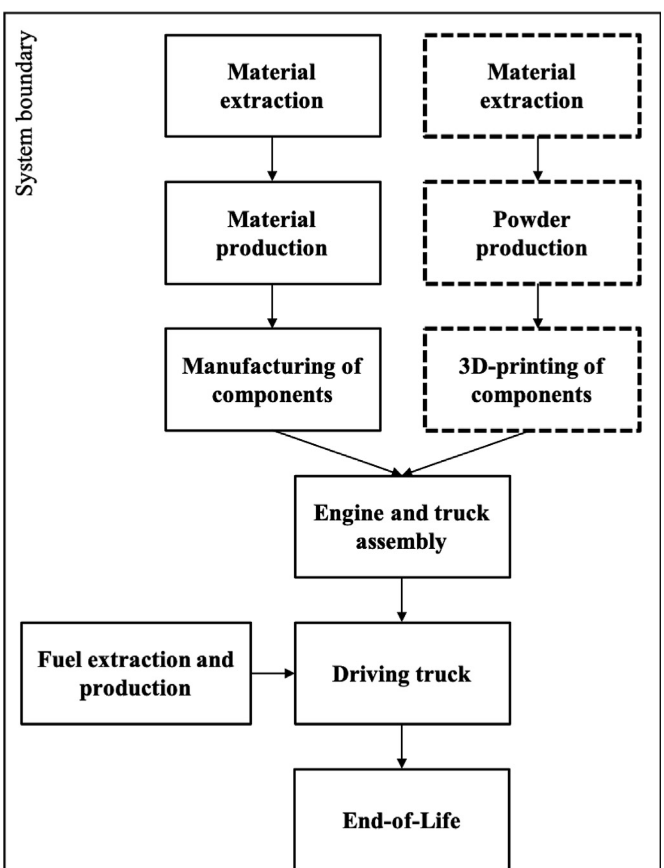

Fig. 1. Simplified flowchart showing the life cycle of the engine mounted in a light distribution truck, as well as the system boundaries of the study. Dashed lines represent the supply chain for any 3D-printed parts of the engine.

2.2. Functional unit and scenario definition

The studied engine is a 5-L engine (of model D5K210), typically mounted in a light distribution truck with a Gross Vehicle Mass[3] of 14 tons. The functional unit is thus defined as the function of one engine that enables the transportation of 8500 kg load over 300000 km (an approximate average lifetime of a light distribution truck). This gives a reference flow of 2.55 Mton·km. In its original form, the engine weighs 533 kg (excluding the muffler, which is outside this study's scope), but with 3D-printing it can be redesigned to weigh less (see section 1). In assessments of light-weighting vehicles, the functional unit is often chosen to capture the lower fuel consumption that is enabled by a lower weight (Dhingra and Das, 2014; Sun et al., 2017). However, according to Volvo Group experts, it is difficult to accurately estimate fuel consumption based on vehicle weight. Consequently, the functional unit in this study was instead chosen to reflect that weight reduction allows more load to fit on the truck.

Three scenarios are formulated to perform the analysis. The reference scenario (S0), represents the conventional life cycle of a D5K210 engine. Scenario 1 (S1) and Scenario 2 (S2), represent Additive Manufacturing, and correspond to different states of technology development for AM. S1 represents the present state of PBF technology and reflects what experts within Volvo Group believe can be achieved with the technology today. This includes the potential for weight reduction as well as limitations regarding the materials and sizes of components that can be printed. The main material limitation considered is that, presently, low-alloy steel cannot be 3D-printed, and thus all 3D-printed steel in S1 is stainless steel. Conversely, in S2 PBF technology is assumed to have developed roughly a decade into the future. This is assumed to allow for AM of low-alloy steel as well as printing of even the largest engine components, meaning that a larger share of the engine is 3D-printed.

3. Data collection and modelling

The following sections detail the modelling and calculation procedures for each life cycle phase and presents selected datasets.

Data collection was to a large part done with the help of Volvo Group, who provided a Bill of Materials detailing the material composition and weight for each component in a D5K210 light diesel engine (see an aggregated version in Appendix B). Life cycle inventory data were largely retrieved via a Volvo Group internal database, containing datasets from several different databases (see

[3] The Gross Vehicle Mass is the maximum operating weight of a truck, including body, engine, passengers, cargo etc.

details in Appendix A). Complementing data were collected from contacts at Volvo Group, mainly relating to recycling and the use-phase.

Data regarding additive manufacturing were primarily collected from literature. Furthermore, technical experts within Volvo Group provided input regarding which components could potentially be 3D-printed or not, in both scenario S1 and S2. This was based on each component's size, function, material composition and potential for 3D-printing[4] (detailed component selection is unavailable due to confidentiality).

3.1. Engine material composition

Because not all components in the engine were considered for 3D-printing, a different number of components were 3D-printed in each scenario, resulting in different material compositions. Total weight and aggregated material composition in each scenario are presented in Table 1.

In both S1 and S2, 3D-printed components are assumed to be redesigned to weigh 25% less than in S0, based on an average from test prints by Volvo Group (2017). Others report weight reductions of up to 90% for a hydraulic manifold (Diegel, 2017), while Huang et al. (2016) estimate an average weight reduction of 54% for structural aircraft components. Consequently, 25% is a conservative estimate. Considering this weight reduction, and that roughly 20% and 80% (by weight) of the engine is assumed to be 3D-printed in S1 and S2 respectively, the total engine weights are roughly 533 kg in S0, 499 kg in S1 and 418 kg in S2.

