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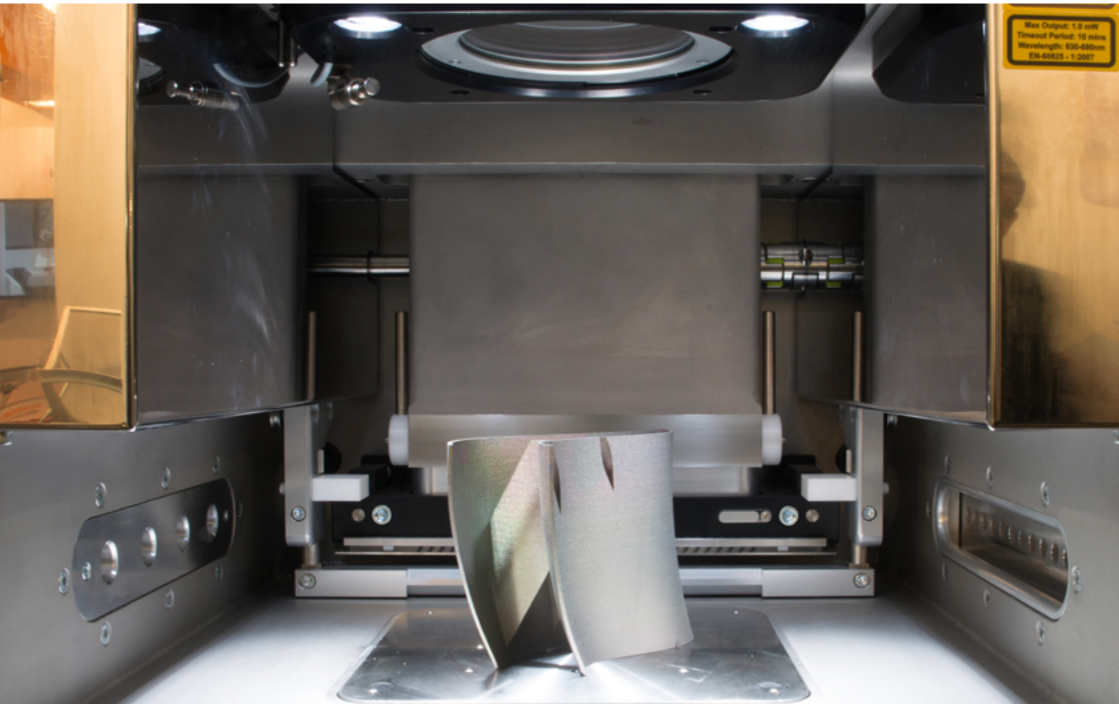
Ecological and Economic Assessment of Resource Use

Additive Manufacturing Processes in industrial Production



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Study: Ecological and Economic Assessment of Resource Consumption - Additive Manufacturing Processes in industrial Production

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Ecological and Economic Assessment of Resource Consumption

Additive Manufacturing Processes in industrial Production

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS

Al	Aluminium
AM	Additive manufacturing
AlSi10Mg	Aluminum alloy
ASTM	American Society for Testing and Materials
BJ	Binder jetting
CAD	Computer-aided design
CEM	Composite extrusion modelling
CNC	Computerised numerical control
CO_2	Carbon dioxide
CPU	Central processing unit
DED	Directed energy deposition
DIN	Deutsches Institut für Normung e. V. (German Institute for Standardisation)
DIS	Draft international standard
DIW	Direct ink write
DMLS	Direct metal laser sintering
EBM	Electron beam melting
EMI	Fraunhofer Ernst Mach Institute
EN	European Standard
EOS M 400	3D printer model
eq	equivalent
EU	European Union
FDM	Fused deposition modelling

FEM	Finite element method
FU	Functional unit
FFF	Fused filament fabrication
FLM	Fused filament modelling
GB	Gigabyte
GER	Gross energy requirement
GHz	gigahertz
GPa	gigapascal
h	hour
ILCD	International Reference Life Cycle Data System
ISO	International Organisation for Standardisation
n. d.	no database
CED	Cumulative energy demand
Kfz	motor vehicle
kg	kilogram
SMEs	small and medium-sized enterprises
CRMD	Cumulative raw material demand
kW	kilowatt
l	litre
LBM	Laser beam melting
LCA	Life-cycle assessment
LDM	Liquid deposition modelling
ME	Material extrusion
MJ	megajoule

µm	micrometre
m^3	cubic metre
mm	millimetre
MPa	megapascal
NPV	Net present value
PBF	Powder bed fusion
Pkw	Passenger car
PPE	Personal protective equipment
RAM	Random-access memory
RC	Reference component
SIMP	Solid isotropic material with penalisation
SL	Sheet lamination
SLM	Selective laser melting
STL	Stereolithography
Ti6Al4V	High-strength titanium alloy
VDI	Association of German Engineers
VDI ZRE	VDI Zentrum Ressourceneffizienz GmbH

ABSTRACT

Additive manufacturing processes (AM) are characterised by the generation of structures in layers and are a key technology in digitisation (Industry 4.0). Currently, the so-called 3D printing processes are on the threshold of producing small and medium-sized series. In the future, they will play a central role for small and medium-sized enterprises (SMEs) in the manufacturing sector.

From a resource and economic point of view, the question currently arises as to how high the resource consumption of additive manufacturing processes is compared to conventional production processes (casting, milling, etc.) and how the cost-effectiveness of the two processes compares. Studies comparing the resource requirements of additive and conventionally produced components already exist.[1, 2, 3] However, there were no structural optimisations were carried out to reduce the volume of the components manufactured by additive processes. But volume reduction of the component in particular contributes significantly to production and use that saves on resources. Studies have shown that greater effects can be achieved here than through pure selection of simply selecting a plant technology or a manufacturing process (Chapter 1).[4, 5]

The aim of the present study is therefore to carry out a comparative ecological and economic evaluation of a component made by additive manufacturing and one made conventionally, taking into account structural optimisation of the component to be manufactured by additive methods. The focus is on additive processing of metals, as German companies are considered to be leading in this field in particular (Chapter 2).

The following use case was defined to carry out a comparison of the ecological and economic assessment of resource consumption:

1 See Telenko and Seepersad (2012), pp. 472 – 481.
2 See Faludi et al. (2015), pp. 14 – 33.
3 See Morrow et al. (2007) pp. 932 – 943.
4 See Wohlers et al. (2016).
5 See Bierdel and Pfaff (2017).

“Production of vehicle components in a batch size of 10,000 pieces per year.”

This use case is based on the assumption that conventional manufacturing processes for small to medium-sized series can be replaced in future by additive manufacturing processes. The study therefore outlines a scenario that is relevant for the medium term and has a prospective character (section 4.1).

As a reference component, a vehicle component, specifically a shock absorber fork, was provided by an automotive supplier. It consists of a drop-forged aluminium casting alloy and has a total weight of 1.3 kg. Two aluminium powders were chosen as materials for the additive production of this damper fork: an aluminium powder (supplier APWorks) of the alloy Scalmalloy© AlMg4.5Sc0.7Zr0.3 and the aluminium alloy AlSi10Mg.

The damper fork underwent a topology optimisation via the software OptiStruct: first, a simulation model was created, the optimisation target defined, the topology optimisation carried out on this basis and the results interpreted. Finally, the redesign was worked out. Figure 1 shows the conventionally produced and the digital CAM model of the structurally optimised reference component.

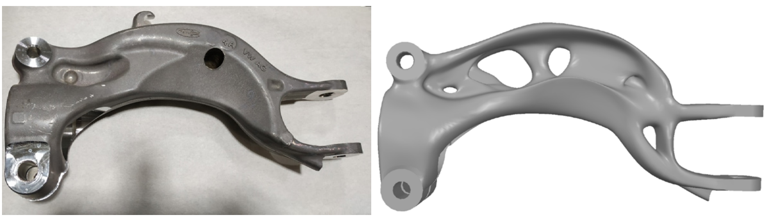

Figure 1: Left: Conventionally manufactured component. Right: Digital CAM model after structural optimisation

As a result, the topology optimisation achieved a mass saving of 12% with Scalmalloy© and a mass saving of 5% with AlSi10Mg (section 4.2).

The process selection for additive production of the structurally optimised reference component was carried out according to ISO DIS 20195[6]. Laser beam melting (LBM) was used in the study because it achieves similar material properties to conventional processes, has a good build-up rate and productivity, and has high market relevance. In order to collect data for the ecological and economic assessment, the structurally optimised component was produced in an EOS M 400 LBM system. For the conventional manufacturing process, the actual production process of the car manufacturer was used, which includes the steps of casting, drop forging, deburring, heat treatment and milling (section 4.3).

The comparative ecological and economic assessment presupposes definition of a uniform reference point (functional unit). For the present study the following functional unit has been defined (section 4.4):

"A shock absorber fork for passenger cars, designed for a service life over the assumed total mileage of the vehicle of 150,000 km."

The conventionally produced and additively manufactured damper fork thus performs the same function in its utilisation phase, but differs in its properties such as material, geometry and mass. The specified functional unit thus represents the lowest common denominator of the function of the reference components considered here: over their entire product life cycle from raw material extraction to disposal (system limit, section 4.4).

On the basis of the findings and aggregated data, the comparative ecological assessment is based on the impact categories of cumulative energy demand, cumulative raw material demand, water consumption, land use and global warming potential. The results of the ecological comparison show that additive manufacturing has significantly greater impact than conventional production across all environmental impact categories. This is mainly attributable to the high basic electrical consumption of the LBM system and points to

[6] See ISO/DIS 20195:2015(E).

a system technology with optimisation potential in terms of energy efficiency. A sensitivity analysis showed that technical improvements to the LBM system can cut the environmental impact by around half and reduce the gap between conventional and additive manufacturing. Here it can be estimated that subsequent generations of additive manufacturing processes will open up such optimisation potential in their development and thus lead to a reduction of the environmental impact.

The powder alloys used for additive manufacturing also had a significant impact on resource consumption. The aluminium alloy Scalmalloy© has scandium as a constituent, the extraction of which has a significant impact on raw material costs and is also classified as a critical raw material. Since Scalmalloy© is more suitable for highly optimised components and less for generic vehicle components, use of AlSi10Mg is recommended as the preferred powder alloy, as it has fewer resource-related effects for the use case. From this it can be deduced that the choice of the metal powders used must be precisely matched to the use case in order to minimize environmentally relevant effects. In addition, effective use of an additive manufacturing process depends on the use case in question. In the present study, the savings in the utilisation phase due to the mass savings of both powder alloys are so low that the fuel consumption is only marginally reduced. For other application areas such as aerospace or for products that follow an overall bionic concept, higher savings potentials can be achieved in the utilisation phase and the advantages of additive manufacturing can be improved (section 5.1).

The economic assessment also shows that, in addition to the investment costs, the material and operating costs in additive manufacturing are much higher than in conventional production. The deciding factors here are the powder and maintenance costs for the LBM system. However, the sensitivity analysis carried out also shows that technological innovations can significantly improve the profitability of additive manufacturing plants in the future (section 5.3). Overall, the results of the study thus allow the derivation of the following general findings (Chapter 6):

- The product type and quantity to be produced essentially determines the appropriateness of the use of additive manufacturing processes. Above all, the degree of mass saving through structural optimisation and the type

of equivalent, conventional manufacturing process (casting or milling, etc.) has an influence on the ecological and economic impacts.

- The choice of materials also significantly influences the ecological and economic effects and should be tailored exactly to the requirements of the use case, i.e. the type and quantity of product to be produced.

- Permanent capacity utilisation (e.g. optimised space utilisation) and technical optimisation (e.g. reduction of energy consumption) of additive manufacturing systems reduce the ecological and economic impacts and can open up new fields of application in the future.

In summary, additive manufacturing of metallic workpieces can be seen as a supplement to conventional production. It is on the threshold of small and medium-sized series production and plays an increasingly central role in various sectors, in particular in aerospace, medical technology and bionic product concepts. It is expected that the technological development of additive manufacturing processes will optimise process flows, opening up new application areas and efficiently replacing conventional production processes where the two technologies intersect (batch size). In this connection, the present study offers an exemplary insight into helpful assessment mechanisms in decision making concerning investments in additive manufacturing processes.

1 INTRODUCTION

Additive manufacturing (AM), also referred to as “3D printing”, is a key digitisation technology in industry (Industry 4.0) through its production flexibility and through the possibilities it offers in terms of functional integration, product customisation and accelerated innovation times. Layered generation of structures offers a new freedom of design, so that technology is expected to grow steadily in almost all sectors of manufacturing industry.[7, 8, 9]

The use of structural optimisation methods, in particular topology optimization, makes it possible to make targeted and efficient use of freedom of design. Thus, a reduced component weight and, as a consequence, a reduction in operating costs in the utilisation phase of 3D printed products is possible, along with resource-efficient production.[10, 11] Particularly in connection with the latter, studies show that volume reduction of components (for example, through numerical structural optimisation) is an essential prerequisite for resource-saving production. With a suitable design choice, even greater effects can be achieved here than through the decision in favour of a specific system technology.[12] Broad cross-technology assessments of the sustainability of additive manufacturing processes have already been carried out by Huang, Ford, Gebler and Kohtala.[13, 14, 15, 16]

Currently, 3D technology is on the threshold of producing small and medium-sized series in addition to the already established production of prototypes and pilot products. General series production of products is traditionally carried out by conventional manufacturing processes such as casting or milling. But here, too, the question of the most effective production process both ecologically and economically will arise in future, in particular

7 See Gartner (2014).
8 See Kianian (2016).
9 See Richter and Wischmann (2016).
10 See Wohlers et al. (2016).
11 See Bierdel; Pfaff (2017).
12 See Pfaff et al. (2018).
13 See Huang et al. (2013).
14 See Ford and Despeisse (2016), pp. 1573 – 1587.
15 See Gebler et al. (2014), pp. 158 – 167.
16 See Kohtala C. (2015), pp. 654 – 668.

depending on the batch size to be produced and the geometry of the component. Comparisons regarding resource requirements between conventionally manufactured components and those produced by additive manufacturing have already been carried out by Telenko, Faludi and Morrow.[17, 18, 19] Here, however, no consideration was given to an Am design of the component under investigation that is suitable for production. Furthermore, in the development phase no optimisation of the construction was carried out according to economic aspects.

Consequently, Huang[20] and Ford[21] call for further comparisons between additive and conventional manufacturing processes, taking into account technology-specific requirements. A first classification of material flows within the production cycle is carried out by Pfaff, Telenko and Baumers.[22, 23, 24] In order to successfully support the transition from additive manufacturing to small-scale industrial manufacturing, further comparative studies are needed to provide predictions and support the decision-making of potential users.

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17 See Telenko and Seepersad (2012), pp. 472 – 481.
18 See Faludi et al. (2015), pp. 14 – 33.
19 See Morrow et al. (2007) pp. 932 – 943.
20 See Huang et al. (2013).
21 See Ford and Despeisse (2016), pp. 1573 – 1587.
22 See Pfaff et al. (2018).
23 See Telenko and Seepersad (2012), pp. 472 – 481.
24 See Baumers et al. (2011), pp. 2228 – 2239.

2 AIM OF THE STUDY

The aim of the present study is to compare environmental and economic aspects of additive and conventional manufacturing processes in industrial production. In particular, the possible improvement potentials of additive manufacturing processes with regard to energy, resource efficiency and cost-effectiveness are to be analysed and compared with conventional manufacturing processes, such as casting and forging. In addition to the actual production process, it is also important to consider the optimisation of geometric structures possible with AM processes using computer-aided development methods.

The comparison is based on a relevant assessment framework for industrial production in small and medium-sized enterprises (SMEs). Since German companies are considered to be leading the way in the field of additive metal processing in particular, this is the focus of the considerations. In addition, a use case is selected that represents as generically as possible the production processes of metal processing SMEs: the production of lightweight aluminium components for vehicles. The reference component is a damper fork made of an aluminium alloy which is used in automobiles and is actually produced in practice. Prior to additive manufacturing, this damper fork undergoes structural optimisation. The reference component was used as the basis for the following considerations:

- The workpiece can be manufactured effectively using both additive and conventional manufacturing processes and consists of materials with similar properties.
- A functional equivalence of the structurally optimised component made by additive manufacturing and the conventionally manufactured component is ensured.
- The application of the lightweight reference component allows an analysis of the impact of structural optimisation on energy and resource efficiency as well as the economic costs during the utilisation phase of the product.

- The conventionally manufactured component comes from a current conventional production process, which makes it possible to collect primary life cycle inventory data for ecological and economic analysis.

- The assumptions on which the comparative assessment is based represent business models relevant to SMEs.

The comparison of the additive-manufacturing and conventionally manufactured reference component is carried out on the basis of a life-cycle-oriented assessment approach, which includes the entire product life cycle of the components considered in the analysis. The following research questions are examined in detail in this context:

- What is the energy and raw material consumption (cumulative energy demand (CED) and cumulative raw material demand (CRMD)) over the entire life cycle of the components? What differences result from the use of additive technologies and computer-aided structural optimisation of the components?

- What consumption of supply-critical raw materials, water and land is necessary?

- What are the greenhouse gas emissions (in CO_2 equivalents) for each variant?

- What costs arise for the considered variants over their respective life cycle? What are the economic benefits of using AM and using structurally optimised components in vehicles?

The main target groups of the study are

- small and medium-sized enterprises (SMEs) of the metalworking industry as potential users of AM manufacturing processes,

- machine and system manufacturers,

- the vehicle industry as a potential user of structurally optimised components,

- research institutions and consultants and
- initiatives, associations and federal and state institutions.

SMEs should be empowered by the results of the study to evaluate the benefits of investing in additive manufacturing processes from an environmental and economic perspective. Furthermore, the study should be useful as a source of information for initiatives, associations and federal and state institutions and their representatives.

3 BASICS AND STATE OF THE ART

3.1 Classification of additive manufacturing processes

Currently, the DIN EN ISO 8580 standard does not yet provide for an explicit classification of additive manufacturing processes into the six main groups of manufacturing processes of casting, forming, cutting, joining, coating and modifying material properties.[25] However, the specialist literature often assigns them to 'casting' or 'joining' (for example, see Gebhardt[26]).

