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APPROACH FOR A COMPARATIVELY EVALUATION OF THE SUSTAINABILITY FOR ADDITIVE MANUFACTURED ALUMINUM COMPONENTS

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Abstract

Nowadays new manufacturing technologies like the additive manufacturing in conjunction with the associated resources utilization requires a rethinking about sustainability. To continue the idea of an efficient technology the evaluation of sustainability is analyzed in this article.
The examination starts with a general description of sustainability by the combination of different definitions. Based on this knowledge, the challenge to evaluate different process chains in various manufacturing technologies is investigated. As a result an approach for the evaluation of the sustainability in relative comparison of different process chains is developed.
In the study the additive manufacturing process chain is faced with the shape cutting process chain regarding an aluminum component. After the introduction of the approach to evaluate the sustainability of both technologies the methodology is applied at a demonstrator. Thereby a geometrically complex component is used, which is shown based on a reflector from the automotive industry. The calculated results allow an assessment of the sustainability of individual process chains in a relative comparison to each other.

Keywords: Sustainability, Design methodology, Additive manufacturing

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1 INTRODUCTION

In the course of industrialization mass production and mass consumption gained significantly in their importance. In central production sites a high number of components are produced and globally exported. Beside of the actual production, this approach requires a high level of logistics as well as a steady transport system to ensure that all products arrive promptly at the recipient. As a result of the increasing freight traffic in general, this approach comes gradually to their limits. In the recent time the sustainability and further environmental aspects of this procedure are criticized. (Graeßler, 2004)

In response to the increasing environmental pollution and by using modern technologies there are new ways of thinking and also new process models which address both the consumer and the producer. A significant development is the increasing digitization and modularization of processes, whereby synergies can be used and processes can be outsourced selectively. There is a change in the product development and manufacture from a pure cost-orientation towards resource efficiency and sustainability. (Petschow et al., 2014) Not at least, the turnaround of centralized production systems towards decentralized production systems (respectively a hybrid of both systems) has an important significance. In addition to outsourcing in the traditional sense, innovative manufacturing processes become more important.

In this context the technology of additive manufacturing becomes increasingly popular. As a result of decreasing acquisition costs both the processing of plastics by the end user and also the additive processing of metals by industrial companies obtain widespread. In general, these methods have differences to conventional shape cutting processes, which relate to the costs and quantities in the production, the material properties and geometric possibilities of the products as well as limited availability in the supply chain. (Gebhardt, 2008)

However, especially the sustainability of the additive manufacturing processes is largely unexplored. In the following, an approach is described which represents an opportunity for a relative evaluation of the environmental impact referring additive manufacturing to the conventional shape cutting process. On the basis of a demonstrator the both process chains are analyzed, starting from the extraction of raw materials, through the preparation and the processing of the components up to the recycling of excess material. So the manufacturing of a component is the major part of the investigation. Application and recycling aspects of the component are not part of the approach. By using general defined criteria a relative comparison of the both processes occurs. In order to satisfy the described potential for additive manufacturing the approach refers to a geometrically complex mono-material-system. Lot size effects are ignored.

2 METHOLOGY

The increasing scientific investigation of the additive manufacturing allows an expansion of this technology. To satisfy this trend and to be able to relate on a sustainable environmental technology in future, the question of the process sustainability comes up.

Regarding the process chains, an approach to evaluate a relative comparison in context of sustainability is developed, referring to the environment and energy consumption. By analyzing similarities between the both process chains criteria are defined, which are used for the evaluation. Based on a demonstrator theoretical aspects are developed and validated by using their practical application. Thereby aluminum manufactured components are in focus of the investigation. Subsequently, the approach can be generalized and used for other components. So the influence of the geometry on the sustainability can be illustrated.

The meaning of sustainability covers a wide range in the product development so that there are different understandings. For example the definitions from Ninck (1997) or Bell and Morse (2008) as well as different models like the "triple bottom line" for business strategies from Elkington (Henriques and Richardson, 2004). For a common understanding a description of sustainability is made. Regarding the challenge for a comparatively evaluation of different process chains the definition is set as follows: "Sustainability is the influence of a process chain on the use and regeneration of resources as well as the pollution and environmental degradation." This definition forms the basis for the derivation of the approach.