For each component that was considered for 3D-printing, its metal parts are assumed to be substituted by a 3D-printable material. In most cases, the material is not altered significantly, a notable exception being that in S1, cast iron and low-alloy steel are substituted with stainless steel, whereas in S2 they are substituted with low-alloy steel instead (see material mappings in Appendix A).

3.2. Conventional manufacturing

To create a cradle-to-gate model based on the defined material composition, production of each material in the Bill of Materials is represented by an appropriate dataset in the Volvo Group database (see sources and mapping list in Appendix A). Thus, an LCI model is generated for material production. However, this dataset excludes component manufacturing and assembly, assumed to take place in an engine factory in southern Sweden, for which new, representative, inventory data was obtained from Volvo Group (not publicly available). The data include average electricity use, heat and fuel consumption, as well as relevant inputs and outputs from factory operations, allocated by weight to the production of one generic engine.

The data from the engine factory do not include material losses from component manufacturing and assembly. To ensure comparability between conventional manufacturing and Additive Manufacturing, losses from conventional manufacturing are estimated from database data, as seen in Table 2. The losses entail an increase in upstream material production. The resulting scrap is accounted for as a flow leaving the system boundaries, with no further assumptions regarding its fate.

Table 1
Mass composition of engine in each scenario (see Appendix B for further details).

Material	S0 [kg]	S1 [kg]	S2 [kg]
Aluminium	61.7	49.8	47.3
Cast iron	275.6	233.7	3.4
Low-alloy steel	150.2	107.0	325.4
Stainless steel	27.0	89.7	27.4
Rest	18.7	18.7	14.1
Total	533.3	498.9	417.7

3.3. Additive manufacturing

AM is modelled in two parts, Gas atomisation and Powder Bed Fusion. Each 3D-printed material is modelled separately, to undergo gas atomisation and PBF. Several metallic materials are available as feedstocks, e.g. aluminium-alloys, steel-alloys, nickel-alloys and titanium-alloys (Wohler's Associates, 2016). Raw material inputs are approximated with cold rolled coils for stainless steel, ingots for aluminium and billets for low-alloy steel (details and sources in Appendix A).

Atomisation is the process where a pressurised gas, liquid or plasma is shot at molten metal falling in a chamber. This breaks it into droplets that solidify into spheroids on their way down (Dawes et al., 2015; Yule and Dunkley, 1994). The resulting powder particle diameters can range from 0 to 500 μm for gas atomisation. The particles are then sieved into fractions of different size distributions, to be used for various applications. Gas atomisation is in this study modelled as an input of raw material and energy and an output of metal powder. Energy use for gas atomisation consists of melting energy and energy for production and pressurisation of the atomising gas following Yule and Dunkley (1994), in accordance with Table 3. The thermal energy for melting is assumed to come from combustion of propane gas, like in the engine factory. The atomising gas is assumed to be argon, produced and pressurised using electricity (Dawes et al., 2015; Yule and Dunkley, 1994).

Due to limited data availability, all numbers in the table are approximations, and there is no differentiation between different steels in this step. Results presented by Lavery et al. (2013) indicate that the value used for gas production and pressurisation is an overestimation. Conversely, Faludi et al. (2017) and Morrow (2007) report atomisation energy use for tool steel and aluminium alloys of roughly 8–26 MJ/kg, which instead indicates an underestimation. Despite this, the estimate is deemed acceptable, because the electricity use in the subsequent PBF process is an order of magnitude larger. Material losses from the atomisation process are estimated at 5.3% by weight (Lavery et al., 2013). Subsequent sieving of the powder to achieve a suitable size distribution is not modelled. The powder not used for PBF is sold for other purposes.

Powder Bed Fusion is modelled as an electricity-powered laser that melts the powder into the desired shape, one layer at a time according to digital specifications (Louvis et al., 2011). The thickness of every layer (ca 20–40 μm) depends on the powder and machine specifications and settings, which in turn affects the resulting surface quality and need for post-processing (Dawes et al., 2015). The feedstock is metal powder. Net material loss is estimated at 20.4% by weight per print, caused by e.g. the use of support structures and scattering of powder (Kellens et al., 2010). Data uncertainty is controlled for by sensitivity analysis (see section 4.4).

Laser electricity use and the precise amount of losses depend on several parameters. For example, a specific machine can have widely different electricity consumption per component, varying by 50–200%, depending on e.g. the chamber utilisation rate or the orientation of a part during printing (Mognol et al., 2006). Such variance complicates modelling of PBF electricity consumption. Furthermore, different sources represent different machines, parameters and materials, and these details are seldom specified. Data from five different sources were found to vary by one order of

[4] A simplification was made to exclude components for 3D-printing if they weighed less than 400 g.

Table 2
Scrap rates from different machining and casting processes (Appendix A; Thinkstep (2017b)).

Process	Scrap rate from casting and machining [%]
Aluminium casting	10.4
Iron casting	6.04
Steel high-alloyed part machining	47.1
Steel low-alloyed cast part machining	60.0

Table 3
Energy requirements for melting and atomisation of steel-alloys, aluminium and nickel-alloys (Yule and Dunkley, 1994).