The additive manufacturing methods themselves can be classified as follows. According to Gebhardt[15], a process classification based on the aggregate state of the starting material is possible:

- gaseous,
- liquid and
- solid (based on foil, wire or powder).

Special cases are the starting materials pastes and aerosols.

An alternative and widely recognised classification can be found in the standards ISO/ASTM 52900 and ASTM F2792-12a. These subdivide the additive manufacturing processes, based on the process methodology, into seven groups:

- **Powder bed fusion (PBF):** The material is in the form of a powder bed and is selectively joined using thermal energy.
- **Directed energy deposition (DED):** The material is melted during application using thermal energy.
- **Material extrusion:** Molten material is applied using an orifice (e.g. nozzle).

[25] See DIN 8580:2003-09.
[26] See Gebhardt (2013).

- **Binder jetting:** Liquid binder is introduced into a powder to bind it.
- **Sheet lamination:** Starting material in the form of a film is cut and joined.
- **Vat photopolymerisation:** Liquid photopolymers are selectively cured.
- **Material jetting:** The material is applied locally in the form of drops.

Within these groups, in turn, there are a variety of technological variants with different nomenclatures. Marketing and patent considerations have contributed to a wide variety of proprietary designations. In addition, for most English-language terms there is still no suitable translation into German. Therefore, the nomenclature in the field of AM is confusing.

As the study focusses on the production of a metallic reference component, the procedures and their properties that can process metallic materials are described below. These processes belong to the groups powder bed fusion, directed energy deposition, material extrusion, binder jetting and sheet lamination.[27]

In order to provide a clear introduction to additive manufacturing processes, the technological and economic details are simplified. Special processes which are currently in commercial use only to a very limited extent are not considered here (e.g. thermal spraying).

3.1.1 Powder bed fusion (PBF)

Laser beam melting (LBM)[28]

Principle: The method is based on processing a metal powder with typical grain sizes between 5 µm and 100 µm. Layer-by-layer generation of the component lying in a powder bed takes place through selective melting of the powder by means of a laser beam and subsequent solidification of the local molten metal on the existing surface of the resulting workpiece. The laser processes successive single layers with typical thicknesses of 10 µm to

[27] See Kianian (2016).

[28] Synonyms/associated processes: Laser beam melting, selective laser melting (SLM), laser curing, direct metal sintering (DMLS), laser melting and others.

90 µm. After exposure of a single layer, the powder bed lowers over the build platform by the appropriate layer thickness, followed by the application of a fresh powder layer by a blade-based coating system[29]. The iterative principle is shown in Figure 2.

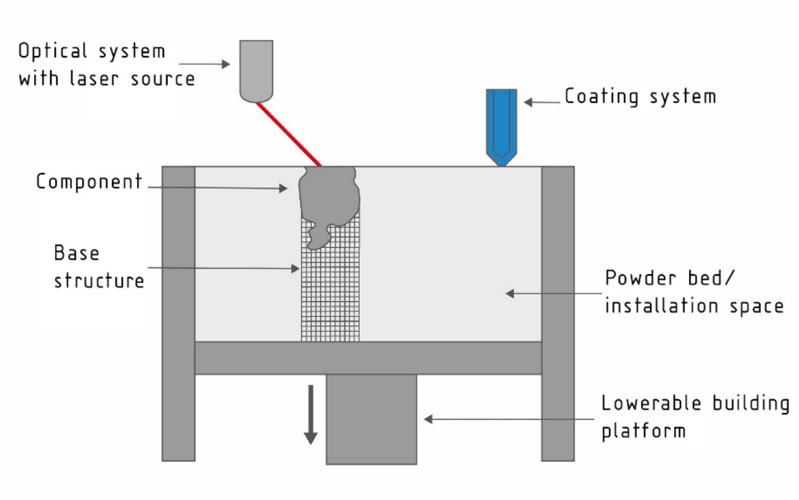

Figure 2: Functional principle of laser beam melting

Available materials: Due to the high market relevance and flexibility of this manufacturing process, the largest selection of powder materials is currently available on the market. The powder materials can be used for a variety of applications, such as lightweight engineering, high-temperature applications and toolmaking. The range of available materials has been expanded in recent years by new materials for laser beam melting developed through various research activities. In principle, all weldable alloys can be processed easily using the laser beam melting process.

Material properties: Due to the high cooling rates in the process, laser beam melting produces a characteristic microstructure with typically fine grain precipitates. This provides significantly greater strength than in

[29] See Gebhardt (2013).

conventionally processed materials, but reduced ductility[30]. The relative density of laser-melted solids is usually well over 99%. The additive material has a similar material properties profile to a conventionally processed material. The degree of the anisotropy in the material depends heavily on the selected process parameters[31]. Due to the very high solidification rate of the melt, internal stresses in the component are induced in the laser beam melting process. These can be reduced by means of subsequent heat treatment.

Surface properties: The surface properties depend heavily on the alloy used, the process parameters (e.g. layer thickness), the component design and the orientation in the installation space. However, as in all additive manufacturing processes, the roughness is typically high, requiring reworking of the functional surfaces. The dimensional accuracy of the layers produced is higher parallel to the build platform than at right angles to the superimposed layers. These surfaces have a certain staircase texture. However, the so-called step effect with this technology is relatively small due to the comparatively thin layers and the thermal effects in the process. Unfavourably positioned surfaces may have microcracks, which may later act as crack initiators in the utilisation phase of the products.

Process limitations: During component production, support structures are needed that fix the resulting component on the build platform and allow heat to dissipate. These support structures are made by the same additive process as the component itself. The support structures and the powder must then be removed manually after the process. Since the design freedom of additive manufacturing processes compared to conventional manufacturing processes is nevertheless high[32], the technology is increasingly being used for the production of functional components. As a result, quality assurance systems and methods continue to evolve rapidly[33].

Costs: The investment costs are relatively high compared to other additive manufacturing processes due to the complex system design.[21] The operating

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[30] See Buchbinder (2013).

[31] See VDI 3405 Part 2.1 (2015).

[32] Due to the residual stresses in the material and the thin metal powder layers, which cause an interaction of forces between the coating system and the workpiece, the design freedom of the additive manufacturing methods is limited.

[33] See Kianian (2016).

costs are also comparatively high because of the current prices for metal powders, the necessary aids (e.g. inert gas, protective measures such as personal protective equipment (PPE)) and the complex reworking of the components.[21] In addition, the work required for manual removal of the support structures, the time-consuming erection and disassembly work and cleaning of the facilities is high. This requires specially trained technical personnel. In addition, there are material losses for support structures, large space requirements and disposal costs for filter units. Unmelted powder, however, can be reused without significant loss.

Current market relevance: In terms of metallic additive manufacturing processes, this is the most widespread process across industry.[21] Powder and machine sales have grown exponentially over the last few years. Forecasts predict further development. In 2015, 808 machines were sold worldwide (2012 comparison: 202). The biggest drivers of demand are the aerospace industry and medical technology.

Due to the impressive universality of this technology, there is now a wide range of manufacturing equipment from different manufacturers. Depending on the system type, it is possible to produce microscopically small components as well as large-volume components of up to 1 m^3 (and research systems can achieve significantly larger volumes). The trend is towards large volume automated manufacturing systems to drive economical small batch production.[34]

Conclusion: This is the most widely used additive manufacturing process for metallic materials. The technology is costly, but already offers a large selection of materials, which will grow significantly in the future. The strengths of the technology lie, above all, in the resulting material properties. The method is therefore particularly suitable for the production of structural and functional components.

[34] See Kianian (2016).

Electron beam melting (EBM)[35]

Principle: This is a process related to LBM. However, the powder is melted using an electron beam instead of a laser. This explains why there is no inert gas in the process chamber, unlike LBM, but there is a high vacuum.

Available materials: The high energy density of the electron beam allows a much faster exposure than in laser-based systems. This allows, among other things, preheating of the powder bed, followed by the actual exposure of the components. This reduces the cooling rate and thus the residual stresses in the workpiece. Accordingly, the strengths of the technology are above all in processing of alloys susceptible to intrinsic stress, such as Ti6Al4V, cobalt-chromium or Inconel 718 (nickel-based alloy). The current range of materials is limited.

Material properties: As in the LBM process, components with a high relative density can be produced. The mechanical properties are equivalent to conventionally processed materials. The lower cooling rate compared to the LBM process causes a correspondingly coarser microstructure. The use of a high vacuum instead of inert gas is better when it comes to preventing impurities in the material.

Surface properties: The use of an electron beam makes it difficult to apply low energies to the powder bed. This results in rougher surfaces than in the LBM process. Functional surfaces must be reworked accordingly.

Process limitations: Despite reduced residual stresses, support structures are also needed here. The design freedom is somewhat higher than in the LBM process but is still limited. The range of systems on the market is still low and is limited mainly to those with medium-sized installation space.

Costs: The investment and operating costs are similar to LBM systems. However, the production times are significantly reduced compared to LBM due to the use of an electron beam.

Current market relevance: To date, commercially available EBM systems are only available from one manufacturer on the market, resulting in a

[35] **Synonyms/related processes: none known (presumably due to patent situation).**

monopoly position.[36] This is one reason why EBM systems are much less common in industrial environments than LBM systems.

Conclusion: The strengths of the EBM process compared to the LBM are above all the higher productivity and the lower intrinsic stresses in the material. However, there is a monopoly on the market, so the technology is less common. Furthermore, the surface quality produced is lower. The method is particularly suitable for the production of structural and functional components made of titanium, Inconel and cobalt chrome.

3.1.2 Directed energy deposition (DED)[37]

Principle: Energy source and material supply are usually located on a freely movable robot arm (5-axis system). The material supplied in powder or wire form is applied to an existing substrate. The energy supply for melting the supplied material is a laser, an electron beam or a plasma beam. A protective gas flow prevents contamination of the material. The DED process is not bound to a planar layer principle, so three-dimensional layers can also be applied (e.g. curved surfaces). The principle is shown in Figure 3.

[36] See Kianian (2016).

[37] Synonyms/associated processes: Electron beam additive manufacturing, laser consolidation, LENS, direct metal deposition, laser engineered net shaping, directed light fabrication, 3D laser cladding, EBFFF and others.

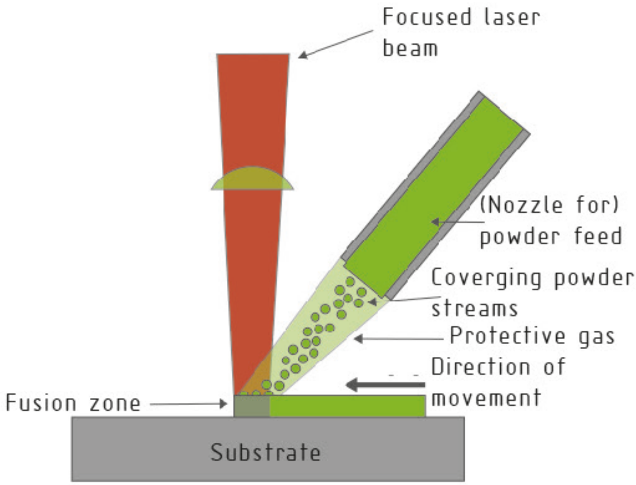

Figure 3: **Functional principle of the DED process using the example of powder with laser**

Available materials: Typical welding materials can be used, which makes the material portfolio very extensive. Examples of available materials are titanium and nickel alloys, tool steels, stainless steels and other steels.

Material properties: Due to similar thermal boundary conditions, the microstructure resembles that of LBM materials. The porosity increases, however, due to less control over application of the powder.

Surface properties: Due to the less precisely controllable application rate, the surfaces are rougher compared to other additive processes. The dimensional accuracy is lower. The individual layers are clearly visible.

Process limitations: The size of the manufacturable objects is limited only by the working space of the 5-axis unit. Thus, even very large components can be produced. Undercuts must be supported by support structures. The DED process is particularly well suited to building up structures on existing components. Thus, hybrid production and repair work can be carried out particularly well. Since the DED process has a low build speed, it is suitable for one-off production but not for mass production.

Costs: Investment costs are low compared to other additive manufacturing processes.[38] However, operating costs are comparatively high compared to powder bed processes due to the higher protective gas requirements (protective gas is not cycled).

Current market relevance: The technology is used in view of its strengths in hybrid manufacturing of components and repair of worn components. Well-known examples include the repair of turbine blades.

Conclusion: The achievable material properties are very good, but the surface quality is lower than in the LBM process due to the higher particle distribution. The DED process is primarily used for repair applications and is a widely used additive manufacturing process. Due to the low build-up rate, the process is unsuitable for mass production.

3.1.3 Material extrusion[39]

Principle: In this process a liquefied or paste-like filament is forced through a heated nozzle or orifice (extruded) and deposited in layers (Figure 4).

[38] See Kianian (2016).

[39] Synonyms/associated processes: FDM, FFF, CEM, FLM, freeform fabrication, DIW, EFF, G3DP, LDM and others.

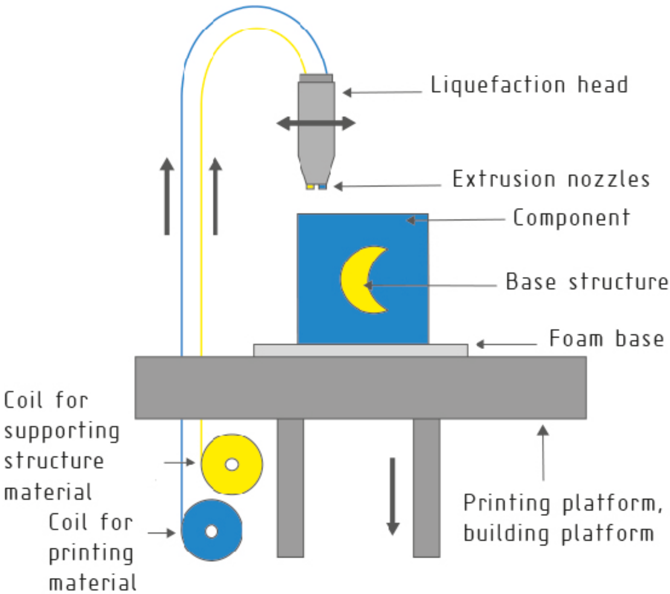

Figure 4: Functional principle of material extrusion. For metallic materials, the process is used to produce green compacts

Functional principle of material extrusion. For metallic materials, the process is used to produce green compacts

The build platform and print head are moved vertically to each other. Typically, polymers are processed in this manufacturing process. In order to process metallic materials, fine metallic particles are introduced into a polymer matrix. The filament is produced as extruded material. From the filament, a so-called green compact is first produced in the material extrusion process, which is subsequently burned out, infiltrated with a selected material and sintered as appropriate. In this process, shrinkage effects may occur, which must be considered in the design.

Available materials: The process is suitable for a variety of materials that can be produced in powder form and then processed as filler into a filament. Theoretically, all alloys that are suitable for the sintering or infiltration process are suitable. The infiltration process creates a hybrid material system.

Material properties: Since green compacts are produced, the result is a comparatively porous solid. As in the case of plastic-based material extrusion processes, the material resulting after sintering has weaker mechanical properties than conventionally produced materials.

Surface properties: The surface finish is good for an additive manufacturing process. Accuracy of shape is rather low due to the use of a filament.

Process limitations: Support structures are needed, and design freedom is low compared to other additive manufacturing techniques. However, the freedom of design is still greater than with conventional methods. The material extrusion process has a low build-up rate, resulting in long process times. There are also time-consuming post-treatments. Due to the large installation spaces required for systems available on the market, it is possible to produce very large components. For production of metallic components, the available volume is currently limited to approx. 300 x 300 x 300 mm.[40]

Costs: The simple system design explains the low investment costs. The operating costs are also relatively low, since few aids are needed, and the waste is low. However, it is one of the slowest processes compared to other additive manufacturing processes.[27]

Current market relevance: The origin of material extrusion processes lies in processing thermoplastics. Processing of metals is a relatively new technology on the market. Accordingly, there are only a few system types. The relevance for industrial use is low at the moment. The technology is currently used in the consumer sector to manufacture simple, customised components in the smallest quantities.

Conclusion: This is the cheapest, but also slowest procedure with low market relevance at the moment. The mechanical material properties are also very low, which is why there are few industrial applications.

[40] See Kianian (2016).

3.1.4 Binder jetting[41]

Principle: Like LBM and EBM, binder jetting is based on the powder bed principle and iterative application and processing of powder coatings. The material is not melted but bonded with a liquid binder into a green compact (Figure 5). Printheads similar to those used for inkjet printing are used here. The actual binder jetting process is followed by shrinkage-related post-processing steps (sintering and infiltration processes as in the material extrusion method).

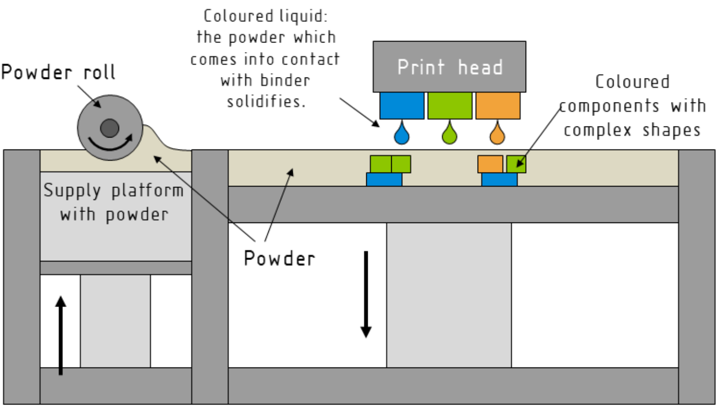

Figure 5: Functional principles of binder jetting

Available materials: The process is flexible with respect to the alloys that can be used, which means that an extensive range of alloys is available. Theoretically, all alloys suitable for a sintering or infiltration process are suitable. The infiltration process creates a hybrid material system.

Material properties: The material properties are similar to those of materials produced in the material extrusion process. The material is comparatively porous and has weaker mechanical characteristics.

[41] Synonyms/associated processes: 3DP and others

Surface properties: Due to the use of printheads like inkjet printer heads, the resolution of the process is very good. This results in a high surface quality and very high dimensional accuracy.