For the topic of product sustainability some approaches are available. In addition to material specifications (RoHS, 2015), recycling oriented product design (Ruhland, 2006) or minimization of waste production ("lean production") life-cycle-specific approaches are available. For example the Design for Environment (DfE) approach deals with the idea of a sustainable production and shows regulations for the early development and design steps. (EPA, 2015) LCAs give an early indication for product modifications and the development of sustainable products.

Based on this idea and by using the definition described the evaluation approach is established. Figure 1 shows the process sequence to evaluate the sustainability, which is used in the investigation for aluminum components.

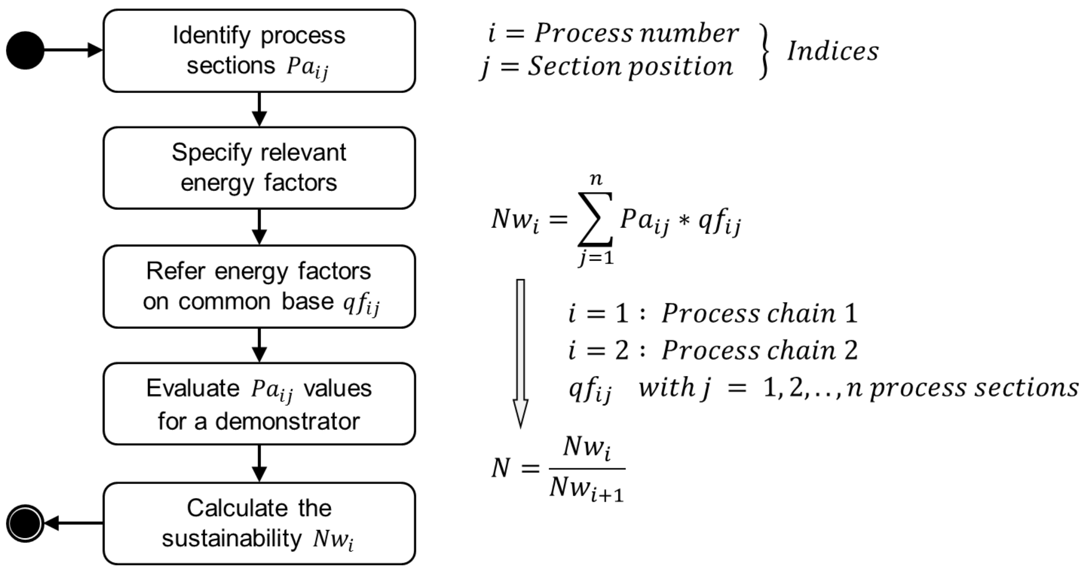

Figure 1. General approach to evaluate the sustainability of different process chains

The chosen process chains are divided into process sections (Pa_{ij}) to allow a relative comparison. Afterwards the weightings of the different process sections have to be determined. Therefore the decisive energy factors are identified and filled with actual energy values. Because these energy values are influenced by different parameters a transformation to a common basis is performed (qf_{ij}). As a common ground the CO_2 emissions of the process sections are suitable because they provide information about the environmental degradation and regeneration of resources potential. After determining the weighting factors as well as the process section the formula for the sustainability value Nw_i for each process chain can be set up. This formula consists of the amount of the process sectors Pa_{ij} while taking the individual weighting factors qf_{ij} into account.

$$Nw_i = \sum_{j=1}^{n} Pa_{ij} * qf_{ij} \qquad (1)$$

To evaluate the sustainability the process sections Pa_{ij} have to be calculated. These dependents on geometry properties, so that the evaluation is performed by referring to a demonstrator. Based on quality criteria an objective assessment is carried out. This evaluation is performed for each process sections Pa_{ij}.

Afterwards the actual sustainability values Nw_i for each process chain can be calculated using Formula (1). These values can be used to establish the entire sustainability N, which represents the result of the comparatively evaluation of the sustainability from the different process chains. If the value becomes small close to zero, the first process chain is more sustainable. Whereas the value rises above 1, the second one is more sustainable. The last possibility is that the value becomes close to 1, which means that both process chains have quite the same sustainability. The value of the result reflects the relative comparison of the two regarded process chains; a statement of absolute values is not given.