	Melting energy [MJ/kg]	Gas production and pressurisation [MJ/kg]
Steel alloys	2.5	0.44
Aluminium	1.15	0.44
Nickel alloys	2.5	0.44

magnitude (see Appendix C.1). The median value, 133.8 MJ/kg is used to approximate the electricity consumption, assuming full chamber utilisation (in accordance with the aim to model a future large-scale production). Variability in electricity use is controlled for by sensitivity analysis. For simplicity, energy use from post-processing is assumed to be included in PBF electricity use. Consequently, in accordance with Mami et al. (2017), post-processing is not modelled in further detail, except for an additional 1% material loss by weight.

3.4. Use-phase

Impacts from the use-phase can be divided into impacts from maintenance activities and the impacts of the truck's fuel use, which include impacts from fossil fuel extraction, refinement and combustion. The cause of all these impacts is the driving of an entire truck, however any specific component within the truck can be said to only be the cause of a part of the impact. Thus, the engine itself is in this study considered to only bear the part of the total use-phase impact related to moving the weight of the engine itself. Allocation is done by weight, because the fuel consumption depends on vehicle weight, although this is a simplification. Consequently, use-phase calculations are done in two steps; firstly, calculation of total fuel consumption on a vehicle level, and secondly, allocation to the weight of the engine.

To fulfil the reference flow of 2.55 Mton·km in the reference scenario S0, 82500 L diesel is consumed (based on a driving distance of 300000 km and a fuel consumption of 27.5 L diesel/100 km for a fully loaded light distribution truck (Volvo Group, 2018)). In S1 and S2 the engine has a lower weight, therefore vehicle weight is saved. Assuming a fixed Gross Vehicle Mass, the weight saving allows for more load to fit on the truck.[5] As the fuel consumption per vehicle kilometre remains constant, less fuel is needed in S1 and S2 than in S0 to achieve the same transport work. This is presented in Table 4, along with the subsequent weight allocation, which gives the final fuel consumption per engine and functional unit.

Combustion of the fuel leads to emissions of different gases, which are assumed to be at a level in accordance with Euro6-standards, and depends on the drive cycle and share of bio-based diesel in the fuel (7% in this case) (Volvo Group, 2018), see Appendix C.2. As indicated in section 1, engine components can also be redesigned for added functionality, potentially leading to reduced fuel consumption, but this is only taken into account via sensitivity analysis.

Diesel production is modelled as fossil oil extraction and production of diesel at a refinery (Thinkstep, 2017b). In addition, urea is used to control NO_x-emissions, at an amount corresponding to 8% by volume of the fuel in the truck (Volvo Group, 2018). Finally, in accordance with Volvo Group reporting, maintenance is approximated by an amount of coolant yellow (13.2 kg) and engine oil (59.4 kg) used over the truck lifetime (Appendix A).

3.5. End-of-life

End-of-Life is modelled in a simplified manner where the vehicle, and hence the engine, is assumed to be sent to a shredder where the major recyclable metal fractions are recovered at rates according to Table 5. These fractions are then sent to recycling, with additional impacts from e.g. metal melting and material losses (estimated at 13%). Credits are subsequently given, based on the avoided impacts from primary material production, except in the case of aluminium, where 10% is assumed to be down-cycled. The

Table 5
Recovery rates of different materials from shredding of engines (Thinkstep, 2017b).

Material	Recovery rate [%]
Aluminium	95
Cast iron	90
Copper	83
Stainless steel	87
Steel	100

Table 4
Fuel consumption per functional unit, for the entire truck, and allocated to the engine.

	Fuel consumption for vehicle, per f.u. [l]	Fuel consumption allocated to engine, per f.u. [l]
S0	82500	3141
S1	82171	2929
S2	81399	2430

[5] Valid if the truck load is assumed to be limited by weight and not by volume.

same raw material datasets were used as for the inputs (see Appendix A). Note that this assumes almost all successfully recycled material replaces virgin production, which overestimates the benefits of recycling.

3.6. Background systems

Environmental impacts from background systems, such as electricity production and transportation, are included in most of the used datasets (see Appendix A). However, for the engine factory, electricity production and district heating are modelled explicitly. The former is taken as the Swedish electricity mix (see Appendix C.3), and the latter is modelled according to the production mix of a thermal plant in southern Sweden (Skövde Värmeverk AB, 2016).

4. Results

The results are presented in two stages (as described in section 2). First, three separate weighting methods are used to filter the results in order to identify impacts of significance for the overall results (section 4.1). Based on this, three key indicators are chosen and subsequently presented and analysed in detail in sections 4.2-4.3. Finally, a sensitivity analysis is carried out in section 4.4.

4.1. Weighted environmental impacts

Results are here presented as weighted indexes, using three different weighting methods, namely EPS, EI99 and EDIP. Fig. 2 shows EI99 impacts for all three scenarios, in units of *eco-points per functional unit*. For S1 the results are only marginally different from S0, while S2 impacts are reduced significantly. It is clear that the largest contribution comes from the category "Resources, Fossil fuels", making up around 60% of total impacts in each scenario. Consequently, *fossil fuel depletion* was chosen as the first key indicator for further scrutiny.

EDIP impacts are presented in Fig. 3, in units of person equivalents per functional unit. The relative results between S0, S1 and S2 follow a similar pattern to the EI99 results. According to EDIP, the most dominant impact category is "Global warming", making up almost half of the impacts in each scenario. These are mostly due to fuel combustion in the use-phase, particularly tailpipe emissions of CO_2 and NOx. Hence, the choice of second key indicator was *greenhouse gas emissions*.