Process limitations: Since the process does not cause any significant intrinsic stresses, no support structures are needed. The process has the highest design freedom of all the additive manufacturing processes. Adaptation of the component design to the manufacturing process is hardly ever necessary. The second advantage of the method lies in the high production efficiency. However, it should be noted that, as in the material extrusion process, lengthy and complicated post-processing steps are necessary. At the moment, systems with a construction volume of 800 x 500 x 400 mm are on the market.[42]

Costs: This is a cost-effective process. Both investment costs and operating costs are comparatively low.[29] There is little waste.

Current market relevance: The origin of binder jetting can be found in prototype production and mould making. As in the case of the material extrusion process, processing of metals is relatively new, with correspondingly low market relevance.

Conclusion: This is a productive process. The principle allows the highest design freedom at low cost. The mechanical material properties are reduced, however.

3.1.5 Sheet lamination[43]

Principle: In metallic sheet lamination, sheets are welded together ultrasonically. Contouring of the individual sheet metal layers takes place by means of machining methods. The two-step processing stage of a layer is shown in Figure 6.

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42 See Kianian (2016).

43 Synonyms/associated processes: Laminated object manufacturing (LOM) and others.

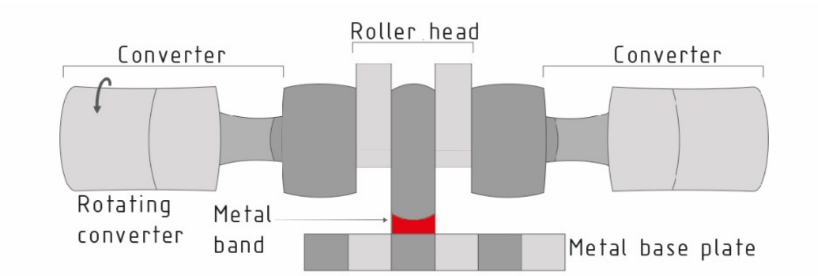

Figure 6: Functional principle of sheet lamination

Available materials: A big advantage of the technology is that different alloys can be welded together to create hybrid composite material systems. Common types include aluminium, copper, steel and stainless steel. Theoretically, however, all weldable and machinable alloys can be processed.

Material properties: The resulting material properties depend on the material. However, the material is always weakened due to the weld lines and has a high anisotropy.

Surface properties: As a result of the machining stage, the surface quality and dimensional accuracy are very high for an additive manufacturing process.

Process limitations: The freedom of design is relatively limited. Although undercuts can be strengthened with support structures, implementation is complicated. The construction volume of current systems is comparatively large (1800 x 1800 x 900 mm). No post-processing steps are necessary.

Costs: During the process, a large amount of non-recyclable waste accumulates. This leads to high material and disposal costs, making the technology less suitable for mass production.

Current market relevance: Due to its suitability for special applications, there is no particular market relevance for the technology and there are only a few machine manufacturers on the market.

Conclusion: It is a niche technology whose lies in special applications (e.g. hybrid materials, internal structures or sensor integration). No post-processing steps are needed, but large amounts of waste accumulate. The technology is therefore not suitable for structural components and should primarily be used for the special applications mentioned above.

3.1.6 Summary

Table 1 shows an overview of the advantages and disadvantages of the additive manufacturing processes described, based on the above explanations. It should be noted that this is a qualitative assessment that highlights the differences between the different methods relative to one another.

Table 1: Summary of assessment of the process groups under consideration

Requirement	PBF	DED	BJ	ME	SL
Mechanical properties					
Relative density	+	+	O	O	-
Strength	+	+	O	-	-
Ductility	O	O	+	+	O
Fatigue properties	O	n. d.	n. d.	n. d.	n. d.
Intrinsic stress	-	O	+	+	+
Anisotropy	+	+	+	O	-
Costs					
Investment costs	-	O	O	+	O
Operating costs	-	-	+	+	-
Build speed	O	-	+	-	O
General applicability					
Existing alloys	+	+	O	O	O
Surface finish	O	-	+	O	+
Staircase effect	O	-	+	O	-
Accuracy of shape	+	-	+	O	+
Design limitations	O	-	+	-	-
Construction volume	O	+	O	O	O
Market relevance					
Dissemination of the process	+	O	O	O	-
Industry relevance	+	O	-	-	-

PBF: Powder bed fusion; DED: Directed energy deposition; BJ: Binder jetting; ME: Material extrusion; SL: Sheet lamination

+ Good | O Average | - Bad | N/D = no database

As a matter of principle, it should be noted at this point that the appropriate additive manufacturing process should be used for each specific application (see ISO / DIS 20195), as the benefits of the different manufacturing processes vary. The processes are thus not in competition with each other, but are complementary.

3.2 Product development processes and computer-aided structural optimisation of 3D components

Traditionally, a **conventional development process** is used for the design and construction of components (Figure 7).

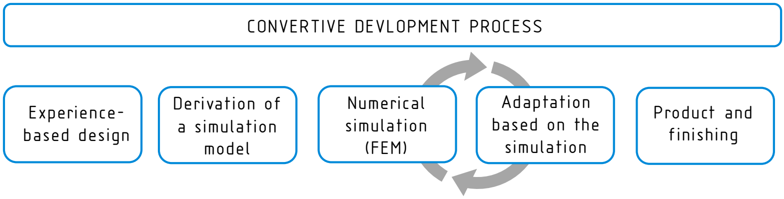

Figure 7: Conventional development process

The conventional product development process describes the iterative procedure of construction and subsequent calculation of the designed component through to the final product. It is common that designs have be changed several times until, for example, the specifications regarding rigidity and strength in the calculations can be met. The efficiency of the conventional product development process thus depends heavily on the experience of the designers and can be difficult to automate using conventional product development methods. In addition, entire generations of engineers and designers are taught a conventional product development process and design guidelines during their training. This process is based on the manufacturing restrictions of conventional manufacturing processes (e.g. turning, milling, casting), which do not apply to additive manufacturing processes.

In order to exploit the full potential of additive manufacturing processes and the associated design freedom, a dedicated product development process and the use of modern development methods for additive manufacturing are required (Figure 8).

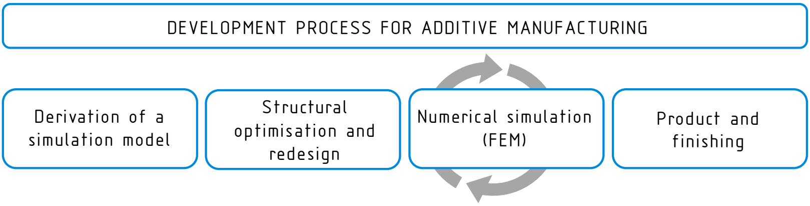

Figure 8: Development process for additive manufacturing

Derivation of a simulation model: In contrast to the conventional product development process, a simulation model is created in the first step. In this model, the boundary conditions such as bearings and loads, for example in the form of forces, moments or vibrations, are defined. In the next step, the maximum installation space is determined and a division into design and non-design areas made.

Design areas are areas in which the topology optimisation algorithm is allowed to remove or apply material in order to arrive at an optimised structure.

Non-design areas, on the other hand, define areas in which material is absolutely necessary to attach to other structures, for example, or to absorb forces.

Structural optimisation and redesign through topology optimisation: After defining potential loads and classifying design space, objectives and limitations of optimisation are defined. Typical goals of topology optimisation include reducing component volumes, maximising component stiffness and reducing component tensions. Since the sole definition of an optimisation goal would lead to mathematically trivial solutions, restrictions to the scope of the solution must be applied. Possible restrictions are the limitation of the component volume or a limitation of the maximum voltages. A concrete optimisation task could thus be:

- Maximise component stiffness with a defined force exerted on the component, using only 40% of the specified design space.

The optimisation algorithm would then distribute the given material (40% of the original volume) in the design room in such a way that an improved stiffness of the component is achieved under the defined loads (force). The optimised material distribution is determined in an iterative process. The most commonly used topology optimisation algorithms are based on the solid isotropic material with penalisation (SIMP) method.[44] In this gradient-based optimisation method, each element is assigned an artificial density between 0 and 1. The density has an influence on the modulus of elasticity and thus the rigidity of the component. In an iterative process, the stress distribution in the component is calculated and the density adjusted. The elements in low voltage regions are assigned a density near 0 and high voltage elements are assigned a density near 1. The result of the topology optimization is a material distribution in the form of a density distribution of the material, which is used to derive a CAD model (redesign) (for more detailed explanations on topology optimisation, see Appendix A).

In summary, it can be stated for this step that, for the most part, topology optimisation is undertaken in order to exploit the high degree of design freedom in additive manufacturing. The aim of this optimisation is to obtain an initial design proposal for the topology of the design. This serves as the basis for further optimisation methods such as optimisation of shape. In terms of optimisation of shape, an existing topology is changed only minimally until the defined requirements for the component can be met. At this point, it should be noted that there are other structural optimisation methods, which are described in detail in Walzl et al.[45]. However, the combination of topology and shape optimisation is most commonly used in the product development process for additive manufacturing.

Numerical simulation (FEM)/automated shape optimisation: The CAD model of the redesign is the starting point for a new simulation. The load scenarios defined at the outset are used to check whether the topology-optimised component can withstand the loads. Automated shape optimisations are often included in this step, too. The topology of the component remains

[44] See Sigmund and Maute (2013).
[45] See Walzl and Buchmayr (2017).

the same and minor changes are made to radii or adjustments to the component thickness, for example, to reduce stresses within the component.

Production and finishing: Depending on the additive process selected, different preparatory work is required for printing. In the LBM method, for example, support structures are required, which connect the component to be manufactured with the build platform. Furthermore, the orientation in the installation space plays an important role in manufacturing the component efficiently (section 4.3.1). In order to improve the component quality, there is the option to simulate the construction process. As a result, critical component areas can be identified and, for example, deformations in the component can be reduced by additional support structures or an adaptation to the component orientation. Suppliers of such simulation software include Materialise, Additive Works and Ansys.

It should be noted that the automation options for the product development process for additive manufacturing described above are far from exhausted. Analysing more complex topology optimisation results and interpreting them correctly still requires the intervention of an experienced designer. However, the topology optimisation algorithms are constantly evolving, so less intervention will be required from designers in future.

4 DEFINITION OF TECHNOLOGIES, FUNCTIONAL UNIT AND LIFE CYCLE INVENTORY ANALYSIS

4.1 Defining a use case for the application of additive manufacturing processes in SMEs

The first step in the ecological and economic assessment for a comparison of additive and conventional manufacturing processes is the definition of a scenario for a realistic use case. For the purpose of this study, the production of structurally optimised vehicle components in medium-sized series is defined as the use case. This scenario is based on the assumption that conventional manufacturing processes previously used in medium-sized series could in the future be replaced 1: 1 by the AM technology. At the same time, the possibilities for structural optimisation can be fully exploited. Thus, this study has a prospective character at the time of its publication. This means that the application scenario considered has not yet been realised on an industrial scale at present, but rather represents a situation that is realistic in the medium term.

Definition of the use case for AM in SMEs

The use case specified for this study includes the

“Production of structurally optimised vehicle components in batch sizes of 10,000 pieces per year.”

The specific application example concerns the production of structurally optimised shock absorber forks in a lightweight design for use in vehicles (section 4.2).

The following boundary conditions must be taken into consideration for comparison with manufacturing processes used in the past:

- The modalities of design and order logistics (e.g. contract manufacturing) are disregarded. It is assumed that the numerical structural optimisation, regardless of the actor, represents a required part of the design and development process in each case.

- Options for implementing subsequent design modifications to improve upward compatibility with the technical environment are not taken into consideration.
- The scope of the application scenario discussed here is limited to the circumstances of an SME.

The definition of the use case presented is based on the following considerations:

For companies in manufacturing industry, it is important to harness the benefits of additive manufacturing techniques to their specific needs. They represent an enormous potential for companies in continuing to make products that demand the highest quality and efficiency. However, the integration of AM into rolling production is still in its infancy, especially in medium-sized companies. On the one hand, for technical and economic reasons AM has not yet been able to keep up with conventional mass production. On the other hand, established production processes cannot easily be replaced by new technologies such as AM. A comparison of conventional and additive production technologies therefore only makes sense for applications in which both technology variants can at least theoretically fulfil an equivalent function[46].

Examples of AM applications already in industrial use are listed below:

- Generation of prototypes from computer models for use in the product development process (rapid prototyping),
- Manufacture of special tools, fixtures, mouldings and customised production tools (rapid tooling),
- Production of one-of-a-kind or customised products based on digital computer models (rapid manufacturing),
- Small series production of workpieces with the option for individual modification (customisation) and

[46] **In terms of batch size, cost-effectiveness and realisable product properties**

- Production of spare parts on demand (on-demand production).

AM enables large-scale structural optimisation in component design. Complex components are designed on the computer with the help of numerical algorithms and produced under computer control. Thus, the entire lightweight engineering potential or the full functional integration potential can be exploited by manufacturing using additive manufacturing processes. Due to technical limitations, this would not be possible to a comparable degree with conventional production methods. Although the above-mentioned applications can be achieved with low complexity of the component topology using conventional manufacturing methods, the production of optimised and especially bionic component structures is almost only possible by means of AM.

Compared to AM, conventional methods also require a higher production lead time and produce relatively high fixed costs for tooling and mould making (e.g. casting moulds). In a fast-paced market environment, a shorter production lead time can bring a cost advantage, in the case, for example, of rush orders or unpredictable peak demand. AM's shorter production lead time also gives new product lines a significant competitive edge through prompt market launch.

So far, however, additive manufacturing processes are more likely to be used for small series production, while conventional processes such as casting, forging or milling are particularly suitable for mass production. Even if structurally optimised structures made by additive manufacturing cannot yet be achieved in the same way as conventional mass production, it is nevertheless of great interest for companies to understand and adapt the potential of AM technology.

Based on these considerations, this study focuses on a use case in the automotive industry as an example. This industry is characterised by the constant need for production technology innovations in a highly competitive market. Various applications for 3D printing are already of interest in the automotive industry. These include, among others

- Manufacture of vehicle components with structurally optimised lightweight design in medium-sized series as a contribution to the achievement of CO_2 reduction targets for motor vehicles,

- On-demand spare parts production as replacement for the long-term storage of spare parts,

- Production of special components for custom commercial vehicles in medium quantities (especially for leasing contracts) and

- Special production of unique pieces for the upper price segment in the automotive industry.

Whether and for how long the current limitations of AM in the field of large and medium series production remain, will be seen in the coming years. Current innovations such as the increase in installation space and the reduction in production time suggest that AM technologies will be of interest in the medium term for mass production. Therefore, this study is based on the above use case of manufacturing structurally optimised vehicle components in a medium-sized series. In view of the previously discussed differences in the manufacturing processes, the comparison scenario is intended to represent a relevant application for the industrial use of conventional and additive technologies. The following assumptions apply to the selected scenario:

- Relevance for industrial application even outside highly specialised market niches,

- Prospects for economic benefits for SMEs: it is assumed that companies are particularly interested in increased competitiveness through AM

- Compatibility with other manufacturing processes in SMEs and their market environment (in particular quality requirements, test and verification procedures, approvals and certificates),

- Compatibility with regulatory frameworks and standards and

- Technically feasible parameters for the use of AM for the intended purpose.

The economic and ecological assessment relates exclusively to the common intersection between the two manufacturing processes defined in the scenario. Universal comparability of the evaluation results for conventional and additive technologies is not the aim of this study.

4.2 Definition of the reference component for the assessment

4.2.1 Characteristics and technical boundary conditions for additive manufacturing of the reference component

As a basis for comparison, this study is based on a concrete component provided by an automotive supplier. Figure 9 shows this shock absorber fork of a car, consisting of a drop-forged aluminium casting alloy. The conventionally manufactured damper fork has a weight of 1.3 kg.

Figure 9: Conventionally manufactured damper fork

The damper fork transmits forces from a spring damper system to an integral support on the chassis and is thus a central structural component of an automobile. In view of the characteristics of a spring damper system, the components used must withstand a variety of load changes during their lifetime. Figure 10 outlines the damper fork in the vehicle's installed position.

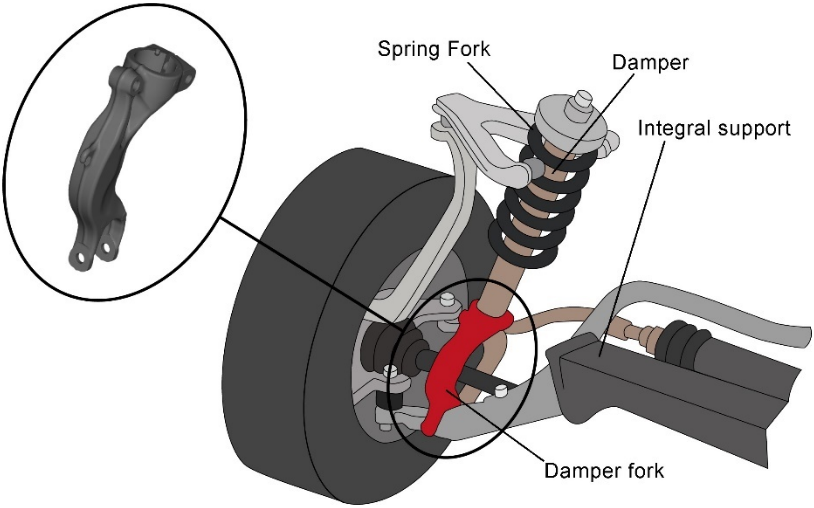

Figure 10: Schematic illustration of the installation position of the damper fork in a vehicle

When designing the damper fork, it must be ensured that high loads such as driving over kerbs or other obstacles at higher speeds do not lead to a sudden failure of the entire system. That is why car manufacturers define exact requirements for built-in components. In the case of the damper fork, the manufacturer has defined a critical load case. Figure 11 shows in simplified form the force transmission and mounting of the shock absorber fork.

