



## Methodology for Cost Estimation using Characteristic Factors in Additive Manufacturing

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### Abstract

The cost of additive manufacturing (AM) processes is today typically higher than traditional manufacturing processes such as casting or machining for series production, particularly of medium and large batches. A fair comparison is often complex, since the true costs of the AM part become only visible after leveraging the design freedom through a Design-for-AM (DfAM) process. Thus, for the analysis of the manufacturing costs of additively manufactured parts versus conventional production methods a simplified cost estimation model based on component volume is introduced. Considering at first the same volume as in the conventional part design, the price for the component using powder bed fusion and sinter-based AM methods is approximated. The resulting, typically higher costs are then transduced into a weight saving requirement for matching the costs of the conventional process. Finally, this requirement is assessed against the typical weight saving potentials of each technology to predict the economic feasibility.

**Keywords:** Additive Manufacturing (AM), Cost Estimation, Sinter-based AM, Laser Powder Bed Fusion (PBF-LB/M), Methodology.

### Introduction

In recent years, the production of components has been revolutionized by the additive manufacturing (AM) <sup>1</sup> for a variety of reasons. Particularly to the possibility of realizing more complex geometries with significantly increased mechanical properties <sup>2</sup> and which cannot be produced subtractively, the efficient use of resources with reduced material losses is one of the greatest advantages <sup>3</sup>.

Investment in companies is increasingly relying on AM, but the number of increases is nothing compared to conventional methods. However, the potential long-term benefits of investing in AM technologies far outweigh the limited number of current increases. AM offers a range of advantages such as cost-effectiveness, customization, and rapid prototyping, which can revolutionize various industries and lead to significant returns on investment in the future. According to <sup>4</sup> the key factors for AM production transfer are the design particularly lightweight construction approaches e.g. as discussed in <sup>5</sup> and <sup>6</sup>, which is not manufacturable conventionally, the geometric complexity where ribs or undercuts may appear, the organization management such as the staff has to be trained in AM, the sustainability e.g. the decentralized manufacturing, the supply chain such as packaging and the production e.g. the machine costs for the conversion. There are different reasons for the stagnation in growth compared to the traditional manufacturing: costs for conventional production are cheaper, reluctance to change a functioning product that has a demand in the market and the redesign is not assessable in terms of effort in preparing the part for future challenges to name a few. Not to mention the lack of know-how of the new process chain and the supply chain of the component which can be further hurdles. Different approaches exist for identifying potential AM applications but the obstacles are very complicated and require an experienced AM user <sup>4</sup>. One machine learning (ML) approach for an automated part screening of an AM design has been developed to evaluate the potential design in the AM application. However, the hurdle of the ML application lies in the small and non-uniform data set meaning that the model is limited in its potential evaluation <sup>4</sup>. Another approach is the 'design 2 cost' methodology which analyzes the computer-aided design (CAD) model of a part, transfers the geometry into an octree representation and calculates the model complexity as well as the fabrication costs <sup>7</sup>. This tool evaluates the costs and complexity of a part for laser metal deposition, selective laser melting, wire-arc additive manufacturing and milling based on the criteria wall spacing, hardness, overhangs, tortuosity and maximum dimensions. However, the number of units and other processes are not taken into account. The criteria also need to be expanded for a more precise cost analysis <sup>7</sup>.

Current approaches show how difficult and problematic it is to systematically identify the appropriate manufacturing process for a component. Different criteria are defined with various values, which in return are dependent on other criteria. Creating a standardized tool that is universally applicable requires a high degree of abstraction. The applications are also not always freely accessible, so that any interest always requires the exchange of contact details and possibly also assistance in using the tool. For this reason, a methodical approach is chosen that estimates the production costs based on the component dimensions and the component volume, regardless of the component complexity, and outputs them easily and clearly understandable in relation to the conventional manufacturing process. In this paper, the design is indirectly taken into account by specifying the necessary weight reduction as a characteristic factor in order to achieve cost savings. Based on the simplified data, the approach can be used as a very good initial estimate. Using different machines to get an orientation a modular and tailored application is developed to have a relation to the conventional manufacturing process.