Finally, EPS impacts can be seen in Fig. 4, where S2 also gives a small improvement in impacts. Notably, the results for S1 are worse than both S0 and S2. This is mostly due to the high stainless steel content in S1, and that the metal resources are given high scores in EPS, as indicated by the roughly 80% of impacts coming from the impact category of "Non-renewable elements". Therefore, *material resource use* was chosen as the final key indicator.

As a result of the above analysis, three indicators are chosen for further scrutiny, namely fossil fuel depletion, global warming (presented in detail in section 4.2) and material resource use (presented in detail in section 4.3).

4.2. Fossil fuels and global warming

Fig. 5 shows results for the mid-point indicator fossil fuel depletion, for different stages of the engine life cycle (in units of *kg*

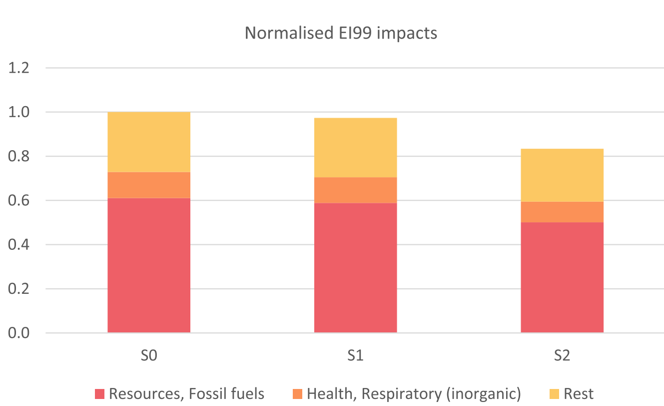

Fig. 2. Eco-Indicator 99 impacts per functional unit, weighted according to the hierarchist approach, and normalised to S0.

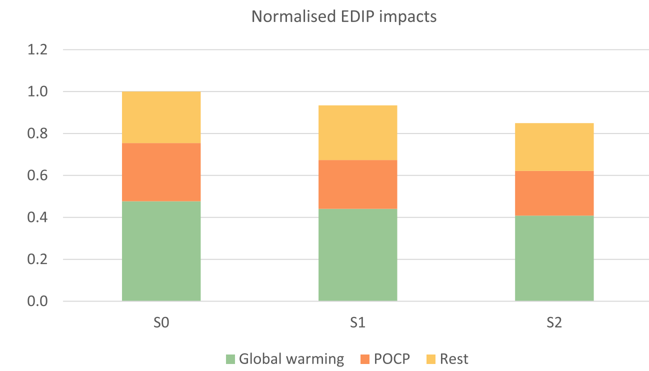

Fig. 3. EDIP2003 weighted impacts, per functional unit, normalised to S0.

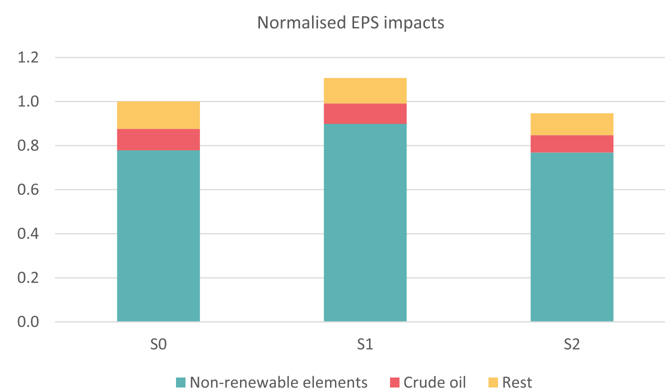

Fig. 4. EPS2015 weighted impacts, per functional unit, normalised to S0.

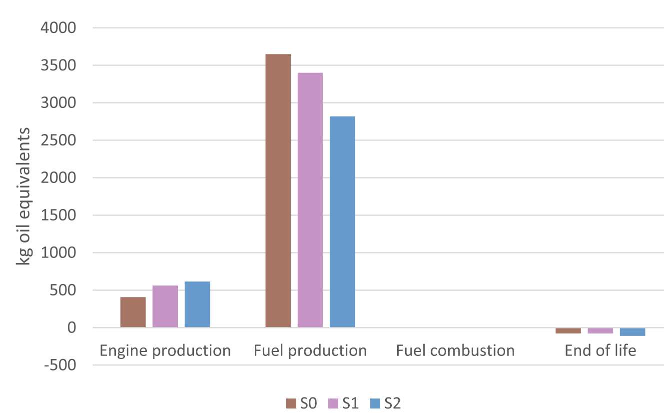

Fig. 5. Fossil fuel depletion for the different life cycle stages of the engine, as represented by kg oil equivalents per functional unit, according to the ReCiPe Midpoint (H) Fossil Depletion category.

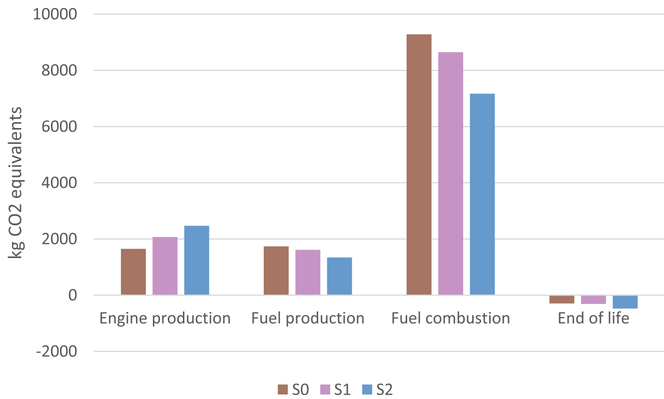

Fig. 6. Emissions of greenhouse gases for the different life cycle stages of the engine, as represented by kg CO2-equivalents per functional unit.