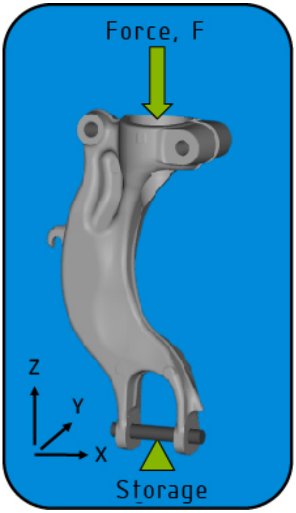

Figure 11: Defined load scenario for damper fork

The load scenario presented represents the basis for the boundary conditions of the simulation model. The force acts vertically from above on the damper fork and is transferred by it to the lower axis. The axis serves as a mounting point. In the illustrated simplified model, all three degrees of freedom are blocked in the respective spatial directions.

4.2.2 Structural optimisation of the reference component to be made by additive manufacturing

For the reference component, an aluminium powder (supplier APWorks) of the alloy **Scalmalloy© AlMg4.5Sc0.7Zr0.3** with the following material properties is provided as the material:

- Tensile strength: 520 MPa
- Modulus of elasticity: 70 GPa
- Density: 2.7 g/cm^3
- Poisson's ratio: 0.33

In addition, the **aluminium alloy AlSi10Mg** is considered as a potential material. Although its maximum tensile strength of 370 MPa is lower than that of Scalmalloy©, the procurement costs for AlSi10Mg metal powder (see section 5.3) are significantly lower than for Scalmalloy©.

The choice of aluminium powder is determined by two factors. On the one hand, the reference component is a lightweight structure and on the other hand, the metal powder that has not melted in the process can be recycled. For this purpose, the workpieces are removed from the powder bed and the residual powder is sieved to remove impurities, agglomerations or welding beads.

The software package OptiStruct from the company Altair is used to optimise the topology of the present damper fork, and the following steps are carried out. The working hours information refers to the completion of the topology optimisation of the damper fork described in this study.

Structure of the finite element (FE) model/simulation model: In order to optimise the topology of a component, a maximum design space is defined and a FE mesh is created, as described in section 3.2. Tetra elements are used to create the FE mesh. Depending on the complexity of the given design or non-design space, it may be necessary to simplify the CAD model used beforehand. Chamfers, fillets and the like are removed in order to simplify the mesh for the body. In the case of optimizing the damper fork, the geometry of the conventional design as the maximum design space resulted from consultation with the manufacturer. In addition, it is determined which areas of the component geometry cannot be changed because, for example, they represent contact surfaces with other assemblies. Figure 12 shows the described division into design space and non-design space.

A load scenario is defined below. The forces and mounting points described in Figure 11 are used as a basis for the simulation model (workload 7 hours).

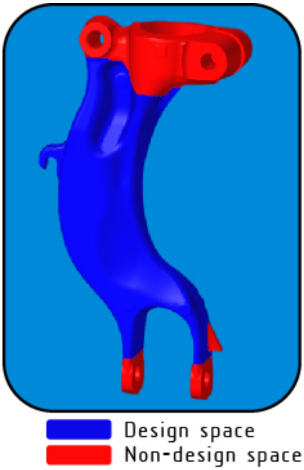

Figure 12: Optimisation model of the damper fork with division into design and non-design areas

Definition of the optimisation objective: In order to maximize the stiffness of the damper fork, minimisation of the strain energy or compliance is chosen as the optimisation objective. The strain energy is a global measure of the deformation in the component (workload 2 hours).

Completion of topology optimisation: Once the boundary conditions have been defined and the optimisation objectives formulated, the topology optimisation is carried out. Depending on the complexity of the optimisation model, the calculation time can vary greatly. The main influencing factors are the type and number of defined load cases as well as the number of elements used. The topology optimisation for the damper fork took 55 minutes on a desktop computer (Windows 8.1 (x64), Intel (R) Core (TM) i7-4770 CPU @ 3.40GHz, 32 GB RAM) and 1.4 mill. Tetra elements for the meshed component.

Interpretation of topology optimisation results: The result of the topology optimization is a material distribution with an associated artificial density of 0 to 1 for each element (Figure 13). Element densities near 1 (red) identify areas where material is needed. Green elements represent areas of medium density (0.5) and turquoise elements represent segments of lower density where little material is needed.

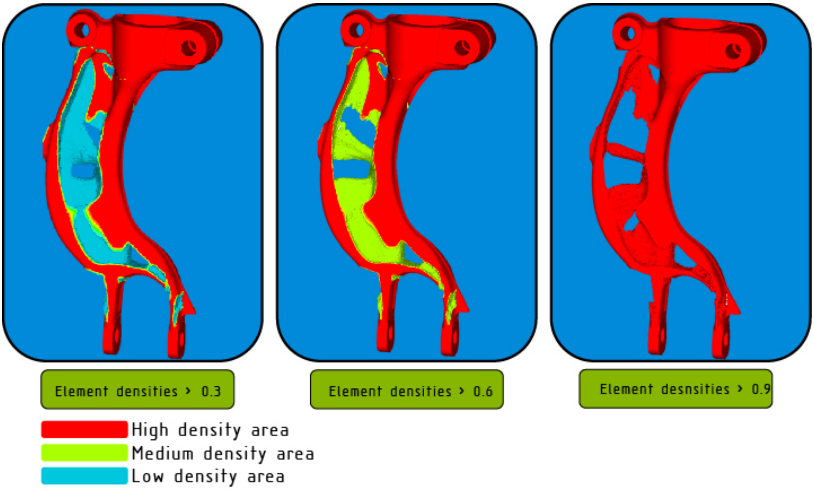

Figure 13: Material distribution in various planes as a result of topology optimisation of the damper fork

Typically, results of topology optimisation require interpretation because of the occurrence of larger areas of average density. This ensures a consistent and smooth surface structure for a component. There are ways in most topology optimisation programs to improve interpretation, such as manufacturing restrictions or filters. But especially with more complex optimisation models, these methods are currently reaching their limits.

For an optimal overview of the topology optimisation results, it is advisable to consider different ranges of density distributions and divide them into primary and secondary load paths. Figure 13 shows the various areas of the topology optimisation results for the damper fork. All elements with an artificial density of more than 0.3 are displayed on the left and all elements with more than 0.6 in the middle. The areas with a density greater than 0.6 but less than 0.9 are designated as secondary load paths. On the right of the figure, elements with a density greater than or equal to 0.9 are shown. These are primary load paths. This differentiation facilitates and simplifies a constructive interpretation of the structures by an engineer, but can also serve as a design guideline for a later automation of this process. Density ranges between 0.3 and 0.6 are available as design areas for subsequent shape optimization.

Creation of the redesign: Based on the load path differentiation, the so-called redesign is created. Here, the topology results are imported in the form of ISO surface models as an STL file of the density limits (0.6 and 0.9) into an appropriate CAD software package and redesigned in detail. Figure 14 shows the redesign of the damper fork, which was created in CATIA V5. With the 'Generative Shape Design' and 'Imagine and Shape' modules, CATIA V5 offers a number of possibilities for creating free-form bodies.

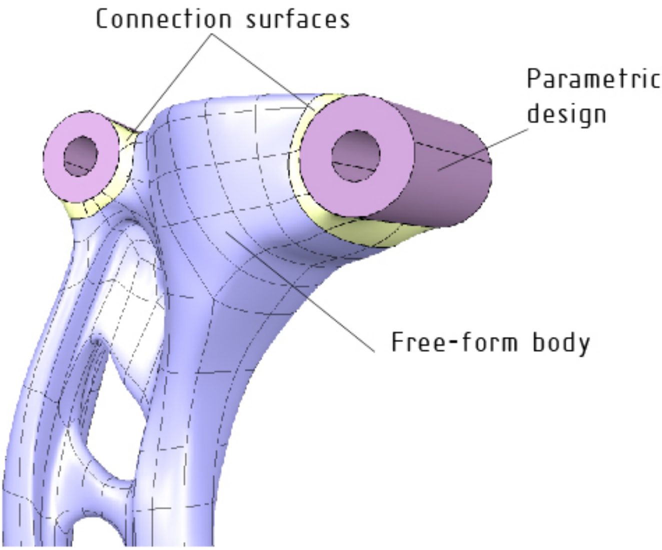

Figure 14: Redesign of the damper fork with application of the concept of hybrid transitional areas of Hoschke et al.

In the redesign of the damper fork the concept of Hoschke et al.[36] of hybrid transitional areas has been applied. The topology optimisation result is modelled using free-form bodies. Connecting areas to other components are designed parametrically. Free-form bodies and parametric elements are linked by connecting surfaces. This hybrid CAD concept brings together the best of both worlds of design. On the one hand, the use of the parametric design makes it possible to define surfaces for interface structures precisely and to adapt them effectively and accurately for post-processing (e.g. milling of functional surfaces). On the other hand, the use of free-form modelling offers the possibility to map the topology optimisation result in its geometric complexity and, if necessary, to adapt it effectively to optimise shape.

Result of structural optimisation:

- Weight of the conventionally manufactured damper fork: **1.3 kg**
- Weight of structurally optimised damper fork with Scalmalloy©:**1.14 kg**
  → corresponds to a mass saving of 12%
- Weight of structurally optimised damper fork with AlSi10Mg: **1.23 kg**
  → corresponds to a mass saving of 5%

4.3 Selection of the additive and conventional manufacturing method

4.3.1 Selection of the additive manufacturing process

To illustrate the possible added value from the use of additive manufacturing processes, it is important to select an AM technology that is suitable for the use case (section 4.1 and 4.2). The reference component under consideration (section 4.2) is a structural component for use in automobiles. This application requires the production of high volumes at reasonable prices. This applies equally to conventional and additive manufacturing processes. Furthermore, since this is a case study, the current relevance of the technology in the industry is crucial. The selection should therefore be based on the following priorities:

(1) good mechanical material properties,

(2) a high market relevance and

(3) a high production rate.

The following process selection is based on the method presented in ISO DIS 20195. First, the **AM potential of a component (1)** is identified. Then the **AM process is selected (2)** and **the costs are reviewed (3)**, which provides an iterative design optimisation taking into account the advantages of the additive manufacturing processes.

Identification of the AM potential of the component (1)

The AM potential of the reference component is found primarily in the area of structural optimisation and thus in lightweight design (section 4.2). Since it is a component from the automotive industry, pure spare parts production could also be an advantage. Further potential could lie in integral construction and functional integration. It would be conceivable, for example, to integrate redundant grid systems and thus fail-safe mechanisms.

Selection of the AM process (2)

ISO DIS 20195 proposes an assessment based on an assessment table. The following assessment is based on Table 1 (section 3.1.6).

Sheet lamination processes are unsuitable for structural components due to the high anisotropy and relatively weak material properties. In addition, there is an unfavourable freedom of design for structurally optimised bionic design bionic design and a low market relevance.

Material extrusion processes produce unfavourable mechanical characteristic values for structural components and are characterised by a very low build speed.

Binder jetting technologies have a high degree of design freedom and speed but, like material extrusion processes, are based on the production of green compacts which have to be fired in sintering processes. This results in mechanical weakening of the material.

Processes in the group *directed energy deposition* are usually not used for complete structural components, since the poor surface quality of parts made in this way requires costly reworking. The material properties are good, but the build-up rate is not sufficient.

Powder bed fusion processes are the best suited in view of the similar material properties to conventionally manufactured materials[47], the acceptable build rate/productivity and the associated high market relevance. The method is typically used for structural components. Since the reference

[47] See VDI 3405 Part 2.1 (2015).

component is a lightweight part, aluminium or titanium alloys with high specific characteristic values should be used. The reference component already specifies the use of an aluminium alloy. EBM has its strengths in alloys with strong intrinsic stresses (e.g. Ti6Al4V) but tends to be less suitable for materials with a low melting point, such as aluminium, as the high energy input is difficult to control. The LBM method is therefore more suitable. For titanium components, EBM would be more advantageous. The choice thus falls on the LBM process.

The characteristics of the LBM process used for producing the presented structurally optimised reference component are as follows:

(a) System used for the production of the reference component

The investigation is based on a modern system designed for productivity and small batches (EOS M 400, Figure 15, left). This is particularly evident in the large layer thicknesses (90 µm), the double-path coating, which is faster, the large installation space (400 mm x 400 mm x 400 mm) and the high laser power (1 kW), which provides faster exposures and thicker layers. Since the powder is highly flammable due to its fine grain in an oxygen-rich atmosphere and thus poses a safety risk, the process takes place under a protective gas atmosphere. In addition, a protective gas flow is directed over the build platform to remove welding by-products formed during exposure (Figure 15, right). The build platform is heated to 45°C to keep the thermal conditions during the process approximately constant.

Figure 15: **Left: EOS M 400 used for production/Right: M400 process chamber with central build platform, coating system and inert gas protective film (direction of flow: from right to left)**

As a nitrogen atmosphere is sufficient for many materials, the system is equipped with pneumatic nitrogen generators. Most machines, however, are supplied with nitrogen or argon via external sources. For assembly and disassembly and for powder processing and support structure removal, a number of peripheral devices (e.g. wet scrubber, sieve unit and bandsaw) with low resource requirements are used. Furthermore, the laser in the system is cooled by an external cooling unit.

(b) Component positioning and orientation

Due to technical production limitations, the orientation of the workpiece is crucial for manufacturability and quality.[48, 49] Even if it were favourable from an economic point of view to position a workpiece with the lowest possible projection area on the build platform in order to produce as many workpieces as possible in one production run, this is not always feasible for technical reasons. For the following investigations, the workpiece was always positioned with a favourable orientation for production and quality.

(c) Support structure generation

The support structure consists of filigree elements which are made of the same material as the workpiece. To save build time and powder, structurally

[48] See Gebhardt (2013).
[49] See Kianian (2016).

optimised geometries are used. For the following investigations a standard support structure of the type “block” was used (Figure 16).

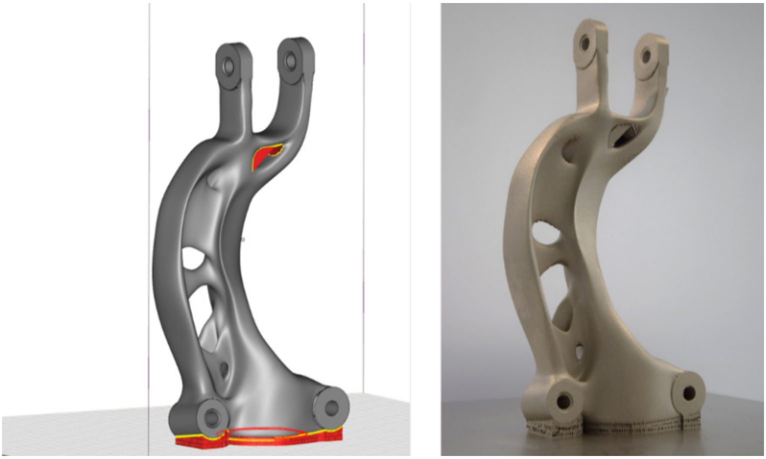

Figure 16: Support structure for fixing the component. Left: Preparation of digital CAM models. Right: Manufactured component with support structures

The standard support structure “Block” consists of grid-shaped walls, which are created by individual laser tracks. The walls are perforated for faster manufacturing, powder removability and material savings. Fine teeth at the transition to the workpiece allow easy support structure removal and a clean surface.

(d) Production parameters

Numerical generation of the layer information takes place by calculation of polygons, which represent the cross-sectional contour parallel to the build platform at regular intervals. This is followed by the assignment of exposure parameters. In order to keep the manufacturing time of the support structure low, the exposure is usually fast and at high power. The exposure of a real work piece, on the other hand, is far more complex involving subdivision of the object into different sectors (Figure 17). The core (inskin) was fabricated with a stripe exposure strategy for high densities and better mechanical properties. Here, the volume is generated by undulating[50] laser tracks in the form of strips. In order to avoid a superposition of welds and thus creation of a weak point, the strips rotate from layer to layer.

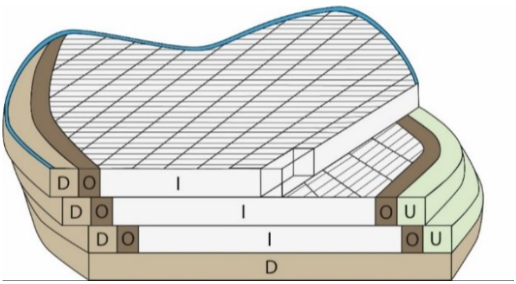

Figure 17: Layer-dependent LBM exposure principle using a common exposure strategy (stripe rotating from layer to layer) with contour exposure (blue), core exposure I (inskin, white) and other exposure sectors (D: downskin, U: upskin, O: overlap)

Exposure of the workpiece contour is usually via a single laser path with increased energy input, so as to improve the surface quality. Areas close to the surface require modified exposure parameters, particularly if the angle is shallow, as this results in other thermal boundary conditions. These sectors (upskin and downskin) are therefore exposed separately. The overall exposure principle is shown in Figure 17. Due to the complex arrangement of the laser tracks and associated exposure parameters, time and energy requirements for the production of a workpiece are not only machine and material-dependent, but also dependent on the workpiece geometry and its orientation in the installation space.

(e) Powder

As already explained in section 4.2, an aluminium powder (supplier AP-Works) of the alloy Scalmalloy© AlMg4.5Sc0.7Zr0.3 was used for the investigation. In addition to the lightweight construction of the reference component, the high recyclability of aluminium played an important role.

[50] **Wave-form arrangement of the laser tracks.**

The production of primary aluminium is associated with a high expenditure of energy and the use of toxic ancillary components. Primary aluminium has an energy balance (GER value, *Gross Energy Requirement*) of 270 MJ/kg.[51] By contrast, recycling of aluminium is characterised by better energy efficiency. For example, secondary aluminium has a GER value of only 16 MJ/kg.[52,53]This is due to the high recycling rate of aluminium, since it can be run almost in a closed cycle (possibility of recycling without loss of quality).[54] No chemicals that react easily with aluminium are needed for recycling. As a result, no foreign atoms are incorporated into the crystal lattice and there is no local change in the physical and chemical properties. Aluminium is therefore not transferred chemically during recycling. Producing secondary aluminium saves up to 95% of the energy required for primary aluminium.