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### Methodical Approach

The methodology aims to evaluate components specifically for additive manufacturing, using a metric-based cost estimation derived from readily obtainable CAD data, production volume, and material choice. This approach compares the cost-effectiveness of additive manufacturing techniques such as the material extrusion of metals (MEX/M)<sup>1)</sup>, the laser powder bed fusion of metals (PBF-LB/M)<sup>1)</sup>, the binderjetting of metals (BJT/M)<sup>1)</sup> and the metal injection molding (MIM) against traditional manufacturing methods, such as milling or casting, calculating necessary material savings to make additive processes viable. The provided graphic (figure 1) illustrates the schematic structure of the cost calculation, showing the relationship between material, machine, overhead, and post-processing costs leading to the total cost estimation. The total costs for manufacturing are calculated by summing up various cost positions:

- Material costs
- Machine costs
- Post-processing costs
- Overhead costs

The material costs are calculated based on the component volume, material density, material price, number of parts, and a factor dependent on the manufacturing process that accounts for shrinkage in the sintering process, where necessary. Machine costs are

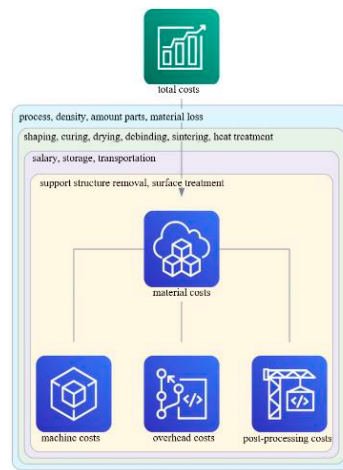


Figure 1: Methodology of the total costs and their impact factors.

calculated by considering the process steps shaping, curing, debinding, sintering, and post-heat treatment. The total machine costs ( $K_M$ ) are the sum of the costs for individual process steps, which are calculated as:

$$K_M = k_M * (t_p + n_{charge} * t_R) \quad (1)$$

The setup time  $t_R$  has a value that is determined for each machine. The number of batches  $n_{charge}$  is addressed in formula (3). The machine hourly rate  $k_M$  is derived from the acquisition costs  $A_M$  of the respective machine, the depreciation period  $t_d$  and the percentage annual utilization  $\alpha_i$  as follows:

$$k_M = \frac{A_M}{8.760 * t_d * \frac{\alpha_i}{100}} \quad (2)$$

The calculation of the process time  $t_p$  varies between the individual process steps. A fixed process time is defined for post-heat treatment, curing and the sintering process. This is a simplified approach. The actual process times depend on the component geometry and the material selection, as the different materials also require different heating temperatures for the different holding times and higher temperatures correlate with longer heating and longer cooling times. For shaping, the process time is calculated from the print volume, the batch size and the printing speed, which in turn depends on the choice of material and differs between the individual production processes. The number of batches  $n_{charge}$  is calculated from the number of units and the batch size  $X_{charge}$ . The size is rounded up to a whole number.

$$n_{charge} = \left\lceil \frac{n_B}{X_{charge,i}} \right\rceil \quad (3)$$

For the majority of the process steps, it is assumed that the components are not stacked. To determine the batch size  $X_{charge}$  for these process steps, the length  $l_B$  and the width  $b_B$  of a rectangle assumed around the base area of the component are added as further input variables. The batch size can thus be determined with a distance between the components  $x_B$ . Here,  $b_{Br}$  describes the width and  $l_{Br}$  the length of the installation space. This is a simplification due to the assumption of a square body.

$$X_{charge} = \left\lfloor \frac{b_{Br}}{b_B + x_B} \right\rfloor * \left\lfloor \frac{l_{Br}}{l_B + x_B} \right\rfloor \quad (4)$$

In the shaping process, the BJT/M process is an exception to this calculation. With this type of production, it is common for parts to be stacked. In order to map this, the height of the installation space is considered equivalent for the calculation of the batch size of the BJT/M process and as a further input variable.