Table 6
Summary of four key indicators and mass flows, per functional unit, for each scenario: fossil resource use (kg oil equivalents) as well as CO_2, NO_x and CH_4.

	S0	S1	S2
kg oil eq.	4062	3968	3407
kg CO_2	11581	11215	9818
kg NO_x	16.34	14.57	13.20
kg CH_4	15.98	16.67	15.34

oil equivalents per functional unit, according to the ReCiPe Midpoint (H) Fossil Depletion category by Goedkoop et al. (2013)). The major share of fossil fuel use comes from diesel production for the use-phase. S1 and S2 show that implementing AM can decrease overall fossil depletion. Increased fossil depletion for engine production in S1 and S2, due to the energy intensive 3D-printing, is outweighed by gains in the use-phase, giving an overall decrease of 2.3% for S1 and 16.1% for S2.

When instead considering global warming potential (European Commission - Joint Research Centre, 2010), the results shown in Fig. 6 are, as can be expected, similar to those for fossil depletion, but the majority of impacts originate from tailpipe emissions in the use-phase rather than diesel production. Again, emissions from engine production are increased by the electricity consumption for 3D-printing in S1 and S2, but this is compensated by the substantial decrease in tailpipe emissions, giving an overall decrease in greenhouse gas emission of 2.8% in S1 and 15% in S2.

As a complement to the aggregated graphical results in Figs. 5 and 6, the mass flows of key substances that contribute the most to fossil depletion and global warming are presented in Table 6. For S1 most of these flows display marginal reductions or increases. In contrast, S2 performs better, with a reduction of 4–19% for each flow, which corresponds well with the weighted results presented in Figs. 2–4.

4.3. Material resource use

EPS weighting gives high scores for material resources, and is thus used here to investigate the material resource use. As shown in Fig. 4, “Non-renewable elements” is the dominant category. S1 had the worst performance, while S2 had the lowest impacts. The main reason for these results is the assumption that stainless steel is used in S1, but that technological development allows the printing of low-alloy steel in S2.

To further illustrate this, Table 7 and Table 8 show material composition, weight and impacts for two different components; the flywheel and the connecting rod. For the connecting rod in Table 7, low-alloy steel in S0 is substituted for stainless steel in S1, resulting in a 40-fold increase of EPS impacts from Non-renewable elements. In S2 however, it is possible to 3D-print low-alloy steel due to assumed technological development, resulting in impacts similar to those in S0. Hence, it is clear that the increased impacts in S1 are due to the stainless steel and its alloying elements. For the flywheel, in Table 8, the cast iron cannot be 3D-printed and is thus replaced by stainless steel in S1. This might be an unrealistic substitution, but it illustrates the potentially enormous increase of EPS impacts depending on material choice. In S2 the substitute material is low-alloy steel instead, which results in only moderately increased impacts.

Table 7
Weight and EPS impacts in the category of Non-renewable elements for the connecting rod in S0, S1 and S2.

Connecting rod			
	Material	Weight [kg]	Impacts from Non-renewable elements [ELU]
S0	Low-alloy steel	11,1	18.6
S1	Stainless steel (PBF)	8.3	729
S2	Low-alloy steel (PBF)	8.3	20.7

Table 8
Weight and EPS impact in the category of Non-renewable elements for the flywheel in S0, S1 and S2.

Flywheel			
	Material	Weight [kg]	Impacts from Non-renewable elements [ELU]
S0	Cast iron	27	0,6
	Low-alloy steel	3	5.02
S1	Stainless steel (PBF)	20.3	1792.8
	Low-alloy steel	3	5.02
S2	Low-alloy steel (PBF)	20.3	50,3
	Low-alloy steel	3	5.02

4.4. Sensitivity analysis

There are several parameters and assumptions to which the results are more or less sensitive. Table 9 shows a summary of nine tested parameters that were altered within different ranges while noting the effects on the results. The parameters were chosen because they were identified or suspected to be the most relevant factors influencing the results. Most show limited variations (PBF electricity consumption, PBF material losses, truck lifetime, stainless steel content, losses from manufacturing and assembly), indicating robustness, while the results were sensitive to the other parameters.

In the case of the assumed electricity consumption for the PBF process this was set to 134 MJ/kg, based on widely varying data. Changing this parameter did not show large effects on the results, but it was noticeable enough to indicate the importance of decreasing electricity consumption from PBF and post-processing, especially when using electricity with a large share of fossil fuels (see Fig. 9 below). Another notable example regards the assumption that low-alloy steel can be 3D-printed in the future. Without this assumption, there is a larger content of stainless steel in the future scenario of S2, resulting in moderately increased impacts from material production.

The parameters to which the results were most sensitive are analysed in detail below. These include the potential that AM offers

Table 9
Sensitivity analysis for nine different parameters, detailing the default option, the range of tested options and the consequent change in results due to the change in the parameter. The results are normalised to S0 and then averaged over the changes in EPS, EI99 and EDIP results.