(f) Post-treatment

An essential step in post-processing is releasing the printed workpieces from the build platform and removing the support structures. The entire build platform can first be heat treated (four hours at 325 °C) to release intrinsic stresses before the support structures are released by hand.

Depending on the application, production parameters and material, additional post-processing of the workpiece may be required. Interfaces are sometimes post-machined. Sandblasting can be used to create a smoother, glossy surface can be created. The micro-machining process can also be used with metallic components. This combines a chemical reaction on the material surface with a solution process through a constant fluid flow. In this way, a reflective surface can be created[55].

[51] See Frees (2008).
[52] See Leroy (2008).
[53] See Norgate (2001).
[54] See Jacob (2014).
[55] See Kianian (2016).

Verification of costs (3)

A review of the costs is currently not possible due to lack of data for the individual manufacturing processes.

4.3.2 Selection of the conventional manufacturing process

The conventional production process selected for the damper fork is based on the actual industrial manufacturing process used by the manufacturer of the damper fork and is divided into four different sub-processes.

(1) **Casting:** For casting, negative moulds are first produced, which are then filled with the melt. After the cooling process, the workpiece is transferred to the next process step.

(2) **Drop forging:** Forming tools are also produced for the forging process. At the appropriate temperature, the cast workpiece is then reshaped.

(3) **Deburring and heat treatment:** Methods such as grinding or brushing are used to remove the burrs on the workpiece.

(4) **Milling:** Finally, the workpiece is brought into its final shape by milling. The damper fork is then ready for use.

An aluminium casting alloy is used for production.

4.4 Defining the functional unit and the system boundary

4.4.1 Definition of the functional unit

A comparison of the environmental impact and economic costs of two production systems (conventional and additive manufacturing) and the products produced with them requires definition of a single reference value. In the LCA, this baseline is referred to as a “functional unit”. The standard term describes a quantified benefit that should have properties that are as equivalent as possible for the product systems to be compared.[56] For the purpose of comparability of components manufactured in different ways, this study

[56] See DIN EN ISO 14044:2006 (2006), p. 11.

considers functionally equivalent reference components. Damper forks for passenger cars are selected (Figure 9) as the reference components. These damper forks perform the same function in their utilisation phase, but can differ in their properties depending on the manufacturing process (material, geometry, weight). Consequently, the functional unit represents the lowest common denominator of the function of the reference components considered here.

On the basis of section 4.2 and taking into account the assumptions for the use case outlined in section 4.1, the functional unit has been defined as follows. This applies to both the ecological and the economic assessment:

Definition of the functional unit

"A shock absorber fork for passenger cars, designed for a service life over the assumed total mileage of the vehicle of 150,000 km."

The narrative description of the function includes the following elements:

- Purpose: Suspension of the vibration damping on a wheel.
- The dimensions of the component are such that it can be operated throughout the average vehicle life cycle in normal operation without repair.

Simplifications: In order to reduce the complexity of this study, the following points regarding function are not taken into consideration:

- A car usually has several damper forks with different geometries (left/right). Only one geometry is considered.
- Automotive components are subject to industry-specific meta-requirements of function (e.g. building type approvals, certificates for safety tests, etc.). The procedures required for this are not included.

The structural optimisation considered here serves the purpose of analysis and therefore does not have to represent the requirements of the automotive sector in any way.

For the reference components made conventionally and by additive manufacturing analysed in this study, the benefit to be provided, i.e. the functional unit, takes into account certain boundary conditions (the duration of use).

The function of the reference component (damper fork) is derived from its purpose in the utilisation phase and makes no reference to the materials used, the manufacturing methods or the supply chains. The different properties of the manufacturing processes and the reference components thus result in different material and energy flows and different costs. These aspects flow into the life cycle inventory analysis (section 4.6) and are then related by comparative calculation to the functional unit. It is only on the basis of this functionally uniform reference value that a meaningful comparison can be made between the different production technologies throughout their entire life cycle. The characterisation of the technical prerequisites required to fulfil the function and the allocation of the quantities of material and energy required (the so-called reference flows) are described in the following sections 4.5 and 4.6.

In addition, it should be noted that the comparative period of one year was chosen for the manufacturing systems and describes a period analysed in the life-cycle assessment for the purpose of comparing different technologies with different service lives. The actual period of use of SME manufacturing equipment is longer. A possible parallel use of the production lines for other product lines is taken into account by means of allocation: in conventional manufacturing, only the proportion of equipment that is required for the production of the component is considered economically and ecologically. In additive manufacturing, only one year of system operation is considered. For the remaining nine years of its service life, the printer is available for other production processes, so these are not considered. In the period under consideration of one year, it is assumed that the systems will not be at a standstill, i.e. the systems are not available for other production.

4.4.2 Definition of the system boundary

The system boundary denotes the scope of the comparative assessment. For life-cycle assessments as in this study (LCA and life-cycle costing), the system boundary comprises the entire life cycle of the components under consideration (Figure 18): the extraction of raw materials, the actual manufacturing processes, transportation, the utilisation phase and disposal of the components. This also includes the immediate upstream chains of the auxiliary materials and energy sources used. The life-cycle assessment includes all relevant material and energy flows from the environment and into the environment (emissions), insofar as they are related to the object of observation defined in the functional unit. The economic assessment accounts for the monetary costs of the object of observation as well as its economic benefits (e.g. savings potential).

In the case considered here, the system boundary for the use case “Production of structurally optimised vehicle components in batch sizes of 10,000 pieces per year” is defined in such a way that the main production processes and the utilisation phase of the lightweight components are the focus of the assessment. In addition, the extraction of raw materials is included, because the material and energy savings through lightweight construction are particularly effective here (this is especially true for the material savings in the production process and for the possible savings on fuels in the utilisation phase).

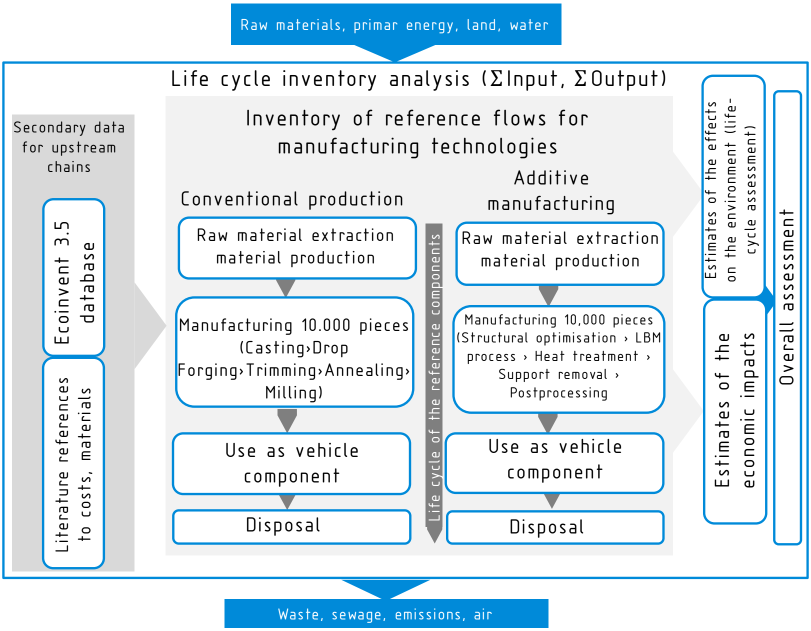

Figure 18: System boundary of the study

This study uses an orientational life-cycle assessment that does not cover all the impact categories typically considered in LCA studies. In particular, the characteristic values "cumulative energy demand" (CED) [57], "cumulative raw material demand" (CRMD)[58], supply criticality, land use and water consumption corresponding to the environmental impacts are determined. These input-based indicators are also based on the life-cycle approach and allow an ecological assessment of products based on their technically detectable parameters. Recycling credits are not taken into account because the underlying methodological basis for life-cycle assessment in accordance with VDI Guidelines VDI 4600: 2012 and VDI 4800, Part 1 [59] does not provide for credits for resource savings through recycling. Rather, commercial market shares in recycled materials are taken into account for the materials used in component production (especially metals). This will enable a reliable assessment

[57] See VDI 4600:2012-01.

[58] See VDI 4800 Part 2:2018-03.

[59] See VDI 4800 Part 1:2016-02, p. 15.

of resource efficiency, which is considered to be particularly relevant to the SME target group. In addition, the global warming potential is identified as an essential category for environmental impacts.

Analysis of the life cycle costs takes into account the same system boundary. The following cost types are taken into account: the investment costs (proportional), the material and energy costs, the operating and personnel costs and the disposal costs.

Monetisation of the competitive advantages by shortening the production lead time does not take place, since this aspect is determined by very individual, case-dependent factors which are difficult to generalise. The costs of the conventional product development and design process is also omitted.

4.5 Data collection for additive manufacturing of the structurally optimised component

4.5.1 Experimentally determined resource requirements

Due to the complexity of the manufacturing principle, a large number of energy and mass flows have to be considered in additive manufacturing. The sub-processes of LBM-based component production and their input and output flows can be found in Figure 19.

In the course of this work, only the LBM process is measured. Consumables such as detergents, personal protective equipment and small tools have not been included. It should be noted that a large number of additive systems require an external supply of inert gas. This is not the case for the system used. In the present case, nitrogen is used as an inert gas, which is obtained by means of nitrogen generators installed in the plant. This causes a significantly higher compressed air requirement than with other system types (partially compressed air-free). The power consumption was measured for the entire system. Direct subdivision of the power consumption into the laser unit, the heating or anything else is not possible.

The process chain was considered for the material Scalmalloy© and for AlSi 10Mg. The values for Scalmalloy© were determined directly in the experiment and the values for AlSi10Mg were partly generated from previous studies. However, as the material requirements for the LBM processes depend on the component, slight inaccuracies may occur.

To assemble and disassemble the LBM system, peripheral units such as a vacuum cleaner/wet scrubber, a powder conveyor module, a sieve unit and a lifting device (e.g. crane or industrial truck) are required. To operate the units, compressed air and electricity are used. The consumption of the peripherals was averaged over twelve runs. The following steps are included in the measurement data “Preparation” (Table 2): calibrating the machine, setting up the coater blades, cleaning the protective glass, applying the first layer of powder, flooding the machine with inert gas, heating the build platform, cooling the powder bed, cleaning the process chamber, vacuuming, sieving and refilling the powder, and replacing the build platform.

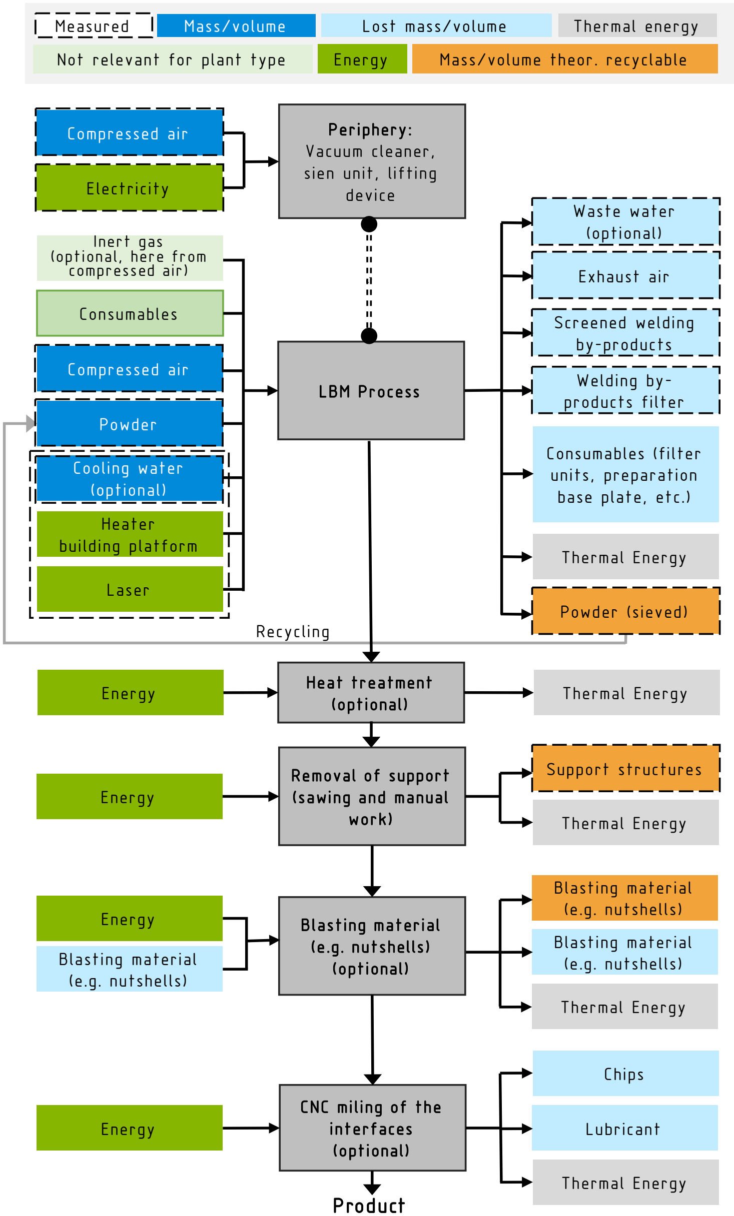

Figure 19: Sub-steps of LBM-based component production and their energy and mass flows

Table 2: Material and energy demand determined for the LBM process.

Batch size:	Individual part	Batch (total)		Batch (per part)	
Material:	Scalmalloy©	AlSi10Mg	Scalmalloy©	AlSi10Mg	Scalmalloy©
Preparation					
Number of components	1	18	18	1	1
Electricity	6.51 kWh	12.26 kWh	6.51 kWh	0.68 kWh	0.36 kWh
Machine time	4.85 h	7.00 h	4.85 h	0.39 h	0.27 h
Working time	4.60 h	4.60 h	4.60 h	0.26 h	0.26 h
Compressed air	24.90 m^3	29.09 m^3	24.90 m^3	1.62 m^3	1.38 m^3
Working time Support structure	0.12 h	1.80 h	2.16 h	0.10 h	0.12 h
Production					
Electricity production	105.40 kWh	711.02 kWh	890.94 kWh	39.50 kWh	49.50
Layer fraction	59.19 kWh	45.99 kWh	59.19 kWh	2.56 kWh	3.29 kWh
Exposure	46.21 kWh	665.03 kWh	831.75 kWh	36.95 kWh	46.21 kWh
Build time	22.15 h	118.70 h	166.95 h	6.59 h	9.27 h
Coating time	13.63 h	9.09 h	13.63 h	0.50 h	0.76 h
Exposure time	8.52 h	109.61 h	153.32 h	6.09 h	8.52 h
Compressed air	617.99 m^3	3311.73 m^3	4657.87 m^3	183.99 m^3	258.77 m^3
Support structure mass	0.03 kg	0.35 kg	0.43 kg	0.02 kg	0.02 kg
Powder loss	0.15 kg	1.72 kg	1.59 kg	0.10 kg	0.09 kg
Total					
Machine time	27.00 h	133.94 h	171.80 h	7.44 h	9.54 h
Working time	4.72 h	6.40 h	6.76 h	0.36 h	0.38 h
Energy demand	11.91 kWh	723.29 kWh	897.45 kWh	40.18 kWh	49.86 kWh
Powder consumption	1.28 kg	23.95 kg	21.89 kg	1.33 kg	1.22 kg
Powder costs	€457.73	€838.11	€7815.62	€46.56	€434.20
Compressed air consumption	642.89 m^3	3379.08 m^3	4682.77 m^3	187.73 m^3	260.15 m^3
Cooling water consumption	0.06 m^3	19.66 m^3	27.35 m^3	1.09 m^3	1.52 m^3

Grey: Readings; Yellow: Theoretically determined values (calculated digitally or from preliminary investigations for similar components); White: Calculated values (from theoretical values or measured values).

The power consumption and volume flow were recorded with the following sensors/methods:

- Electricity:
  - 16-amp supply: Voltcraft Logger 4000
  - 32-amp supply: TIP 43201
  - Fixed connection (LBM system): Eltako DSZ15D-3x80A
- Compressed air: Festo SFAB-1000U-WQ10-2SV-M12
- Powder mass: Core DS 36K0.2
- Cooling water: Volumetric sampling

In order to determine the material requirements for the present reference component (damper fork), it was manufactured as an individual unit in a single run and the production time, the power consumption and the powder requirements (grey fields in Table 2) determined. The powder requirements were calculated on the basis of a mass balance. For this purpose, the mass of the build platform was determined before the start of the process and after the start of the process (build platform with component and supporting structure), the mass of the particle collecting container on the filter unit was measured before and after the end of the process and the mass remaining in the sieve was determined. This results in the loss of powder shown in Table 2. 92% of the powder loss is in the sieving unit and theoretically recyclable, while 8% is in the filter unit and thus must be treated as hazardous waste. Cooling water and compressed air requirements were determined in more than 17 sample measurements during operation and multiplied by the production time for the total demand:

- Cooling water: 0.00273 m^3/h (σ = 0.00018)
- Compressed air: 0.465 m^3/h (σ = 0.002)

From preliminary investigations it is known that the production of a maximum production batch can be derived from the production of a single component.[60] For this purpose, it is necessary to determine the power demand

[60] See Norgate (2001).

for the system in the steady state, i.e. the power demand for maintaining the operating state (heating, inert gas generators, control technology, etc.) without the use of the laser. For this purpose, the operating status of the system was maintained for 24 hours and the power demand averaged (for results see Table 3 “Steady state output”). The increased demand for AlSi10Mg results from heating the build platform to 160 °C instead of 45 °C. Further general figures, machine parameters and components can be found in relation to the material used in Table 3.

Table 3: General characteristic values with regard to the reference component, machine parameters and machine characteristic values

	Scalmalloy©	AlSi10Mg	Unit
Dimensions	73 x 144 x 284	73 x 144 x 284	mm^3
Installation height	286.44	286.47	mm
Layer thickness	60	90	µm
Component & support structure volume	425.72	457.28	cm^3
Batch	18	18	Parts
Powder price (gross)	357	35	€/kg
Steady state output	4.34	5.06	kW
Energy density	0.021	0.012	kWh/cm^3

Grey: Measurements. Yellow: Theoretically determined values (calculated digitally or from preliminary investigations for similar components). White: Calculated values (from theoretical values or measured values).