All cost items whose significance has proven to be subordinate in the course of developing the calculation are included as a clearing rate for each asset. Costs that can be allocated to the individual cost unit are also included - these are therefore non-direct overheads. An upper and a lower limit for the costs per batch are defined for each asset. From this, a mean value and a range for the overhead costs are calculated. Overheads can be, for example, salaries, energy costs or storage and transportation costs that cannot be directly allocated to individual positions. For comparison with the costs of conventional production, the known total costs are used as a further input variable. This is used to calculate the difference to the costs of additive manufacturing. When calculating the material savings, only the cost items that scale with the mass are included. In addition to the material costs, these are the shaping costs and, for the MEX/M process, also the machine costs for debinding. This is used to calculate the minimum material savings required to achieve cost parity between additive and conventional manufacturing processes. To check whether the result is reasonable, it is presented as a percentage relative to the total weight. The result indicates the minimum percentage of weight that must be saved for additive manufacturing to become more cost-effective than the previous conventional manufacturing method. A result above 100 % means that cost parity cannot be achieved through material reduction. A negative result indicates that the additive manufacturing process is already cheaper without material reduction and also specifies how much heavier the workpiece can be. This information can be useful if a strength analysis reveals that a printed component does not meet the requirements.

## Results

The equations were implemented in Excel 2016 (Microsoft, Redmond, USA) into a cost application, which represents the total costs from the specific costs and furthermore determines the necessary weight reduction of the component to achieve cost parity as the main characteristic factor. The application is freely available as a download file in <sup>8)</sup> to follow the further explanations and allow reproducibility. Table 1 shows the assumed machines and costs for each process technology. All machine costs are based on requested quotations or invoices and the average of the communicated price range serve as a basis for comparison. The respective material costs are obtained from internet research and are assumed to be AISI 316L (1.4404) stainless steel. The material properties are available in <sup>5)</sup> and the ultimate tensile strength is assumed to be 510 MPa according to the data sheet in <sup>9)</sup>. Two system solutions were analyzed for the MEX/M and two for the PBF-LB/M process. One variant is the more expensive solution and one is the low-cost alternative. For the comparability of BJT/M and MIM technologies, the debinding and sintering steps are assumed to use the same equipment. The powder is also priced in the same way for all processes if possible.

**Table 1:** System configurations for the respective process technologies, including prices and material costs.

	Shaping	Curing / Drying	Debinding	Sintering	Heat Treatment	Material
<b>MEX/M (Markedforged)</b>	Metal X <sup>10)</sup> 99,500 €	-	Wash-1 <sup>10)</sup> 15,000 €	Sinter-2 <sup>10)</sup> 140,000 €	-	170 [€/kg] <sup>11)</sup>
<b>MEX/M (Aim3D)</b>	Renkforce RF2000V2 <sup>12)</sup> 9,041 €	-	Heating Plate 500 €	ExSO90 <sup>13)</sup> 17,490 €	-	280 [€/kg] <sup>9)</sup>
<b>BJT/M</b>	DM P2500 <sup>14)</sup> 600,000 €	TR60/LS <sup>15)</sup> 6,800 €	NA 120/45-1 <sup>16)</sup> 16,000 €	VHT 25/16-MO-1 <sup>17)</sup> 210,000 €	-	260 [€/kg] <sup>18), 20)</sup>
<b>MIM</b>	Arburg Allrounder 470S <sup>19)</sup> 160,000 € Mould 50.000 €	-	NA 120/45-1 <sup>16)</sup> 16,000 €	VHT 25/16-MO-1 <sup>17)</sup> 210,000 €	-	60 [€/kg] <sup>20)</sup>
<b>PBF-LB/M (SLM)</b>	SLM280 <sup>21)</sup> 450,000 €	-	-	-	NR 25/11 <sup>22)</sup> 49,500 €	60 [€/kg] <sup>20)</sup>
<b>PBF-LB/M (OCM)</b>	One Click Metal <sup>23)</sup> 97,800 €	-	-	-	NR 25/11 <sup>22)</sup> 49,500 €	60 [€/kg] <sup>20)</sup>