3 ANALYSIS OF THE PROCESS CHAINS

First the two process chains ($i = 1$ for additive manufacturing and $i = 2$ for shape cutting) are described generally. Afterwards the application of the approach is performed by the comparison of these.

3.1 Process chain: Shape cutting (SC)

The base of the shape cutting process is a semi-finished-part (sfp) which contains the size of the component in all three dimensions. To analyze the entire process chains the extraction of raw materials as well as the corresponding production of the semi-finished-parts must be taken into account. Also transport routes and storage times must be included in the evaluation of sustainability.

After that the actual cutting process of the semi-finished-part occurs. In addition, beside of the starting material also a CAD model hast to be present. The components pass a further (optionally) post-process step, in which surfaces are adjust.
Furthermore the recycling of excess material has to be taken into account. Beside of the storage the excess material has to be transported to the smelting operation in which the material residues are separated in aluminum and salt slag. The created aluminum is recycled for the semi-finish-part production; the salt slag is disposed of. A schematic illustration of this process chain is depicted in Figure 2.

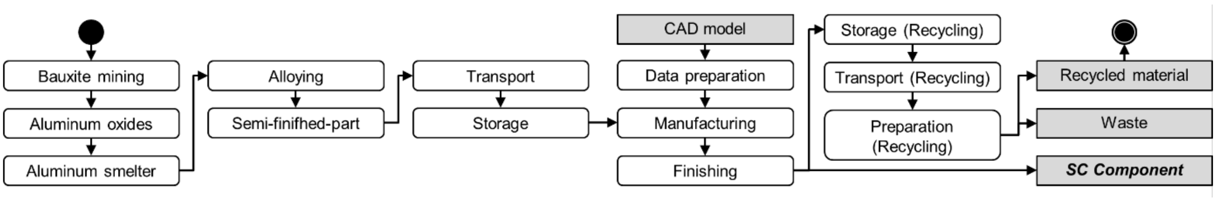

Figure 2. Process chain of a shape cutting component

3.2 Process chain: Additive manufacturing (AM)

At the beginning the additive manufacturing process chain is similar to the one of the shape cutting process. However, this process chain has significant differences. Because of the additive layer structure a semi-finished-part is not necessary. Instead, aluminum powder is made from the alloy which is transported to its destination and is stored there.
Then the additive processing of the metal powder takes place. This process has significant differences compared to the shape cutting because shaping tools are not necessary. After the laser has fused the various layers to a component, excess powder and support structures are removed in a following processing step.

Finally the sintered component is reworked. First the component is cleaned by a sandblasting process. After that a post-processing step is carried out by the adjustment of functional areas and surface properties. A schematic illustration of the additive manufacturing process chain is shown in Figure 3.

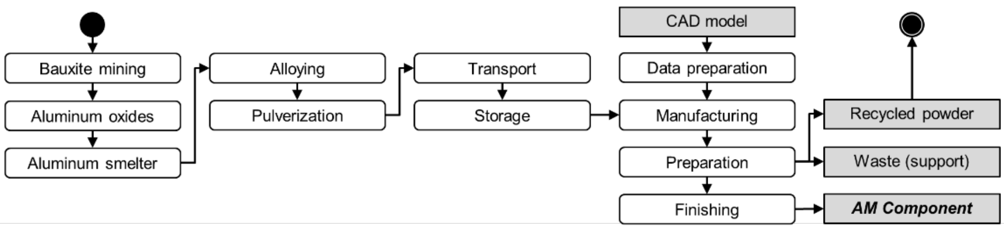

Figure 3. Process chain of an additive manufacturing component

3.3 Comparison of the process chains

To simplify the evaluation similar working packages are identified which are irrelevant for the comparison. These steps can be neglected in the evaluation. An essential similarity is the provision and preparation of the CAD data: In the shape cutting process geometrically complex components are produced by using modern CAD/ CAM systems. During the additive manufacturing mathematical algorithms slice the component in several layers, which are transferred to the machine.