Taking into account the time required to apply a layer, the number of layers and the steady state output, the total requirements for applying the layers is determined. The time required to apply a layer was determined using thirty measurements (10.28 seconds). Preliminary studies show that the multiplying the batch size by the remaining exposure fraction (total fraction minus coating fraction) indicates the total requirement of a maximum batch.

However, the loss of powder cannot be scaled directly, because welding byproducts end up on adjacent parts in a space that is filled to the maximum with components and are re-melted instead of remaining in the powder bed. A factor of 57% was therefore derived from a comparable production setup in order to predict the powder loss of batch production.

Using the component volume and the power consumption for component exposure, the energy density required can be derived (Table 3). This value is, above all, dependent on production parameters, but also on the manufactured component and its orientation in the installation space. The value for AlSi10Mg is known from preliminary studies for a comparable component. The build time for this component made of AlSi10Mg was determined on the basis of the laser tracks and the associated exposure speeds. In combination with the energy density, it is possible to draw conclusions about the power requirement.

Another influencing factor is maintenance work. Basically, LBM systems are largely capable of working without personnel support, so that uninterrupted operation is conceivable. However, from time to time it is necessary to carry out maintenance work on the system. This maintenance work that is included in the results can be found in Table 4.

Table 4: Cost of materials for maintenance work

Work step	Interval	Costs Material (gross)	Costs Disposal (gross)	Working time	Time Machine downtime
	h	h	€	H	h
Filter change	2,500	534	149	4	4
Replacement particle collection container	150	23	30	0.17	0.2
Filter cleaning (automated)	48	n/a	n/a	n/a	0.1
Yearly maintenance	n/a	n/a	n/a	3	72

As a conclusion to this chapter, it can be stated that the high power consumption of the system in a steady state is difficult to understand. A change in the build platform heating from 45 °C to 160 °C causes a difference of approx. 0.7 kWh. Approximately 0.3 kWh is accounted for by the nitrogen generators. Thus, about 4 kWh is left over for heating the build platform to 45 °C and other things such as the computer, sensors, control system and laser (only ready for operation, no emitted power). Correct installation of the "Eltako DSZ15D-3x80A" sensor unit was checked by two state-certified electricians. The measurements could also be reproduced at two different locations, each with different sensor units of the same type. According to the manufacturer's conditions of installation, a connection of 20 kW is necessary. The measurement can thus be assumed to be correct despite the unexplained high demand. It seems that the system is still inefficient at its current stage of development. This is also evident in the build time (22.15 h), the steady state output of the system (4.34 kW) and in the measured total power demand for production (105.4 kWh). For maintenance of the steady state condition of the plant, approx. 96.13 kWh is required. Thus, just 8.8%

(9.27 kWh) of the total power demand remains for exposure of the component, i.e. for melting of the metal powder.

The same applies to the cooling unit. This currently works with the technically specified minimum cooling water (measured consumption approx. 0.00273 m^3/h). The installation conditions even indicate a consumption of 20 m^3/h. The water is only heated by about 7 °C. It is likely that the radiator is oversized and could dissipate significantly more power. Furthermore, a closed circuit for the cooling water would be possible. It should thus be noted that the measured values on which the calculations are based are those which are actually available according to the state of the art but would not be technologically necessary.

4.5.2 Material and energy requirements for optimised system setup

It is clear that the material and energy requirements of a LBM system depend on a large number of factors. The present system is a flexible setup, which can be used to manufacture various components. Some assumptions are therefore necessary to consider a setup optimised for productivity of a single component for a sensitivity analysis (section 5.4). The following assumptions were made for consideration of an optimized system setup:

- Layer thickness is increased from 60 μm to 90 μm for Scalmalloy©
- Largest commercially available installation space (800 x 400 x 500 mm) doubles the batch size from 18 to 36 parts,
- Use of a 4-laser system reduces the exposure time by a factor of four
- Amount of cooling water increases by a factor of four due to the four lasers
- Additional working time required for larger space and additional lasers (here two hours)
- Reduction of existing dead times during coating, so that coating is reduced to seven seconds per layer

- Automated removal and feeding of a build platform and powder into the process chamber enables 24-hour operation. The necessary manual work (removing support structure, removing and processing powder, etc.) can be carried out at any time (no shift operation required).

The material and energy requirements for an optimized setup resulting from these assumptions can be found in Table 5.

Table 5: Determined material and energy requirements for the LBM process for optimised system setup

Batch size:	Batch (total)		Batch (per part)	
Material:	AlSi10Mg	Scalmalloy©	AlSi10Mg	Scalmalloy©
Preparation				
Number of components	36	36	1	1
Electricity	12.26 kWh	6.51 kWh	0.34 kWh	0.18 kWh
Machine time	1.00 h	0.85 h	0.03 h	0.02 h
Working time	6.60 h	6.60 h	0.18 h	0.18 h
Compressed air	29.09 m^3	24.90 m^3	0.81 m^3	0.69 m^3
Working time support structure	3.6 h	4.32 h	0.10 h	0.12 h
Production				
Electricity production	530.25 kWh	697.62 kWh	14.73 kWh	19.38
Layer fraction	45.99 kWh	39.46 kWh	13.45 kWh	1.10 kWh
Exposure	484.26 kWh	658.16 kWh	36.95 kWh	18.28 kWh
Build time	60.99 h	82.85 h	1.69 h	2.30 h
Coating time	6.19 h	6.19 h	0.17 h	0.17 h
Exposure time	54.81 h	76.66 h	1.25 h	2.13 h
Compressed air	1701.75m^3	2311.42 m^3	183.99 m^3	258.77 m^3
Support structure mass	0.70 kg	0.85 kg	0.02 kg	0.02 kg
Powder loss	3.44 kg	3.17 kg	0.10 kg	0.09 kg
Total				
Machine time	61.99 h	83.70 h	1.72 h	2.32 h
Working time	10.20 h	10.92 h	0.28 h	0.30 h
Energy demand	542.51 kWh	704.13 kWh	15.07 kWh	19.56 kWh
Powder consumption	47.89 kg	43.78 kg	1.33 kg	1.22 kg
Powder costs	€1676.21	€15631.24	€46.56	€434.20
Compressed air consumption	1754.79 m^3	2336.32 m^3	48.74 m^3	64.90 m^3
Cooling water consumption	40.47 m^3	54.28 m^3	1.12 m^3	1.51 m^3

Grey: Measurements. Yellow: Theoretically determined values (calculated digitally or from preliminary investigations for similar components). White: Calculated values (from theoretical values or measured values).

The following potential assumptions would further increase productivity. However, these have not been considered, as the factors are difficult to predict or the state of the art has not progressed far enough:

- more productive manufacturing parameters,

- optimised support structures,
- reduced powder prices due to large order quantities or market development,
- reduced machine prices due to market development or simplified plant technology,
- automated support structure removal,
- automated support removal,
- reduced steady state output, compressed air requirement or cooling water requirement due to more sophisticated plant technology,
- lower safety factor with regard to design and thus a reduction of the component volume and
- combination of different component orientations to increase the batch size.

4.6 Quantification of the life cycle inventory analysis

The life cycle inventory analysis comprises a quantitative inventory of the ecologically and economically relevant parameters as a basis for the comparative calculation. Inventory information for conventional and additive manufacturing was compiled in preparation for the life-cycle assessment. The data for conventional manufacturing comes from the information provided by the car manufacturer of the damper fork, i.e. the reference component. For additive manufacturing, the data results from direct trials in the LBM plant of the Fraunhofer EMI (section 4.5).

The background data for the inventory comes from the database “ecoinvent V3.5”[61]. The data for the production of scandium, which is not available in

[61] See Ecoinvent (2014).

the database, is taken from the publication by Nuss.[62] Table 6 shows the data for the preparation of the metal powders used.

Table 6: Input parameters for modelling the production of the two powders for additive manufacturing (based on the production of 1 kg of metal powder)

Input	Scalmalloy©	AlSi10Mg
Aluminium (g)	1143.0	1087.3
Silicon (g)	2.1	121.2
Magnesium (g)	54.5	3.6
Zirconium (g)	4.5	-
Scandium (g)	8.0	-
Argon (m^3)	1.3	1.3
Energy (MJ)	9.8	9.8

The parameters for the necessary inputs of conventional and additive manufacturing (with Scalmalloy© or AlSi10Mg) for the ecological and economic assessment can be found in Table 7.

Table 7: Input parameters per piece for the ecological and economic assessment

Input parameters	Conventional manufacturing	Additive manufacturing (Scalmalloy©)	Additive manufacturing (AlSi10Mg)
Quantity of electricity (kWh)	0.28	49.86	40.64
Quantity of heat (kWh ga	2.83	0.07	0.08
Quantity of raw material (kg)	1.36	1.22	1.33
Quantity of compressed air (m^3)	-	260.15	187.73
Quantity of cooling water (m^3)	-	1.52	1.09
Machine time (h)	No data available	9.54	7.09
Working time (h)	No data available	0.38	0.38

In order to assess weight savings in the utilisation phase of the component, fuel consumption and emissions are recorded when it is burned. The savings for about 100 kg of weight reduction per 100 km is about 0.2 l[63]. This equates to 1.94 kWh. With an assumed mileage of 150,000 km, this results in a saving of 2,910 kWh. Based on 100 g, this is 2.91 kWh. Additive manufacturing with Scalmalloy© achieves a weight saving of 156 g and thus of 4.54 kWh per component over the entire service life of the vehicle.

[62] See Nuss and Eckelman (2014).

[63] See Helms and Kräck (2016).

5 RESULTS OF ECOLOGICAL AND ECONOMIC ASSESSMENT

5.1 Results of the ecological assessment

5.1.1 Cumulative energy demand

For consideration of the cumulative energy demand for additive and conventional manufacturing of the reference component, the methodology of VDI Guideline 4600 "Cumulative energy demand (CED); Terms, calculation methods"[64] is applied (). For reasons of clarity, only the two categories "renewable/regenerative" and "non-renewable/exhaustible" are presented.

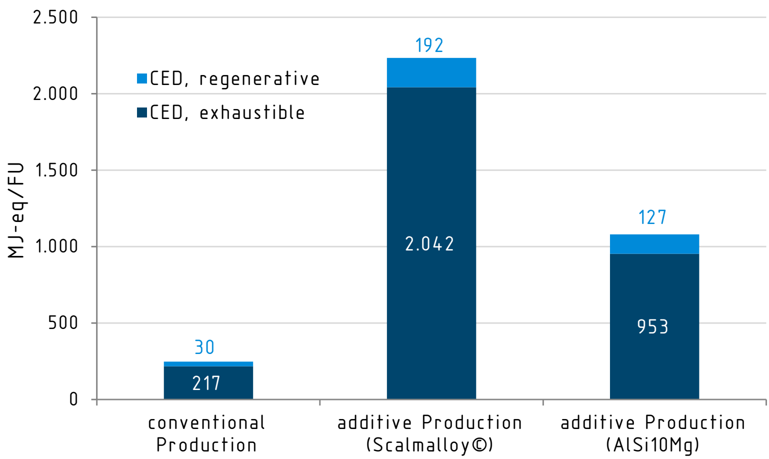

Figure 20: Cumulative energy demand per functional unit

The results show that the conventional manufacturing process consumes nine times or four times less energy (around 250 MJ-eq./FU) than the additive LBM process with Scalmalloy© (around 2,230 MJ-eq./FU) or AlSi10Mg (around 1,080 MJ-eq./FU). In addition, the additive process with AlSi10Mg requires around half as much energy per functional unit as the additive process with the metal powder Scalmalloy©. The possible fuel savings in the

[64] See VDI 4600:2012-01.

utilisation phase of a vehicle due to the lower mass of the structurally optimised component is negligible compared to the total energy consumption (60 MJ-eq./FU).

The big difference between the production processes is due to the direct energy requirements of the processes in the form of electricity and gas (difference between conventional production and additive production with AlSi 10Mg). On the other hand, the production of 1 kg of scandium (a part of Scalmalloy©) requires almost 100,000 MJ-eq. Taking into account the different raw material consumption (additive manufacturing with Scalmalloy© and with AlSi10Mg), this also contributes to higher energy consumption. This pattern is also repeated in the following impact categories.

In conventional manufacturing, about 80% of the energy required results from the provision of aluminium. During additive manufacturing using Scalmalloy©, about 60% of the energy demand comes from powder production (the process steps are always inclusive of raw material supply); with AlSi10Mg the supply of electricity for the production process, at over 40%, and for powder production, with just under 40%, predominate.

5.1.2 Cumulative raw material demand

For consideration of the cumulative raw material demand for additive and conventional manufacturing of the reference component, the methodology from VDI Guideline 4800 Part 2 “Resource efficiency - Assessment of raw material consumption”[65] is used.

The guideline distinguishes between four different types of cumulative raw material demand: energetic, metallic and biotic raw material consumption and the raw material consumption of construction and industrial minerals. The results of the manufacturing processes for cumulative raw material demand are shown in Figure 21.

[65] **See VDI 4800 Part 2:2018-03.**

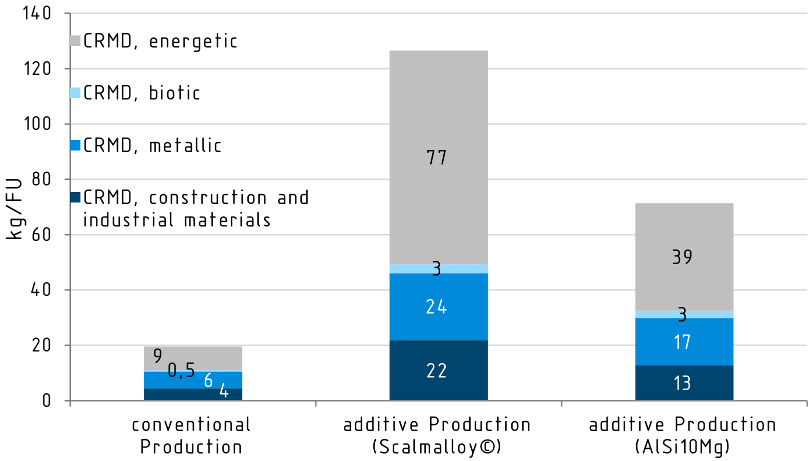

Figure 21: Cumulative raw material consumption per functional unit

The results show that conventional production requires approx. 6.5 times or 3.5 times lower raw material costs (approx. 20 kg/FU) than the additive process with Scalmalloy© (approx. 125 kg/FU) or AlSi10Mg (around 70 kg/FU) respectively. The lower fuel consumption in the use phase of a vehicle with the structurally optimised lightweight component is negligible compared to the total cumulative raw material demand (1.5 kg/FU).

The majority of the total raw material consumption is attributable to the energetic CRMD, especially in the case of additive manufacturing processes. This includes the energy sources required to provide raw materials and electricity for manufacturing. Metallic CRMD and CRMD for construction and industrial minerals also play a major role: the metallic CRMD adds up all the expenses that can be attributed to the movement of ore, in this case to bauxite, for example. In the CRMD for construction and industrial minerals, the requirements of sand or salts are listed. Biotic CRMD plays a minor role. It covers material (e.g. wooden beams in mine construction) and energy utilisation (e.g. wood chips for electricity production) of biomass.

In conventional manufacturing, more than 60% of the raw material consumption in metallic CRMD results from the production of alloy steel tools. Only 35% is accounted for by the aluminium contained in the component. In the case of construction and industrial minerals, around 80% of the raw material costs are incurred in aluminium production. In energetic CRMD over 80% of the demand is a consequence of aluminium production. In biotic CRMD, around 60% of demand is accounted for by aluminium production, while silicon production accounts for a further 35%.

In additive manufacturing[66], more than 50% of the metallic CRMD comes about in the production of the LBM printers required. The reason for this lies in the steel used in them, together with the alloying metals. Only around 20% of the metallic CRMD for Scalmalloy© and around 17% for AlSi10 Mg is associated with powder manufacturing. In the case of building and industrial minerals, around 55% of consumption is accounted for by powder manufacturing with Scalmalloy©. If AlSi10Mg is used, this is also the dominant factor, accounting for a share of more than 45%, while more than 35% goes on the supply of electricity. When using Scalmalloy©, just under 55% of energetic CRMD comes from powder production, while a good 35% goes on the supply of electricity. If AlSi10 Mg is used, the demand for electricity dominates with a share of around 55%, while powder production accounts for more than 30%. In biotic CRMD, around 45% of demand comes from the supply of electricity, while another 30% is for powder production. If AlSi10Mg is used, the power supply dominates with a share of more than 40%, while just under 35% is accounted for by powder production.

5.1.3 Water consumption

For the consideration of water consumption in additive and conventional production of the reference component, the current assessment method ILCD 2011, Midpoint (v1.0.10, August 2016) for openLCA[67] is used. The total water consumption for the manufacturing methods under consideration is shown in Figure 22.

[66] This applies to the use of AlSi10Mg and to Scalmalloy©.
[67] See openLCA (2018).

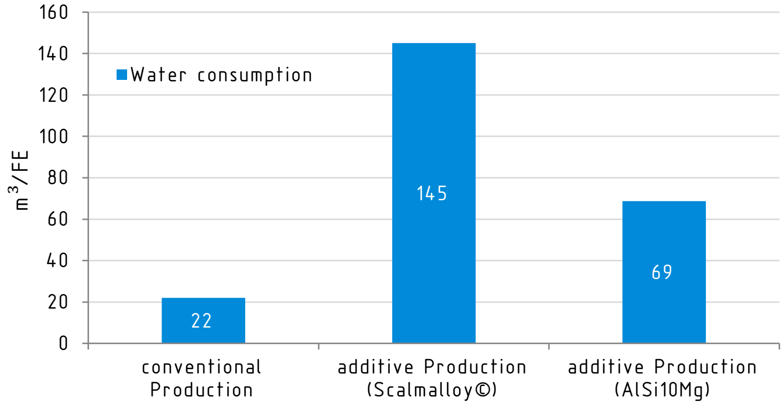

Figure 22: Water consumption per functional unit

The results show that conventional production requires almost seven times or a good three times lower water consumption (around 22 m^3/FU) than the additive process with Scalmalloy© (around 145 m^3/FU) or with AlSi10Mg (around 69 m^3/FU). When it comes to water consumption, the fuel savings in the use phase of the structurally optimised component are negligible compared to the total demand (1.5 m^3/FU).