Figure 2 illustrates the toolbar functions of the cost application <sup>8)</sup>. This toolbar is divided into four areas: the input, the output, the post-processing factor and the selected machine configuration. The specific cost positions for the manufacturing processes MEX/M, PBF-LB/M, BJT/M and MIM can be determined by simply providing the information of eight parameters such as the component volume, the component dimensions, the material, the number of pieces and the post-processing factor in the input box (fig. 2 top left). The post-processing factor  $p_f$  (fig. 2 top middle) is divided into four factors 0 to 3. In the case of  $p_f = 0$  no post-processing effort of the component after manufacturing is necessary and the part can be used as built. If support structures are necessary for successful manufacture and need to be removed in the post-processing step, the factor  $p_f = 1$  has to be chosen. Factor  $p_f = 2$  should be selected if the part has at least one functional surface area (e.g. bearing seat) which has to be finished. Finally, the factor  $p_f = 3$  should be used if there are several functional surfaces that are tolerated with respect to each other. The given examples serve as an estimation aid to help classify the post-processing effort of the respective part. The provided data allow a direct comparison of the costs for each process technology without the necessity of the equations calculation. Fig. 2 (top right) show the selected machines for each technology according to table 1. It is possible to adapt the material costs and the machines for each technology. Furthermore, it is also possible to add new machines for each technology to compare individually the different machine and material combinations.

Additionally, fig. 2 shows an input example for a component with a volume of 25 cm<sup>3</sup>, length 41 mm, width 74 mm, height 75 mm, the material 316L (1.4404), the quantity of 25 pieces, the post-processing factor of  $p_f = 2$  and the conventional total costs of 3,960 €.

Input:			Post-Processing Factor			Machines				
Volume	cm <sup>3</sup>	25	0	No post-processing necessary		Shaping	MEX/M	PBF-LB/M	BJT/M	MIM
Length	mm	41	1	Low post-processing effort			Metal X	SLM280	DM P2500	Arburg Allrounder 470 S
Width	mm	74	2	Medium post-processing effort					TR60/LS	
Height	mm	75	3	Large post-processing effort			Markforged Wash-1		NA 120/45	NA 120/45
Material	-	316L					Markforged - Sinter-2		VHT 25/16-MO	VHT 25/16-MO
Quantity	-	25				Heat treatment		NR 25/11		
Post-Processing Factor	-	2								
Conventional costs	€	3960								

	Output:			
	MEX/M	PBF-LB/M	BJT/M	MIM
Shaping	€ 90	1035	-	50031
Curing/Drying	€ -	-	-	-
Debinding	€ 13	-	-	8
Sintering	€ 198	-	-	149
Heat treatment	€ -	55	-	-
Material costs	€ 2503	380	-	293
Overheads	€ 185 ± 20	98 ± 8	- ± -	85 ± 10
Post-processing costs	€ 1188 ± 813	1188 ± 813	- ± -	1188 ± 813
Total costs	€ 4177 ± 833	2756 ± 820	- ± -	51753 ± 823
Unit costs	€ 167 ± 33	110 ± 33	- ± -	2070 ± 33
Necessary weight saving	% 9	-93	-	16317
Comments	- Process possibly suitable	Process possibly suitable	Build space collision	Process unsuitable

Figure 2: Main operating environment of the cost application with the input parameters and output values <sup>8)</sup>.