After the elimination of similar work packages the customized process chains can be structured in five generalized process sections ($Pa_{ij}\ with\ j = 1, 2, 3, 4, 5$). Regardless of the process a raw material extraction (Pa_{i1} = Rme) and subsequent preparation (Pa_{i2} = Rmp), in which the starting material is produced, can be identified. Furthermore, logistics steps (Pa_{i3} = L) are available in both process chains. Finally the actual production (Pa_{i4} = P) leads in the recycling of excess material (Pa_{i5} = Wr).

Figure 4 shows an overview of the comparison of the both process chains by consider the reduction of identical aspects.

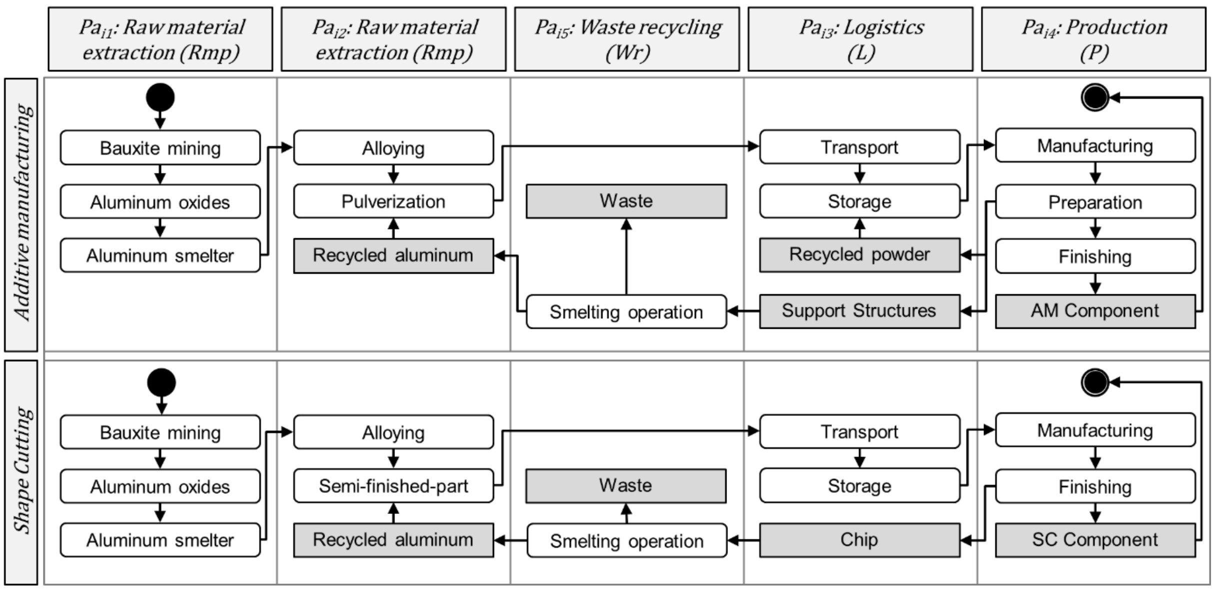

Figure 4. Comparison between the additive manufacturing and shape cutting process chains

For the overall rating the process sections (Pa_{ij}) are weighted. Therefor the energy consumptions of the process sections are considered. Thereby the problem is that the units of the individual sections are different to each other. As an example, the raw material extraction can be related to a weight unit, the production section to a time unit. Therefore, the units must be neutralized for the evaluation of sustainability. So the actual consumptions are converted into CO_2 emissions.

3.3.1 Raw material extraction (Rme)

The process of the raw material extraction (Rme) is the same for both process chains. In an igneous electrolysis the bauxite is converted by the "Bayer process" in aluminum oxide (chemical symbol: Al_2O_3) and further waste products. For the production of primary aluminum, the Al_2O_3 is deposited in an electrolytic cell and poured into aluminum ingots. In this preparation, mostly thermal energy and electric energy are required (Ostermann, 2007). On average, about 15.700 kWh are necessary to obtain 1 ton of pure aluminum (World aluminium, 2014). The consumption value of one kWh, produced by electrical energy, can be converted in the CO_2 emission by using the converting factor $u_r = 0.55$.