In conventional production, more than 80% of water consumption is accounted for by the production of the aluminium required.

In additive manufacturing, when using Scalmalloy© almost 65% of water consumption is attributable to powder production, while AlSi10Mg is also dominated by powder production, but only at around 45%.

5.1.4 Land use

For consideration of the land required for the provision of raw materials for additive and conventional production of the reference component, reference is also made to the valuation method ReCiPe Midpoint (H) V 1.13 December 2016[68] for openLCA[69]. Here, the category "urban land occupation" is used

[68] See ReCiPe (2016).
[69] See openLCA (2018).

for quantification. The total land used for the manufacturing processes considered is shown in Figure 23.

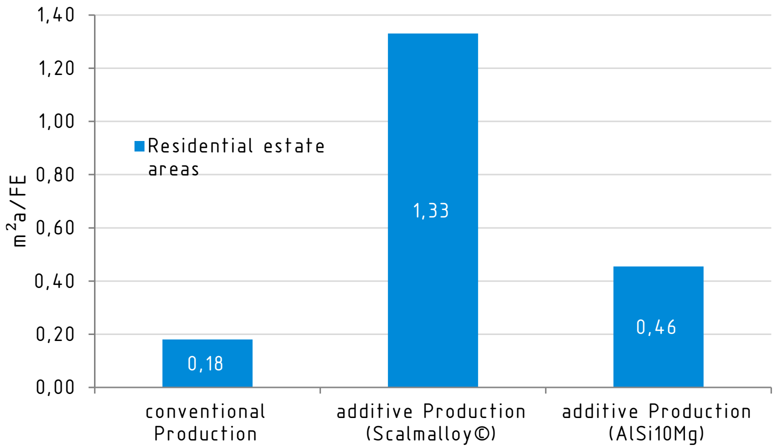

Figure 23: Land use per functional unit

Here, too, the results indicate that conventional production requires around 7.5 times or 2.5 times less area (around 0.18 m^2 residential area) than the additive process with Scalmalloy© (approx. 1.33 m^2 residential area) or AlSi10Mg (around 0.46 m^2 residential area).

In conventional production, more than 80% of the demand also comes from aluminium production in the land use category.

In additive manufacturing using Scalmalloy©, powder production accounts for almost 65% of water consumption. If AlSi10Mg is used, powder production also dominates, but only at around 45%. The rest goes on power and compressed air supply.

5.1.5 Global warming potential

For consideration of the global warming potential, the current assessment method ReCiPe Midpoint (H) V 1.13 December 2016[70] for openLCA[71] is used. This method uses the current values of the IPCC to convert all relevant emissions into CO_2 equivalents. The total global warming potential for the manufacturing methods under consideration are shown in Figure 24.

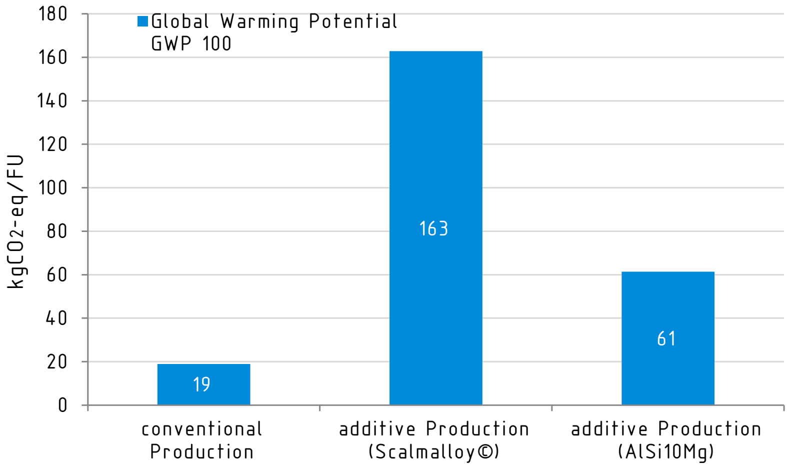

Figure 24: Global warming potential per functional unit

The category global warming potential should be considered in the same way as cumulative energy consumption. Since the CED values largely result from the energy requirements of raw material production, the conditions in the respective raw material countries of origin apply with regard to the global warming potential. Internationally, the energy demands of the raw materials industry are currently met primarily by fossil fuels. The specific global warming potentials are taken into account accordingly.

From Figure 24 it can be seen that conventional manufacturing creates almost 9-times less or a good 3-times less CO_2 (approximately 19 kg CO_2-

[70] See ReCiPe (2016).
[71] See openLCA (2018).

eq/FU) than the additive process using Scalmalloy© (about 160 kg CO_2-eq/FU) or AlSi10Mg (about 60 kg CO_2-eq/FU). The fuel saving in the utilisation phase through the lower mass of the structurally optimised vehicle component is negligible compared to the total demand (4 kg CO_2-eq/FU).

In conventional manufacturing, almost 85% of greenhouse gas emissions occur during aluminium production.

In additive manufacturing with Scalmalloy©, more than 60% of the greenhouse gas emissions are released during powder production[72]. For AlSi10Mg, the supply of electricity to the actual LBM manufacturing process dominates at almost 45%, while powder production contributes about 40% to the global warming potential.

5.2 Assessment of raw material criticality

For assessment of raw material criticality, the methodology described in VDI 4800 Part 2 “Resource efficiency – Assessment of raw material consumption”[73] is applied. The guideline is based on a system of 13 indicators, which are divided into three groups (Table 8).

Table 8: Indicators of the VDI Guideline 4800, Part 2

Geological, technical and structural indicators	Geopolitical and regulatory indicators	Economic indicators
Ratio of reserves to annual global production	Herfindahl-Hirschman index of reserves	Herfindahl-Hirschman index of companies
Degree of combined/secondary production	Herfindahl-Hirschman index of country production	Degree of increase in demand
Extent of distribution of functional end-of-life recycling technologies	Political country risk	Technical feasibility and cost-effectiveness of substitutions in main applications
Cost-effectiveness of storage and transportation	Regulatory country risk	Annualised price volatility
Extent of distribution of natural resources/cultivation areas		

Each commodity receives a rating for each indicator, with the rating scale ranging from 0 to 1 and intermediate steps 0.3 and 0.7. An assessment of individual raw materials is carried out using a number. Here the individual

72 This process is also called “atomisation”.

73 See VDI 4800 Part 2:2018-03.

indicator values are sorted by size. Weighting factors G_i are calculated according to the following formula:

$$G_i = \frac{2^{(i-1)}}{3^i}$$

. These are multiplied by the indicator values and added according to the following formula:

$$K_j = \frac{1}{\sum_{i-1}^{j} G_i}$$

to give a total criticality. VDI 4800 contains valuations for many of the raw materials to be considered based on calculations, estimates and expert opinions. The guideline contains the complete table. However, zirconium and scandium are not included. These missing values were offset by analogy. For zirconium, the data from hafnium was used because these metals are closely associated and the raw materials are extracted together. For scandium, the evaluation of terbium was considered as these metals are comparable in their criticality, extraction (by-product) and full-year production.

The metals relevant for the various production processes, which are incorporated into the respective alloys, and their aggregated criticality value are shown in Table 9.

Table 9: Aggregated and rounded criticality values

Metal	Criticality value		Application in production technology
	Aggregated	Rounded	
Aluminium	0.71	0.7	All
Silicon	0.76	0.7	All
Magnesium	0.76	0.7	All
Zirconium	0.92	1	Additive manufacturing
Scandium	0.93	1	Additive manufacturing

For the metals zirconium and scandium, which are used in the alloy Scalmalloy©, the criticality value is 1 results, i.e. a very high supply risk. They are only necessary for additive manufacturing.

For the other metals a rounded criticality value of 0.7 is calculated. Silicon and magnesium are found in all the technologies under consideration, as they are commonly used in aluminium alloys for the application in question.

The criticality values of the metals used in additive manufacturing suggest that the supply security is currently at high risk when Scalmalloy© is used. In conventional aluminium alloys this is much lower, also due to the closed loop recycling of aluminium.

5.3 Results of the economic assessment

The analysis of the life cycle costs includes the essential cost factors that appear in the entire life cycle of the vehicle component considered here (damper fork). The main focus is on the cost comparison in the production phase. In order to allow cost comparisons of conventional and additive manufacturing processes, the costs of the various process stages are broken down. The comparison is based on the use case defined for the purpose of this study in section 4.1 and the system boundary outlined in Figure 18. As a result, the cost data used in the analysis refer to the production of 10,000 damper forks per year.

The cost comparison for components made with conventional and additive manufacturing processes is based on the functional unit described in section 4.4.1. The costs are therefore presented in relation to one damper fork, based on the limit conditions specified in section 4.4.1.

5.3.1 Investment costs of manufacturing

The investment costs include the costs of providing the production systems and the tools required for workpiece machining. Conventional production includes melting and tunnel furnaces, a casting plant, a hydraulic drop forging press and other metalworking machines. In addition, this includes the costs for tool production, in particular the casting mould and drop forging. The investment costs for these resources are included in the analysis (by allocation) in proportion to the total production output of an exemplary industrial company, in accordance with the batch size of 10,000 pieces considered here.

In additive manufacturing, the investment costs of the LBM systems are included in the analyses. Appropriate, specially made forming tools are not required here, in contrast to conventional production. Only auxiliary equipment[74] with comparatively low investment costs is used. Subsequent machining of functional surfaces of the workpieces is necessary in both conventional and additive manufacturing. However, this is minimal in the given case and are therefore not considered in the comparative analysis.

The number of LBM systems required for the production of 10,000 components per year is derived from the experimentally determined machine and maintenance times during the production of the reference component. These differ depending on the material used (alloys). This results in a different annual production output on the same EOS M 400 LBM system. Therefore, depending on the powder material (alloy), different machine times per workpiece are estimated. For the production of 10,000 components per year, the following rounded number of EOS M 400 LBM systems is required:

- Production process with Scalmalloy© alloy: 14 LBM systems
- Production process with AlSi10Mg alloy: 11 LBM systems

Additional auxiliary equipment such as compressed air generation, component post-treatment and powder processing are already included in the experimentally determined data on investment costs and were extrapolated to the total equipment of the additive manufacturing plant required in the production scenario. Table 10 shows the summary of the proportionate investment costs per piece of the reference component.

[74] A saw for separating the components from the support structures and a furnace for post heat treatment of the workpieces.

Table 10: Investment costs of conventional and additive manufacturing per reference component

Process	Investment costs per RC Individual items	Investment costs per RC Total	Underlying allocation factors
Conventional production		€2.94	
Production facilities incl. land requirements (total)	€2.05		1/20 of the system service life; 3% interest rate (discount); 2.4% of the annual production volume
Injection mould	€0.23		1/10 of tool service life; 3% interest rate (discount);
Drop forging tool	€0.66		1/5 of tool service life; 3% interest rate (discount);
Additive manufacturing		-	
LBM system with Scalmalloy©	€213.36	€213.36	1/10 of the plant service life; 3% interest rate (discount);
LBM plant with AlSi10Mg	€167.64	€167.64	1/10 of the plant service life; 3% interest rate (discount);

RB – reference component

5.3.2 Operating costs of manufacturing

The data basis for conventional production results from information provided by the vehicle manufacturer of the shock absorber fork. This industrial manufacturing process represents an optimised state-of-the-art cost framework including the economies of scale of mass production.

The data basis for additive manufacturing is based on experimentally determined values, i.e. the measured values on the individual plant. These were used to extrapolate the operating mode assumed in the production scenario involving 14 or eleven LBM systems. In doing so, the possible optimisation potential of a mode of operation trimmed from series production was estimated conservatively. The operating costs determined therefore represent the upper limit of the assumed cost framework.

The operating mode of the LBM systems with machine loading times per batch (section 4.6) of 171.80 hours (Scalmalloy©) or 133.94 hours (AlSi10Mg) enables unattended operation at weekends and holidays. From this and including the necessary setup and maintenance times, the LBM plants are expected to operate at a rate of 360 days per year (loading and operation of the 14 or eleven LBM systems takes place at intervals).

The productivity of the systems is primarily due to the machine occupancy times, which are composed of the measurements for the coating duration and the exposure time of the workpieces plus the working time for preparation per batch. On the other hand, reworking of the workpieces (heat treatment, support structure removal, deburring) can take place parallel to the machine occupancy times. The latter times are therefore included in the labour costs, but not in the cost factor of machine time. Maintenance costs comprise an extrapolated share of labour, material and disposal costs (Table 11).

Table 11: Operating costs of conventional and additive manufacturing per reference component

Process	Operating costs of manufacturing per piece	
	Individual items	Total
Conventional production		€6.83
- Raw material costs	€5.50	
- Energy costs	€0.15	
- Labour costs	€1.10	
- Costs of waste disposal	€0.08	
Additive manufacturing with Scalmalloy©		€560.54
- Raw material costs	€402.75	
- Energy costs	€11.99	
- Costs of cooling water	€5.95	
- Labour costs	€6.38	
- Costs of maintenance	€98.74	
- Costs of space	€3.28	
- Costs of waste disposal	€31.45	
Additive manufacturing with AlSi10Mg		€134.90
- Raw material costs	€43.21	
- Energy costs	€9.25	
- Costs of cooling water	€4.52	
- Labour costs	€6.04	
- Costs of maintenance	€70.53	
- Costs of space	€2.57	
- Costs of waste disposal	€3.35	

5.3.3 Costs in the utilisation phase

The damper fork is designed for maintenance-free use as part of a motor vehicle. During the utilisation phase, no direct costs therefore arise. An indirect saving effect would theoretically be possible by additive manufacturing of the reference component in structurally optimised lightweight design, since the weight reduction of the reference component contributes to a reduced fuel consumption of the vehicle. The assumed saving effect per reference component in this study is about 0.5 l of fuel over the entire service life of the vehicle. The effect is thus negligible.

5.3.4 Disposal costs

After use of the damper fork as part of a motor vehicle, it is disposed of together with the old car. As the disposal method, it is assumed that the car will undergo proper end-of-life car recycling including recycling of the metallic components. Regardless of their specific alloy, the reference components considered here are treated as aluminium scrap. This recyclable material achieves a market price, which is considered as a one-off credit in life cycle costing. As this recycling credit will take effect only after a delay of approximately 15 years, the values given in Table 12 represent the discounted values (NPV) of this credit amount.

Table 12: Recycling credits fir reference components made with conventional and additive manufacturing

Reference component	Mass	Credit
Component from conventional production	1.32 kg	€1.41
Component made of Scalmalloy©	1.1 kg	€1.17
Component made of AlSi10Mg	1.2 kg	€1.28

5.3.5 Overall assessment of life cycle costs

Table 13 shows the total cost per piece when manufacturing 10,000 damper forks. Both conventional manufacturing and additive manufacturing with Scalmalloy© and AlSi10Mg are considered.

Table 13: Compilation of life cycle costs of conventional and additive manufacturing per reference component

Process	Life cycle costs of production per piece	
	Individual items	Total
Conventional production		€8.36
- Investment	€2.94	
- Operating costs	€6.83	
- Costs in the utilisation phase	negligible	
- Disposal phase	€1.41	
Additive manufacturing with Scalmalloy©		€837.70
- Investment	€213.36	
- Operating costs	€625.52	
- Costs in the utilisation phase	negligible	
- Disposal phase	€1.17	
Additive manufacturing with AlSi10Mg		€363.94
- Investment	€167.64	
- Operating costs	€197.58	
- Costs in the utilisation phase	negligible	
- Disposal phase	€1.28	

The difference in investment costs for the two additive manufacturing scenarios is primarily due to the number of LBM machines required (eleven for AlSi10Mg and fourteen for Scalmalloy©). In addition, there is a big difference between conventional and additive manufacturing in terms of the production time required per workpiece. This has a considerable effect on the unit costs.

In conventional production, the existing production system is only used to capacity for seven days per year with a batch size of 10,000 pieces. Assuming 300 operating days per year, this means that an allocation of 2.4% of the annual depreciation of investment-related costs is applied (in addition to the pro-rata investment costs for the tools). In the case of AM, on the other hand, in both scenarios all LBM machines are working at around 360 days per year to process the batch size under consideration. Therefore, 100% of the annual depreciation of investment-related costs (not including tools) is applied. As a consequence, the proportionate allocation of the annual investment costs in conventional production is relatively low, while this is attributed to additive manufacturing of the damper forks as a whole. This also applies to the maintenance costs, which, in the case of LBM systems that are already relatively maintenance-intensive, have a full effect on the production unit costs. In contrast, conventional manufacturing allocates only 2.4% of annual maintenance costs.

Furthermore, the different powder prices cause a significant difference in operating costs between additive manufacturing with Scalmalloy© and AlSi10Mg (factor 10). This affects both raw material and waste disposal costs (powder losses).

5.4 Sensitivity analysis

5.4.1 Modified parameters for the sensitivity analysis

Today's state-of-the-art technology for additive manufacturing is at the threshold of single-part production for the production of small and medium-sized series of workpieces. The production of a mean batch size of 10,000 units per year using LBM technology considered in this study would be technically feasible, but somewhat ahead of the times in terms of industrial practice. However, it is foreseeable that additive manufacturing can be further optimised in future by technological innovations. As a result, small and medium-sized batch production for the lot size considered here could become an industrially effective area of application.

The following sensitivity analysis tests the economic and ecological effects of technological innovations for the production of larger quantities using LBM. From the large number of future technological optimisation possibilities in additive manufacturing processes, the following four aspects are considered in this study (all other aspects remain unchanged, section 4.5.2):

- Number of lasers per LBM system increases from one to four. This results in a reduction of the construction time per batch and thus a reduction of the systems required for the production of 10,000 pieces from 14 to three systems for Scalmalloy© and from eleven to two systems for AlSi10Mg.