For the assumed component characteristics, the MEX/M technology total costs are estimated at 4,177 € and consist of 90 € for the shaping step, 13 € for the debinding step, 198 € for the sintering, as well as 2,503 € in material costs, 185 € in overheads and 1,188 € in post-processing costs. The row ‘unit costs’ in € shows the total costs for a single part. The ‘necessary weight saving’ row illustrates the required weight reduction to achieve cost parity with conventional manufactured reference. In this case, for the MEX/M technology a weight saving of 9 % is required to achieve the same manufacturing costs as the conventional method. The comment section indicates a rough assessment of the entered parameters for the respective process technology. An estimation is made wherever the process is ‘possibly suitable’ or ‘unsuitable’ with respect to the entered parameters. Furthermore, an indication of ‘Material  $\frac{z}{z}$ ’ will appear if the material is not available or not deposited for the specific manufacturing technology. Finally, the comment ‘build space collision’ identifies if manufacturing restrictions have been exceeded i.e. the component dimensions are too high and cannot be manufactured. In this example, this is the case for the BJT/M technology and no cost estimations are deployed. The PBF-LB/M process technology requires total costs of 2,756 € for 25 pieces of the part, which is 110 € per unit. Since this technology has no curing/drying, debinding or sintering step no cost values will appear for these rows. As the overall costs of approximately 2,756 € are lower than the 3,960 € for the conventional manufacturing, the necessary weight saving is negative at -93 %. This means that the component can actually become 93% heavier, i.e. increase in component volume, with the aim that the conventional manufacturing costs become equal to the manufacturing costs in the PBF-LB/M process. For the MIM technology, the costs are 51,753 €, which is more expensive than the conventional costs, and a weight reduction of 16,317 % of the component is unrealistic.

**Discussion**

To validate the cost tool, a component is selected for which the conventional costs and general operating conditions are known. The steering gear bracket is a 3-axis milled part that is used in the Formula Student racing car at Hamburg University of Technology. Figure 3 illustrates the steering gear bracket and the dimensions of the component. The material AISI 316L (1.4404) is assumed for the investigations. Two different orientation scenarios were examined to determine the costs. Here, the component is produced upright and horizontally. The post-processing effort must be set at a factor of  $p_f = 2$  as support structures have to be removed and there is a functional surface which has to be toleranced. Fig.3 (a.) displays the validation specimen in horizontal direction, (b.) shows the input data, while ‘X’ is a variable because the costs are directly dependent on the quantity that has to be manufactured. Fig. 3 (c.) illustrates the upright manufacturing direction. For the horizontal direction, the width and the height swap their positions. According to the manufacturer, the manufacturing costs with conventional methods for one part, regardless of the manufacturing orientation, are 1,440 €. Fig. 4 displays the total costs in € depending on the manufacturing quantity for the horizontal manufacturing orientation, comparing two different set-ups for MEX/M (based on a Markedforged and Aim3D printer and sintering oven), two different suppliers