Parameter	Default option	Tested options	Resulting change for S0 [%]	Resulting change for S1 [%]	Resulting change for S2 [%]
Weight reduction	25%	75%	0	−15	−39
		0%	0	8	21
Added function	27.5 l/100 km	22 l/100 km	0	−12	−11
		33 l/100 km	0	12	11
PBF electricity consumption	134 MJ/kg	61 MJ/kg	0	−3	−4
		569 MJ/kg	0	4	14
PBF material losses	20.4%	0%	0	−5	−2
		60%	0	4	5
Truck lifetime	300000 km	200000 km	−20	−19	−18
		400000 km	20	19	18
Nickel alloy printing	No nickel printing	Nickel printing in S2	0	0	86
Electricity mix for PBF	SE mix for PBF printing	US mix for PBF printing	0	8	37
Stainless steel content	Low-alloy steel printing in S2	No low-alloy steel printing in S2	0	0	14
Losses from manufacturing and assembly	6–60% losses	No losses	−2	−2	−1

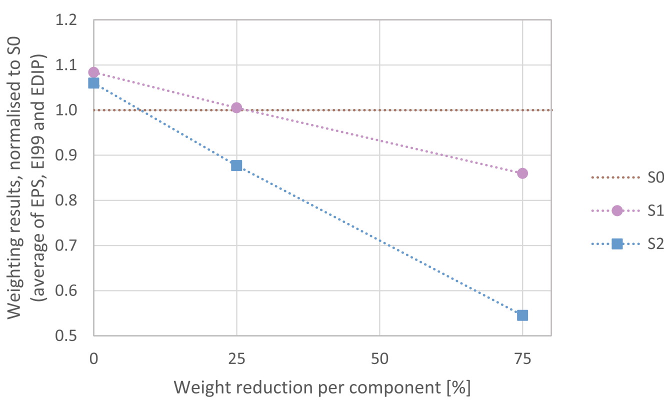

Fig. 7. Weighting results (y-axis) depending on the weight reduction per component achieved by 3D-printing (x-axis). Results are normalised to the reference scenario and have been averaged over the three weighting methods, EPS, EI99 and EDIP. Dots indicate the data points that were interpolated to achieve the lines shown.

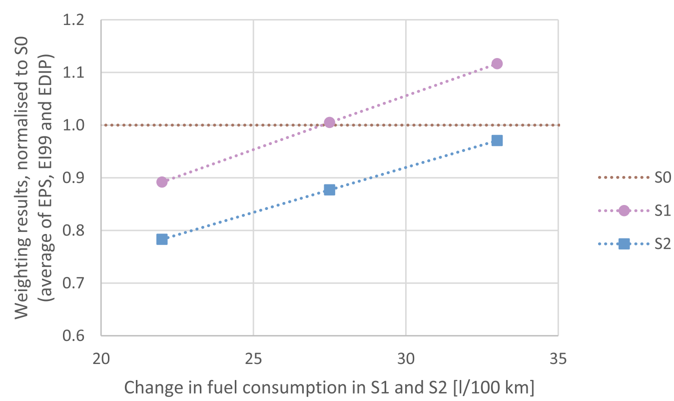

Fig. 8. Weighting results (y-axis) depending on changes in fuel consumption in S1 and S2 (x-axis). Results are normalised to the reference scenario and have been averaged over the three weighting methods, EPS, EI99 and EDIP. Dots indicate the data points that were interpolated to achieve the lines shown.

for redesigning components for reduced weight or added functionality, the assumed electricity mix for the PBF process and the effects of nickel-alloy printing. The details on the remaining sensitivity analyses can be seen in Appendix D.

One of the key assumptions of this study is the *weight reduction potential* from redesigning components for AM. Average weight reduction per 3D-printed part was conservatively assumed to be 25%. In Fig. 7, this number was varied between 75% and 0%, showing the subsequent effects on the results. The impacts have been normalised to S0 and averaged over the three weighting methods (EPS, EI99 and EDIP), to a single index. With 0% reduction, all benefits from avoided fuel consumption in the use-phase are lost, which means that both S1 and S2 perform worse than S0 in such a case. Conversely, a 75% weight reduction gives significantly improved results, especially in S2. It is established that in order for AM to be beneficial from an environmental perspective, some weight reduction needs to be achieved. In this case the minimum threshold was 27% for S1 and 8% for S2.

The potential offered by AM to redesign components for *additional functionality* was omitted from the model, which can be seen as a conservative assumption favouring conventional manufacturing. One example of such redesign is to integrate cooling channels within the material of the printed part, which would enhance the fuel efficiency of an engine. The effects of tentative improvements in engine fuel efficiency were tested here for S1 and S2, along with a test of deteriorated fuel efficiency, for completeness, seen in Fig. 8. The extreme and unlikely case of increasing fuel consumption to 33 l/100 km in S2 barely negates all benefits of 3D-printing. For a similarly extreme decrease to 22 l/100 km, the benefits are instead considerably enhanced. The results for S1 follow the same pattern. Hence, the possibility to design for increased function is an important parameter for maximising potential AM benefits. Likewise, it is important that there is no deterioration in fuel efficiency when shifting to AM.