Because the extraction of raw materials is the same for both process chains, the qf value is also identical. For the extraction of raw materials 8.635 kg CO_2 is produced, based on 1 ton of produced aluminum.

$$qf_{11} = qf_{21} = 15.700\ kWh * ur = 15.700\ kWh * 0.55 = 8.635\ kg \quad (2)$$

3.3.2 *Raw material preparation (Rmp)*

The first step in the raw material preparation (Rmp) is the alloying. The aluminum ingots are melted and mixed up with other metals, which depend on the intended use (Weißbach, 2012). As well as the raw material extraction this step is the same for both process chains. However, the further processing of the molten alloy has significant differences.
For additive manufacturing the aluminum must be pulverized. Therefore the powder is needed in a scale of less than 50 µm. In principle, the liquid alloy can be divided into droplets by using flowing compressed gases and liquids, mechanically moving parts or by the influence of ultrasound. With the help of additional coolant, forming particles solidify immediately (Ostermann, 2007). For the production of aluminum powder, the alloy is pulverized by air atomization in 99% of all cases at which water is used as the cooling medium (Schatt et al., 2007). On average 1.570 kWh must be applied to pulverized 1 ton of aluminum powder. (For powder manufacture an energy requirement of about 10% of the required energy for alloying is assumed) The CO_2 emission results as follows.

$$qf_{12} = 1.570\ kWh * ur = 1.570\ kWh * 0.55 = 864\ kg \tag{3}$$

This additional process step is not necessary for the production of a semi-finished-part in the shape cutting process chain. The liquid alloy is cast in the shell of the semi-finished-part in which the metal hardens. This process requires about 785 kWh per ton. (The energy is set at 5% of the required energy for alloying) By using the converting factor u_r, the qf factor can be calculated as follows.

$$qf_{22} = 785\ kWh * ur = 785\ kWh * 0.55 = 431\ kg \tag{4}$$

3.3.3 *Logistics (L)*

Afterwards some logistic (L) steps are necessary. By using trucks the starting materials (powder or semi-finished-part) are transported to the processing plants. Assuming an average transportation distance l = 1.000 km 1 ton of loading generated about 200 kg of CO_2. (Dekra, 2014)
After arriving at their destination, the materials have to be stored. In general 1 m³ of required space in a warehouse can be calculated with about 140 kWh. (Ages, 2007) Counting the volume of material in a mass order, the following relationship can be represented:

$$\mathrm{m} = V * \rho = 1.000\ dm^3 * 2.76 \frac{kg}{dm^3} = 2.760\ kg \tag{5}$$

The energy consumption of 140 kWh spreads over 2.7 tones, so that 1 ton requires about 52 kWh. Admittedly, the storage conditions of the two processes are different and must be considered accordingly. For the storage of the semi-finished-parts (shape cutting) no special requirements are necessary. In contrast, the regulations for the storage of metal powders, especially of aluminum powder, are executed quietly comprehensive. The powder particles must be protected for moisture, so that the powder does not clump and becomes unfit for use. Also special containers and storage instructions are necessary because the aluminum powder is highly flammable and the danger of explosions must be prevented. The different required energy of both processes can only be estimated. It is assumed that the sustainability of the storage of a semi-finished-part requires about 20% of the storage of powder.

$$qf_{13} = 200\ kg + 52\ kWh * 0{,}55 = 229\ kg \tag{6}$$

$$qf_{23} = 200\ kg + 10\ kWh * 0{,}55 = 205\ kg \tag{7}$$

3.3.4 *Production (P)*

The production (P) is quite different in the both process chains. For the additive manufacturing the stored powder is filled into the machine. After a preheating phase of the process chamber thin layers of powder are melted with a laser. Because of the tool less layer structure a (near-) net-shape component is generated. Special support structures are used for the stabilization of the component in the process chamber. These structures also serve for heat conduction in order to minimize stress effects in the component. The process time and energy requirements depend on the component height and its volume. The complexity of the geometry affects this parameter only marginal. (Gebhardt, 2008) The sinter process requires about 3,2 kWh (Exemplary machine: EOS M280). (Eos, 2014)
Subsequently, the component is removed from the process chamber and freed from excess powder. Especially undercuts and cavities have to be cleaned. After that, the support structures are removed

from the crudely purified component. For the preparation of the future application, the component passes a finishing step. To remove small imperfections and residues of the support structure, the entire component is sand-blasted. This produces a rough shape which is selectively reworked. Function and contact surfaces are reground and polished depending on the component requirement. The finishing process of additive manufactured part is about 0,5 kWh, so that the CO2 emissions can be calculated as follows.