- The layer thickness that can be produced with Scalmalloy© increases from 60 µm to 90 µm, which reduces the build time.
- The size of the powder bed increases to 400 mm x 400 mm x 800 mm, with the result that 36 instead of 18 workpieces can be manufactured at a time.
- Reduced downtime of the LBM systems due to unattended or telemonitored operation (operating time - 360 days per year).

The economic and ecological effects of these future optimization options are calculated on the basis of today's costs and currently applicable impact factors. Therefore, the sensitivity analysis tests changes that would occur if the optimisations that were only possible in the future were already feasible.

In Table 14 the current and optimised parameters of additive manufacturing for the two alloys Scalmalloy© and AlSi10 Mg are shown. These form the basis for the results presented in the next two sections.

Table 14: Changes in the input parameters of additive manufacturing per unit for the ecological and economic assessment

Input parameters	Base (Scalmalloy©)	optimised (Scalmalloy©)	Base (AlSi10Mg)	optimised (AlSi10Mg)
Number of parts per batch	18	36	18	36
Quantity of electricity (kWh)	49.86	19.56	40.18	15.25
Quantity of heat (kWh gas)	0.07	0.07	0.07	0.08
Quantity of raw material (kg)	1.22	1.22	1.33	1.33
Quantity of compressed air (m^3)	260.15	64.90	187.73	48.74
Quantity of cooling water (m^3)	1.52	1.51	1.09	1.12
Machine time (h)	9.54	2.32	6.98	1.75
Working time (h)	0.38	0.3	0.36	0.31

5.4.2 Results of the ecological sensitivity analysis

In Figure 25, the results of the scenario for additive manufacturing with an optimised LBM system compared to unmodified conventional production in the category cumulative energy demand are shown.

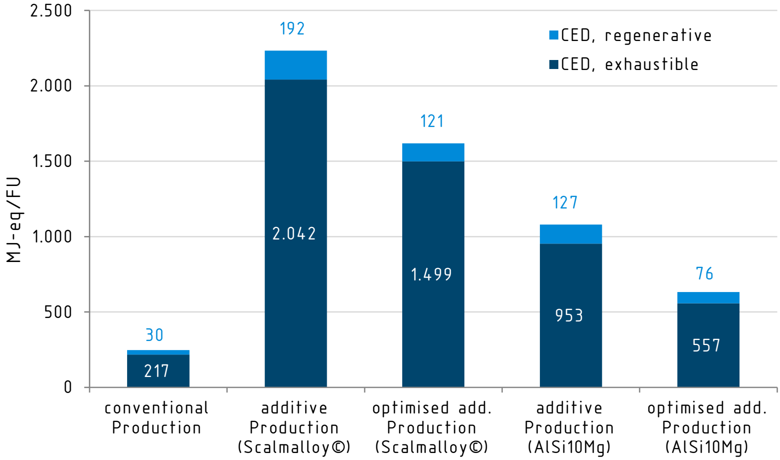

Figure 25: Sensitivity of cumulative energy demand per functional unit

It is clear that with an optimised LBM system, both in the case of Scalmalloy© and of AlSi10Mg a significant saving of almost 30% or more than 40% of the cumulative energy demand could be achieved. In this optimisation case, additive manufacturing with AlSi10Mg requires, for example, only 2.5 times as much energy as conventional production instead of four times as much.

In Figure 26, the results of the scenario for additive manufacturing with an optimised LBM system compared to unmodified conventional production in the category cumulative raw material demand are presented.

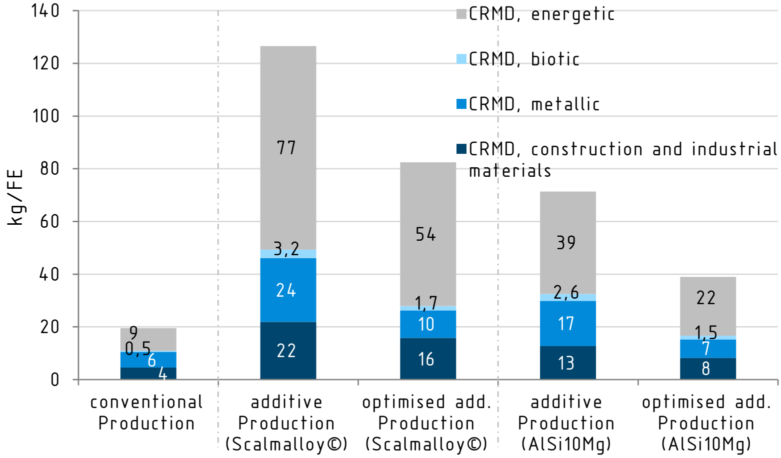

Figure 26: Sensitivity of cumulative raw material demand per functional unit

The CRMD also shows that, in the case of both Scalmalloy© and AlSi10Mg, a significant saving of nearly 35% or around 45% of the cumulative raw material demand could be achieved by optimising the LBM system. Through optimisation, additive manufacturing with AlSi10Mg would only require around twice as much raw material as conventional production.

The results of the sensitivity analysis for additive manufacturing with an optimised LBM system compared to unchanged conventional production in the category global warming potential are presented in Figure 27.

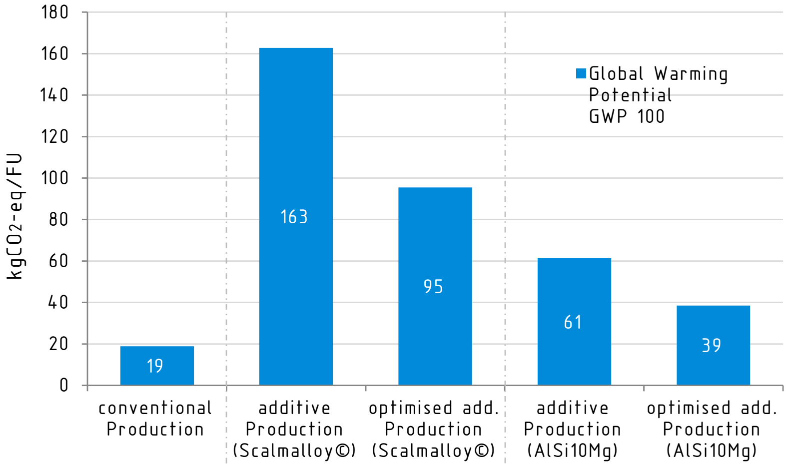

Figure 27: Sensitivity of global warming potential per functional unit

In additive manufacturing with both Scalmalloy© and AlSi10Mg, CO_2 emissions can be reduced by more than 40% and more than 35% respectively. In this optimisation case, additive manufacturing with AlSi10Mg emits only about twice as much greenhouse gas as conventional production.

5.4.3 Results of the economic sensitivity analysis

The investment costs and operating costs calculated for optimised additive LBM production systems are given in Table 15 (comparative values Table 10 and Table 11). There are no changes in the costs for the utilisation phase or the recycling credit.

The results of the economic sensitivity analysis show a significant cost-saving potential for investments (Table 15). This cost share is reduced by technical optimisations by about 80%. The reason for this is the lower number of LBM systems required for the production of 10,000 pieces per year. With AlSi 10 Mg only two optimised systems (instead of eleven) are needed, with Scalmalloy© it is three (instead of fourteen). Due to increasing international competition, a reduction of investment costs for LBM systems is expected in the coming years. However, an accurate forecast cannot be made. That is why this factor is not taken into account.

Table 15: Investment and operating costs of optimised additive manufacturing per reference component

Process	Investment costs per piece	Underlying allocation factors
Optimised LBM system with Scalmalloy©	€45.72	1/10 of the system service life; 3% interest rate (discount);
Optimised LBM system with AlSi10Mg	€30.48	1/10 of the system service life; 3% interest rate (discount);
Process	**Annual operating costs of manufacturing per piece**	
	Individual items	**Total**
Optimised additive manufacturing with Scalmalloy©		€482.61
- Raw material costs	€402.75	
- Energy costs	€4.06	
- Costs of cooling water	€5.90	
- Labour costs	€5.16	
- Costs of maintenance	€32.59	
- Costs of space	€0.70	
- Costs of waste disposal	€31.45	
Optimised additive manufacturing with AlSi10Mg		€81.01
- Raw material costs	€43.21	
- Energy costs	€3.09	
- Costs of cooling water	€4.35	
- Labour costs	€4.82	
- Costs of maintenance	€21.73	
- Costs of space	€0.47	
- Costs of waste disposal	€3.35	

The impact of system optimisation on operating costs is significantly lower. Furthermore, material costs remain the most significant cost factor, especially with Scalmalloy©. In this case, the operating costs are reduced by about 14%. With AlSi10Mg up to 40% cost saving potential can be expected. The most significant savings result from reduced maintenance costs.

6 DISCUSSION AND CONCLUSIONS

6.1 Classification of the results in the overall context

The results of the ecological assessment presented in section 5.1 show that additive manufacturing causes far greater impact than conventional production across all environmental impact categories. This is mainly due to the basic electrical consumption of the LBM systems. In particular, the constant measurable base load of the EOS-M-400 system at about 5 kW has proven to be surprisingly high. The measured basic electricity demand primarily indicates a system technology that is not yet fully developed. In contrast, the power requirement for the actual, laser-based melting process of the powder is comparatively moderate (8.8% of the total power demand, for derivation see section 4.5.1). There is therefore a significant potential for optimising energy efficiency in system engineering.

The sensitivity analysis shows that technical improvements in LBM systems could bring significant potential for improvement in the environmental impact categories. A higher number of lasers operating in parallel and larger installation space alone lead to a significant reduction in the number of LBM systems required for the production of 10,000 components. This increase in productivity would also result in lower energy demand. For example, in the case of Scalmalloy© or AlSi10Mg, a saving of almost 30% or over 40% of the cumulative energy demand can be achieved. In this optimisation case, additive manufacturing with AlSi10Mg powder requires only 2.5 times as much energy per workpiece as conventional production. Further technical improvements, in particular a reduction in the basic electrical load of the LBM systems, could help to reduce the gap between additive and conventional manufacturing with regard to their environmental impact. The optimisations considered here within a single LBM plant generation illustrate the potential of subsequent generations to reduce environmental impacts further.

In addition, the results clearly show the influence of the powder alloy used on resource consumption and the global warming potential. In the case of Scalmalloy©, the cost of providing the raw materials has a significant impact on the overall result. This applies in particular to the alloy constituent scandium, which the EU Commission (2017) has also identified as a critical raw material for the EU.[75]As a high-tech material, Scalmalloy© is primarily suitable for the production of highly optimised components with an above-average market value, but less so for generic vehicle components. For such products, AlSi10Mg is much cheaper and less resource-relevant.

In addition, it can be deduced that the use of a high-strength steel alloy, for example a maraging steel powder of the sort frequently used for LBM processes (strength about 2200 MPa), also offers considerable savings potential. With the same strength, a smaller component volume can be achieved here than with aluminium alloys. LBM production of low volume workpieces requires less energy for the melting process. This would not only result in a considerably lower demand for powder, but also a significantly shorter production time. By contrast, the higher melting point of steel has only a minor influence on the energy demand of the laser-based selective melting process. Depending on the application, the decision factors 'specific material properties' and 'workpiece geometry' should thus be evaluated differently.

The mass reduction achieved by means of numerical structure optimisation of the reference components made by additive manufacturing was too low in the given context of application of the reference components to reduce the fuel consumption of a vehicle in use significantly. For other applications, such as aerospace, lightweight construction would have a much greater impact on reducing the amount of fuel required for lift and acceleration. Nevertheless, structural optimisation is a necessary prerequisite for the use of LBM technology. Without structural optimisation, the economic and ecological characteristic values for additive manufacturing determined in this study would be less favourable.

The results of the economic assessment in section 5.3 show that the application of additive manufacturing for the selected use case. i.e. the manufacture of 10,000 damper forks, is not economically viable. Using AlSi10Mg, the cheaper material, it is still 40 times more expensive than conventional production.

In addition to the investment costs, the material and operating costs are also significantly higher in additive manufacturing than in conventional

[75] See EU Commission (2017).

industrial production. Particularly noteworthy here are the costs of the powder (especially when using Scalmalloy©) and the maintenance costs for the LBM systems. Producing components with a relatively simple geometry and low market price does not achieve the level of value added that would be required to recoup the cost of using what is currently still very expensive LBM technology. For the batch size considered here (10,000 pieces), conventional production is much cheaper at the present time. At the same time, however, it should be emphasised that the economic assessment depends heavily on the particular use case considered. General statements about the profitability of additive manufacturing are therefore not possible. Rather, this study provides a detailed insight into the valuation mechanisms and challenges that need to be overcome in order to make sound decisions regarding investment in additive manufacturing processes.

The sensitivity analysis shows that technological innovations in additive manufacturing systems could significantly improve their profitability in the future. The technical improvements mentioned in section 5.4.1 alone would bring about a significant increase in the productivity of LBM systems. This results in a reduction in the machine time per workpiece and would require a smaller number of LBM systems for the same lot size. The unit price could be reduced by almost 80%, for example when using AlSi10Mg.

However, it can be assumed that the material costs for the powder will continue to be significantly higher than the material costs of conventional production. Powder production will continue to represent an additional cost factor throughout the value chain. In the foreseeable future, LBM-based production will therefore still be at least 10 times more expensive than conventional production (at least in the context of the application considered here).

6.2 Assessment of relevance and scope, taking into account the assumptions made

Under the framework conditions assumed in this study, additive manufacturing could only exploit its technological advantages with a very small batch size. The unit costs of conventional manufacturing processes would also be high in this case. However, in the case of conventional production with a smaller batch size than 10,000 pieces per year, the casting process considered in this study would not be used.[76] This is designed for much larger volumes. Other conventional manufacturing processes such as CNC milling or lost mould casting would be used for conventionally produced small batches. These alternative manufacturing methods have different economic and environmental characteristic values that were not considered in this study, but would provide further interesting insights into the comparison of additive and conventional manufacturing processes.

An essential advantage of additive manufacturing lies in the possibility of topological structural optimisation of lightweight components. This could not be fully exploited with the reference component considered in this study, since the basis of conventional vehicle design (selected for reasons of comparability) allowed only a small amount of design freedom. Overall design of complex product systems, such as vehicles or aircraft, which has been explicitly optimised for additive manufacturing, makes it possible to explore the lightweight engineering potential of individual components more fully. This would improve the cost-effectiveness of additive processes and also bring about more significant energy-saving effects in the utilisation phase of mobile products. Extensive structural optimisation in conjunction with the choice of less expensive materials (e.g. steel powder instead of aluminium alloy) could make LBM production more competitive than conventional production in individual cases. However, this depends very much on the underlying business models. For example, series production of components with identical design will remain the preserve of conventional manufacturing processes in the foreseeable future. On the other hand, additive manufacturing is worthwhile for series production of customised components, such as digitally modifiable unique products with bionic structures that allow functional and integral designs. Despite the high potential of numerical structural optimisation, it should be noted that material efficiency depends heavily on the choice of material.

In view of the high investment costs of the LBM systems, permanent high capacity utilisation of LBM systems is desirable. This can only be achieved through streamlined business models, such as manufacturing by service

76 **The process was nevertheless chosen because the automobile manufacturer had practical data available for the production process for the ecological and economic assessment.**

providers who can achieve optimised space utilisation and largely uninterrupted operation of the LBM systems. In the future, the scope of additive manufacturing could be expanded. However, this requires an improved tolerance of the LBM technology in terms of process technology to enable the use of cost-effective powder materials. Lower requirements for alloy components, grain quality and homogeneity of the powder materials could help to mitigate cost disadvantages and higher environmental impacts compared to the materials used in conventional production. With titanium alloys, for example, where conventional manufacturing involves a subtractive milling process with significant material loss, additive manufacturing could perform better economically and ecologically in the near future. This is partly due to the fact that unmelted powder can be directly recycled, while titanium chips from machining cannot be recycled in a closed cycle due to contamination with cooling lubricants.

In summary, additive manufacturing can be understood as a supplement to conventional production. It can be assumed that innovations will optimise additive manufacturing processes and thus open up other or new fields of application. As a result, conventional production processes in the areas where the two technologies intersect (batch size) can be replaced resource-efficiently. In this context, the present study offers an exemplary insight into assessment mechanisms that can support decision-making regarding investments in additive manufacturing processes.

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APPENDIX A

Remarks on structural optimisation

A modern design approach is the use of structural optimisation methods and algorithms in the design process. This allows designers to assist with complex technical problems in the design process and to automate work steps. In addition, automated draft designs and adjustment of shape simplify the use of complex geometries in the design solution, which a designer could not achieve manually.[77]

Setting appropriate optimisation objectives and boundary conditions for structural optimisation makes it possible for components to perform better (in terms, for example, of stiffness, vibration or thermal behaviour) with low component weight. This lightweight design is of particular interest in additive manufacturing. In contrast to conventional production processes (e.g. material removal), additive manufacturing only builds up material where it is really needed. The lower the mass of a component, the faster it can be made by additive manufacturing and the greater the resource efficiency. Lightweight construction thus becomes an economic imperative for additive manufacturing in order to meet business requirements such as lower material and operating costs[78].

The requirements for CAD programs are also changing. Traditionally, CAD programs are used for parametric design of components. Parameters such as the wall thickness of a rib are entered exactly in the design. In terms of additive manufacturing, however, parametric description represents a restriction on the potential complexity of the shaping. The freedom of design in additive manufacturing allows completely new forms, which are very difficult and often impossible to describe using parameter-based methods. For example, the evolution of the past few years shows that more and more CAD software providers are integrating free-form design capabilities into their software, allowing the designer to develop and construct any structures in the CAD environment. Another trend to be observed is the integration of structural optimisation methods such as topology optimisation into CAD

[77] See Sigmund, O.; Maute, K. (2013), pp. 1031 – 1055.
[78] See Bierdel, M. and Pfaff, A. (2017).

programs. The designer is thus able to calculate optimised design concepts for defined load scenarios and to implement them directly in the CAD environment. Some of the most popular manufacturers of such solutions are, for example, Altair Engineering, Siemens PLM, Ansys, LSTC and Dassault Systémes. The advantage of using structural optimisation algorithms such as topology optimisation lies in the high automation potential. Thus, the resulting design is no longer dependent on the experience of the designer, but only on the defined boundary conditions, which lead to an optimised component.

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