Since the PBF electricity use gives a significant contribution to the results it is relevant to investigate the effects of *electricity production mixes* with different environmental performance. The Swedish mix, used for PBF throughout the study, has a low carbon intensity of 0.038 $kgCO_2$/kWh. The electricity mix of the United States was used here as a contrast, with its higher carbon-intensity of 0.632 $kgCO_2$/kWh, see Appendix C.3. Note that the mix was changed only in the PBF printing process. Fig. 9 shows that switching to a US electricity mix increases EPS, EI99 and EDIP impacts for S2 by 10, 36 and 66% respectively. This is a significant increase that reverses the relative results between S2 and S0 and indicates that the results are highly sensitive to the assumed electricity mix.

Nickel-alloys, often called *Inconels*, are common materials for

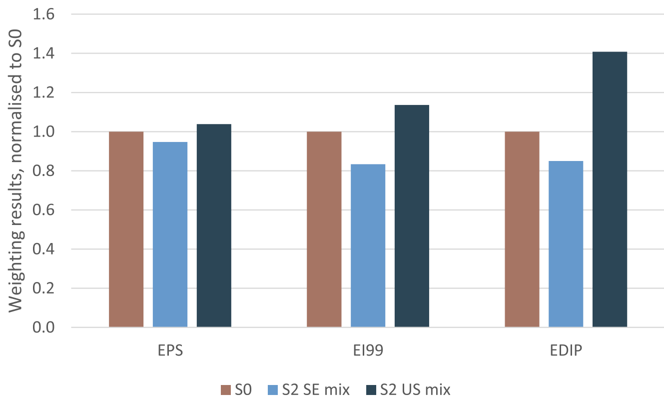

Fig. 9. Impacts of EPS, EI99 and EDIP depending on the electricity mix that supplies the PBF process (Swedish (SE) mix or US mix), for S2 compared to S0. S1 is excluded because it behaves like S2, only less pronounced.

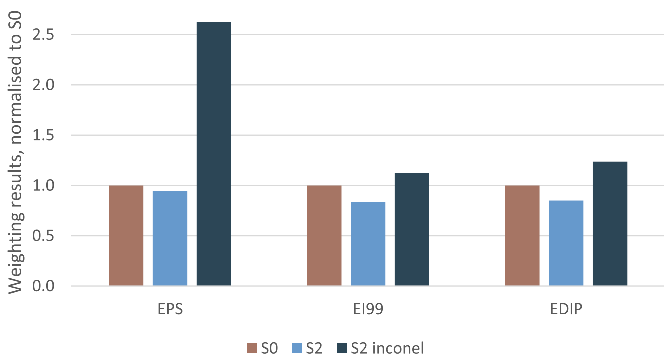

Fig. 10. Impacts of EPS, EI99 and EDIP depending on the substitution of steel for nickel-alloys (Inconels) in a 50 kg component. S2 impacts are shown in comparison to S0, while S1 is excluded since it was not included in the sensitivity analysis.

PBF (Wohler's Associates, 2016). It was therefore investigated how the use of nickel-alloys instead of steel would affect the results. As shown in Fig. 10, substituting steel for nickel in a 50 kg component gives dramatically increased impacts. Consequently, it can be surmised that the use of nickel-alloys in large quantities can reverse any environmental benefits of AM technology.

5. Discussion

Results show that there are potential environmental and resource benefits of AM, but there are also drawbacks to be circumvented. In the future case, reduced impacts in the use-phase more than compensated for the increased production impacts. This was due to components being redesigned for reduced weight, which lowered fuel consumption and hence reduced life cycle impacts. Similar effects are common for all products with a high and weight dependent energy consumption in the use-phase, including most mobile applications. For trucks, the implications are that components other than the engine can also be redesigned and 3D-printed. The larger the share of the total weight that is printed, the more weight can be saved. The technological development toward printing larger components is important for this.

The results are comparable to similar assessments in literature, such as the study by Mami et al. (2017), who conclude that AM of airplane components gives life cycle environmental improvements due to lightweighting. Kamps et al. (2018) also confirm that lightweighting of components is a key factor for reducing energy consumption. Conversely, other studies consider applications where lightweighting is not relevant to the environmental performance. One is by Liu et al. (2018) who find that AM does not yield environmental benefits for high-speed gears in wind turbines. However, they do not consider technological development, unlike Huang et al. (2017) who conclude that environmental improvements can be made in the case of injection moulds using mature AM technology.

Regarding the robustness of the results, conservative assumptions and estimates have been made throughout the study, thus favouring conventional manufacturing and yielding more robust conclusions. An example is the assumption concerning the potential weight reduction, which is likely to be larger than the assumed 25% per 3D-printed component (see section 3.1). Another example regards the assumption of functional equivalency of the engines in the different scenarios. The assumption was made even though it is reasonable to assume that 3D-printing would enable redesigns for improved fuel efficiency, which showed potential to considerably enhance the results in favour of AM (see sensitivity analysis in Fig. 8). Hence it can be concluded that there is a need to thoroughly investigate designs for additional functionality in order to take advantage of the large potential offered.

Furthermore, the electricity consumption for the PBF process was assumed to be equal in both the present and the future scenarios. However, as the technology spreads and matures it is reasonable to expect some reduction in electricity consumption. An indication of this is that most 3D-printing systems are currently not designed with energy efficiency in mind, in terms of e.g. cooling, laser sources and material losses (Baumers et al., 2017; Walachowicz et al., 2017).