$$qf_{14} = 3{,}2\ kWh * 0{,}55 + 0{,}5\ kWh * 0{,}55 = 2\ kg \tag{8}$$

For the shape cutting process chain the semi-finished-part is adapted to the dimensions of the actual component. By sawing off a strand material, a cuboid can be formed. Afterwards the prefabricated semi-finished-part is clamped to a CNC 5-axis milling machine where the component is machined. In addition, the component must be re-clamped and adjusted in order to produce the complex geometry. To satisfy the future application, the reflector inside is polished at the final finishing step.

The production step has an energy requirement of about 2,3 kWh (Exemplary machine: imes-icore premium 4030µ), as well as the pretreatment and finishing step in total about 0,8 kWh. (Imes-icore, 2014) Again the CO2 emissions can be calculated as follows.

$$qf_{24} = 2{,}3\ kWh * 0{,}55 + 0{,}8\ kWh * 0{,}55 = 1{,}8\ kg \tag{9}$$

3.3.5 Waste recycling (Wr)

The last process section is the waste recycling (Wr). As in the case of raw material extraction this step is identical in both processes. In a melting process, the excess aluminum alloy is melted and separated in recycled aluminum and other wastes. The energy requirement can be assumed to be approximately 5% of the energy input from resource extraction. (Schäfer, 2008)

$$qf_{15} = qf_{25} = (15.700\ kWh * 5\%) * 0{,}55 = 431\ kg \tag{10}$$

After the CO_2 emissions from each process section are identified, the Pa_{ij} titles and qf_{ij} values can be inserted into the generalized formula.

$$Nw_1 = Rme_1 * 8.635\ kg + Rmp_1 * 864\ kg + L_1 * 229\ kg + P_1 * 2\ kg + Wr_1 * 431\ kg \tag{11}$$

$$Nw_2 = Rme_1 * 8.635\ kg + Rmp_2 * 431\ kg + L_2 * 205\ kg + P_2 * 1{,}8\ kg + Wr_2 * 431\ kg \tag{12}$$

4 CALCULATION WITH A DEMONSTRATOR

Especially the component sizes and weights as well as processing times have an impact for the use of material, so that the evaluation is detailed by using a demonstrator. The used criteria are derived from the initially given definition. Thus, the minimization of the resource use and their possible regeneration are sought. In addition, a low environmental pollution or degradation acts positively on the sustainability of the process chains.

Due to the defined surfaces of the component inside, the tolerances of connecting dimensions and the shape accuracy a reflector of an automotive application is well suited as a demonstrator (depicted in figure 5). The reflector has to be produced with the aluminum alloy AlSi10Mg.

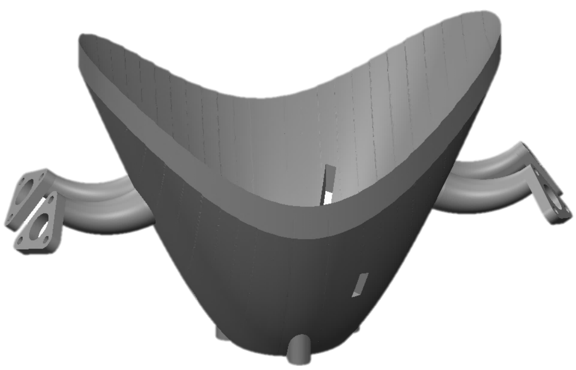

Figure 5. CAD model of the reflector form an automotive application

4.1 Analyze the component properties

Several process sections are not practical for individual parts, thus the proportionate quantities are needed. For example only large amounts of aluminum ingots are produced in the raw material extraction. So the amount of material must be prorated. Because the CO_2 emissions refer to 1 ton, also the required material must refer to the same quantity. Therewith a percentage factor can be calculated which represents how many parts can be produced with an identical amount of raw material. This factor is required for the extraction and preparation of raw materials as well as for logistic steps.
Thus for additive manufacturing the quantity of the molten material is required. Including the support structures this status of the component has a weight of Am_{ub} = 52 g for the reflector (depicted in figure 6)