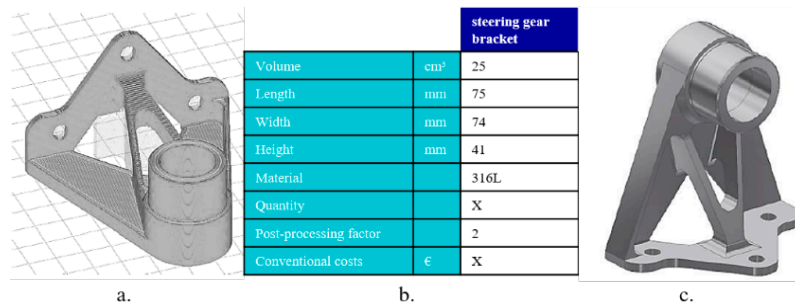
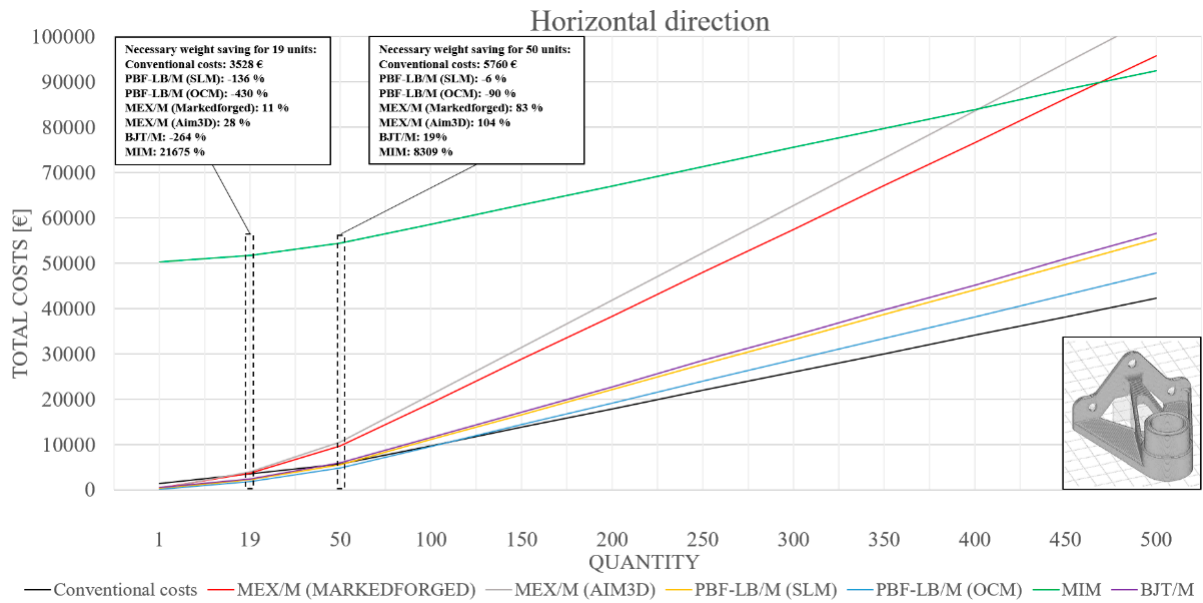


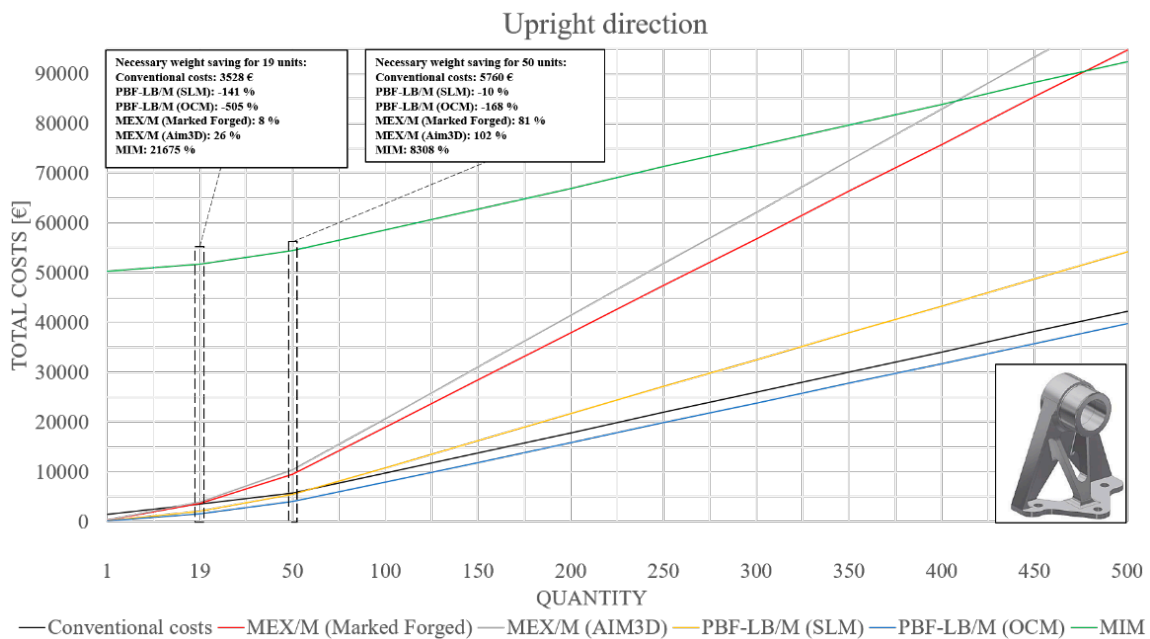
Figure 3: a. Steering gear bracket horizontal orientation, b. Component information, c. Steering gear bracket upright direction.