Crucially, some specific assumptions were not made conservatively. Firstly, the electricity mix used for the AM process was assumed to have a low share of fossil fuels. This was deemed acceptable as the assessment is prospective and it is reasonable to expect cleaner electricity mixes in the future (United Nations Environment Programme, 2018). However, owing to the high energy intensity of PBF, the results are sensitive to the chosen electricity mix for printing and the results are thus only valid with a low share of fossil fuels (see sensitivity analysis in Fig. 9). A comparison can be made with electric vehicles, which also have the potential to decrease environmental impact, but only with a largely fossil-free electricity mix.

Secondly, a couple of assumptions were made regarding what materials can and cannot be 3D-printed with PBF in the future. For example, low-alloy steel can currently not be 3D-printed and thus in the present case (scenario S1) components originally in low-alloy steel have to be 3D-printed with stainless steel, with increased associated impacts. In the future case (scenario S2), it was assumed that it will be possible to print with low-alloy steel. This was showed by sensitivity analysis to have minor effects on the results (except in the case of EPS weighting where metal resources are valued highly, see Table 9 and Appendix D.4). The other example is that printing with nickel-alloys severely increases impacts in almost every category (see sensitivity analysis in Fig. 10). Consequently, material choices and their environmental consequences are an important consideration when implementing AM. Particularly, the use of nickel alloys should be avoided as much as possible, and AM technology should preferably be developed to be able to print using lower-impact materials like low-alloy steel.

5.1. After-market effects

Several characteristics of AM with consequences in the production and use-phase of products have been analysed in this paper, but one aspect that was largely omitted was the consequences for the after-market. This term refers to anything occurring after the sale of a product, such as repair, remanufacturing or recycling. Examples include printing spare parts on demand, which would reduce the need for manufacturers to maintain a complete spare part inventory. As pointed out by Holmström and Gutowski (2017) this can lead to economic savings, e.g. by avoided warehousing costs, avoiding the purchase or production of small volumes of parts, as well as material savings from avoided loss of unused parts that are eventually discarded.

Spare part printing could also enable extended product lifetimes by improving repair opportunities. For example, Kellens et al. (2017) report several examples of repairing and remanufacturing using AM that have shown environmental or energy improvements between 36 and 75%. Further, Walachowicz et al. (2017) corroborated this by showing that AM can support repairing activities with resulting environmental gains. However, spare part printing would require some components to be redesigned and adapted to the AM format, and depending on who 3D-prints the spare part there can be concerns regarding responsibility and warranty for the product. Moreover, if energy efficiency of a product improves year after year, an excessively prolonged life means that inefficient products are kept in circulation, which could lead to increased overall energy use (Holmström and Gutowski, 2017).

Finally, consolidation of components can lead to simplified logistics, reduced tooling needs, and decreased errors and time-requirement from production and assembly. For example, Kellens et al. (2017) describe that components, such as springs or hinged joints, can be integrated into a minimum number of parts. Furthermore, simplified assembly also means improved dismantling opportunities, and thus potential for improved remanufacturing and repairs, the benefits of which were indicated above (Holmström and Gutowski, 2017; Kellens et al., 2017).

6. Conclusions

In this study, LCA has been used to investigate the potential life cycle environmental and resource implications of using AM to manufacture metal parts of a light truck engine in comparison to conventional manufacturing. The assessment was done from both a short-term and a long-term perspective, considering technological development and adoption of AM. Three scenarios were formulated, one for conventional manufacturing and one each for the present and a potential future state of AM technology development, respectively. After building a life cycle model, three different weighting methods were used to filter results and identify key indicators, which were then studied in detail for each scenario. This was followed by a sensitivity analysis which enabled the identification of the most important factors influencing the results.

This study has showed that environmental improvements due to AM are consistent over the key indicators when assuming a future state of technology development for AM. The main reason for the improvements is the (conservatively estimated) weight reduction potential offered by AM, which resulted in decreased use-phase impacts more than compensating for increased impacts from production. Yet, this was only true in the case of a clean electricity mix, meaning that applying AM technology in the automotive industry can only lower life cycle impacts if clean electricity is used for the printing process. However, from a short-term perspective, the results are ambiguous, meaning that AM implementation is not beneficial without some technological development such as the possibility to print large components and to use low-alloy steel as a feedstock.

Limitations of the study include limited data availability for AM processes as well as limits in scope which meant that not all potential benefits and drawbacks of AM could be included in the model. Furthermore, the study includes future scenarios, which are inherently uncertain, although these uncertainties were at least partially handled by conservative assumptions and sensitivity analysis. Based on these limitations and on the results, research needs have been identified, both in terms of further assessments as well as technology development. Firstly, there is a need for assessments of various applications of AM, both within and outside the automotive industry. Furthermore, studies are needed to quantify the potential environmental consequences from spare part printing, facilitated dismantling, integration of components, material choice, reduced material waste and post-processing. Additionally, there is a need for quantified investigations of the possible benefits and drawbacks from localised production and shortened lead times. The results of this study also indicate that the use of highly impacting materials, such as nickel-alloys and stainless steel, need to be avoided as much as possible in order to realise environmental benefits. An identified research need is thus to develop AM technology to be able to use materials with lower environmental impacts, such as low-alloy steel. Finally, industries looking to implement AM should, in addition to weight reduction, focus on designing for added functionality and on exploiting the potential benefits from repairing and remanufacturing introduced by AM.

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Appendix. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.04.086.

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