For the shape cutting process chain a semi-finished-part is necessary which includes the dimensions of the actual component. For the demonstrator a cuboid with the dimensions 110 mm * 70 mm * 55 mm (b*h*t) is needed (Maximum dimensions: 105 mm * 68 mm * 52 mm). With a density of 2,76 kg/dm³ the weight of the starting material is Sc_{ub}= 1.169 g. Relating of the material quantities to the reference value of 1 ton, the percentage factor results. The presented values show that for the considered demonstrator in shape cutting process about a 22 times higher use of material is necessary.

$$Rme_1 = Rmp_1 = L_1 = \frac{0{,}052\ kg}{1.000\ kg} = 0{,}000052 \tag{13}$$

$$Rme_2 = Rmp_2 = L_2 = \frac{1{,}169\ kg}{1.000\ kg} = 0{,}001169 \tag{14}$$

For the actual production of the demonstrator the processing time is relevant. This is due to the use of machinery and its consumption. To determine a percentage factor the process time must refer to 1 hour, similar to the production value qf_{i4}. Here the hourly rates from the example machines where used.

$$P_1 = \frac{8{,}5h}{1\ h} = 8{,}5 \tag{15}$$

$$P_2 = \frac{5\ h}{1\ h} = 5 \tag{16}$$

Figure 6 depicts the unprocessed reflector (left) and the finished reflector (middle) produced by the additive manufacturing as well as the finished reflector produced by shape cutting (right). The reflector finished in additive manufacturing has a weight of $Am_b = 44\ g$; the reflector finished in shape cutting has a weight of $Sc_b = 40\ g$.

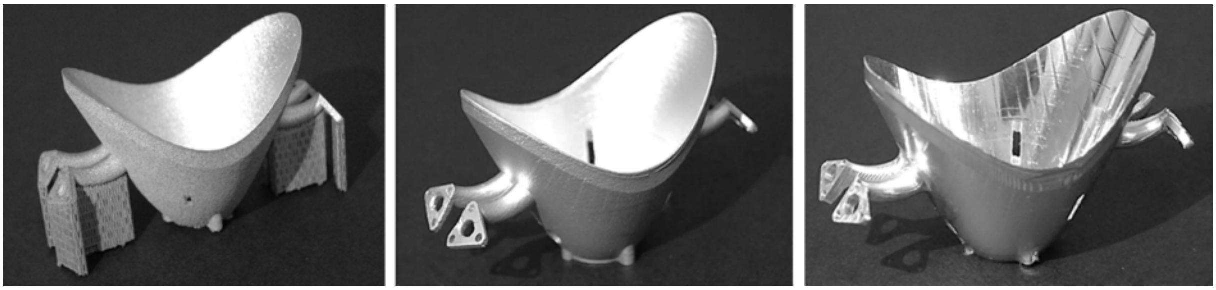

Figure 6. Reflector in additive manufacturing process chain after production (left) and finishing (middle) as well as after finishing in shape cutting (right)

For additive manufacturing excess material can be reuse directly to the material storage. Here, the powder is merely passed through a sieve into the container. Transport routes do not take place. Furthermore, also the removed support structures are collected centrally for reuse. For the demonstrator, the weight of the excess material is calculated by the subtraction of material usage and component weight. This value can also be related to the comparison weight of 1 ton.

$$Wr_1 = \frac{Am_{ub} - Am_b}{1.000\ kg} = \frac{0{,}052\ kg - 0{,}044\ kg}{1.000\ kg} = 0{,}000008 \tag{17}$$