for the powder bed fusion technology (SLM and OCM) and one binder jetting technology, alongside metal injection molding and the conventional manufacturing process. Since the post-process costs are based on factors, they are assumed to be in a similar range for all technologies in dependency of the manufacturing quantity. The production costs for one part is in the range of 181 € to 494 € for the MEX/M and PBF-LB/M additive manufacturing technologies while the costs of sinter-based technologies are overall higher than the laser-based technologies. This discrepancy is due to the higher material costs and additional process steps that are required for the production. Even low-cost machine systems such as MEX/M (Aim3D) are more expensive for a component at 256 € than the more expensive system PBF-LB/M (SLM) at 239 €. The binder jetting technology is the most expensive additive manufacturing technology for one part with 494 €. The reason for the high costs are the additional curing process step and therefore higher overhead costs. Due to the assumed injection mold costs of 50,000 €, the production costs for a component using MIM technology are highest at 50,307 €. It can be easily recognized that up to 10 parts the total manufacturing costs are lower for all additive manufacturing technologies compared to the conventional manufacturing costs, which are 2,880 €. Also, the MIM technology is with over 51,044 € the most expensive technology for a quantity of 10 pieces again due to the assumed high mold development costs. A conventional production of 19 components costs 3,528 €. There are alternative processes such as PBF-LB/M (OCM and SLM), Binder Jetting, and MEX/M (Markedforged) that are more cost-effective and therefore show a negative necessary weight saving of the component. Among them, only the additive manufacturing technology MEX/M (Aim3D) costs more at 4,019 €. Cost parity can only be achieved by reducing the weight of the components by 28 %. It is evident that material costs are much greater than equipment costs in this case, so even with 19 parts, the production technology is inefficient compared to conventional manufacturing, and a redesign of the component is necessary to make the manufacturing more profitable. The MIM technology is also here the most expensive technology and the needed weight reduction of 21,625 % is impossible to achieve. For a volume of 50 components, the costs for production using MIM technology are 54,437 €, which are 48,677 € more expensive than the production using the conventional technique. The second highest manufacturing costs for 50 pieces are 10,497 € produced with the MEX/M (Aim3D) technology followed by the other MEX/M (Markedforged) setup with approximately 8.100 €. In both the variants of the technology the material costs are the most expensive positions. A weight reduction of 104 % (MEX/M (Aim3D)) is impossible, and also a reduction of 83 % (MEX/M (Markedforged)) is hard to achieve while ensuring the necessary material characteristics for the application. The BJT/M process is for 50 parts slightly more expensive, with 5,970 € compared to the 5,760 €. In this case, only 19 % weight reduction is required to achieve a cost parity. It is interesting to observe that the powder bed fusion process (OCM) is the cheapest technology for the production of 50 components. The costs are with 4,843 € lower compared to the PBF-LB/M (SLM) process at 5,609 €. To summarize, it can be assumed that suitable part quantities for the material extrusion technologies are in the range from 1 to 35 pieces for MEX/M (Markedforged) and approx. 