The situation is different at the shape cutting process chain. Here the entire excess material, in form of aluminum chip, is collected centrally. This cannot be recirculated directly into the material cycle. The subtraction of the weight of the starting material from the component weight delivers the weight of the removed chips.

$$Wr_2 = \frac{Sc_{ub} - Sc_b}{1.000\ kg} = \frac{1{,}169\ kg - 0{,}040\ kg}{1.000\ kg} = 0{,}001129 \tag{18}$$

The fact that the excess material in the shape cutting process chain is higher by a factor of about 140 shows that the available resources are used more efficiently in the additive manufacturing. For the excess material of the shape cutting component about 140 additive manufacturing components can be recycled. According to the definition mentioned at the outset, the regeneration of the environment has a significant influence on the determination of sustainability. Similarly, the (energy) consumption affects this authoritative.

4.2 Comparison

Both the evaluation of the process sections Pa_{ij} as well as the weighting-factors qf_{ij} can now be used in the formula established in chapter 3.3. Nw_1 is the sustainability of the additive manufacturing process chain, Nw_2 is the sustainability of the shape cutting process chain.

$$Nw_1 = 0{,}000052 * (8.635\ kg + 864\ kg + 229\ kg) + 8{,}5 * 2\ kg + 0{,}000008 * 431\ kg \tag{19}$$

$$Nw_2 = 0{,}001169 * (8.635\ kg + 431\ kg + 205\ kg) + 5 * 1{,}8\ kg + 0{,}001129 * 431\ kg \tag{20}$$

The values $Nw_1 = 17{,}5\ kg$ and $Nw_2 = 20{,}3\ kg$ has just a marginally difference. The division of both sustainability values results in the degree of the difference.

$$\mathrm{N} = \frac{Nw_1}{Nw_2} = \frac{17{,}5}{20{,}3} = 0.86 \tag{21}$$

The determined value is not an absolute classification of the technology. It indicates a relative dependence. Because that the sustainability value N indicates a tendency less than 1 the sustainability of the additive manufacturing can compete with existing technologies referring to the shown demonstrator. Especially the high material utilization and the redundant tools ensure a highly efficient process.

However, it should be noted that in the evaluation some subjective factors cannot be taken into account. For example, there is an impact of the human health if you inhale some aluminum powder. Such a value cannot be clearly measured in figures. Also wear values can only be formulated vague. Therefore the sustainability value is difficult to define and requires a broader view in general.

5 CONCLUSION

The current trend shows that the use of materials in product development is progressively reduced. Because of scarce resources more parts has to be made at constant use of materials by producing filigree component structures. For this purpose, additive manufacturing exploit its potential optimal. This possibility for an efficient material utilization enables new production systems by decentralizing the production process.

However, the advantage of the good material utilization is particularly true for geometrical high complex or individualized components which have a large excess of material in shape cutting process. For example, if a shaft is taken into account the sustainability of the two processes is completely different. For the case that the starting material of the shaft has a length of $l = 200\ mm$ with a diameter of $\emptyset = 40\ mm$ and it is produced with 2 shaft shoulders, the sustainability value results in $N = 1.86$. This shows that the sustainability of the shape cutting process is much better for this component. Therefore changed time ratios and material conditions are the reason. Admittedly, when considering highly complex components, the additive manufacturing technology is compared very well.

Furthermore the study does not take lot size effects into account. By the observance of the product quantity, synergies for mass production occur as well as a better process utilization for additive manufacturing.
By placing several parts in the proceeding space in an additive manufacturing machine, the energy consumption does not grow proportionally. Calculated on a component, the CO_2 emissions will be reduced further. This relationship requires a further investigation.

However, the continuously progressing development of additive manufacturing allows an increasingly higher material utilization with better surface qualities. For an improved sustainability, the geometric challenges need to be mastered in the additive manufacturing process. The shape optimization enables consequently higher material utilization and better surface quality, which promotes the sustainability of this process.
Therefore, it is planned to analyze design guidelines in additive manufactured aluminum components and realize its potential as good as possible. By using a demonstrator geometry aspects are analyzed and the influence of different parameters on the quality of the component is investigated. Through the parameter variation a better process flow should be identified. Thus, sustainability can be improved.

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