19 pieces for MEX/M (Aim3D). In the case of 35 parts, the necessary weight reduction for the MEX/M (Markedforged) process to achieve cost parity is 35 %. The cheapest PBF-LB/M machine configuration has lower manufacturing costs even for 100 parts at 9,597 € with respect to the costs at 9,760 € for the conventional manufacturing process. Additionally, the PBF-LB/M (SLM) technology requires 11,131 € for the manufacture of 100 units and needs only 26 % of weight reduction for cost parity. It is surprising that the BJT/M process chain for this specific component is only profitable for a manufacturing quantity of 48 units, where no weight reduction is needed. Higher quantities require a reduction in weight and make the process for this component and alignment uneconomical. The MIM technology is the most expensive process up to 400 components. Changing the build direction of the same part has an immense impact on the production time of several additive manufacturing technologies and as a consequence also on the manufacturing costs. Fig. 5 illustrates the total costs in € depending on the component quantity for the upright build direction. It can be observed that no costs are available for the the BJT/M sinter-based process technology because the component height exceeds the construction space for the green part manufacture of the selected machine. It is obvious that the sinter-based and laser-based additive manufacturing technologies are less expensive than the conventional manufacturing technology as well as the MIM process. Considering the total manufacturing costs for 19 units a comparable situation to the horizontal manufacturing direction can be recognized. The MEX/M (Aim3D) process is again the most expensive AM technology. The different build orientation has less impact on the total costs due to the high material prices. Comparing both manufacturing orientations together, the necessary weight reduction for cost parity is 28 % in the horizontal orientation and 26 % in the upright direction, and only 2 % of necessary weight reduction could be saved due to a more suitable alignment. In contrast, the MEX/M (Markedforged) process chain could reduce the necessary weight saving by 8 % for the same quantity. Similar observations can be made additionally for the PBF-LB/M technology. The necessary weight reduction is decreased by 75 % (PBF-LB/M (OCM)) and 7 % (PBF-LB/M (SLM)). It is obvious that the changed orientation does not affect the costs of the MIM process chain. For 50 units, the total costs of each AM technology are reduced with respect to the changed direction. In this case, the PBF-LB/M process technologies are less expensive than the conventional method and also cheaper than in the horizontal direction. Again, the PBF-LB/M (OCM) is the cheapest manufacturing method for 50 parts. The MEX/M (Markedforged) technology is still more expensive for 50 components than the conventional manufacturing method, but by changing the orientation it is possible to reduce the required material savings from 83 % to 81 % to achieve cost parity.



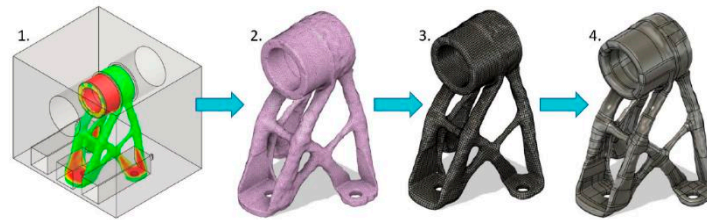
**Figure 4:** Component costs as a function of the number of pieces for the steering gear tab in the horizontal orientation for the considered process technologies conventional, MEX/M, PBF-LB/M, BJT/M and MIM compiled from <sup>8)</sup>.

For 100 components, MIM technology once again offers the most expensive process. In conclusion, it can be stated that the component orientation has a significant influence on the investigated processes in terms of low material costs, and that the upright orientation is more economical for the application and should therefore be preferred. The findings of the suitable processes based on the number of pieces also align with <sup>24)</sup>, where the suitable technologies were classified according to component complexity and the number of pieces. The MEX/M process is therefore suitable for less complex components and for quantities of up to 50 parts, as is the case in the application example for MEX/M (Markedforged) (see fig. 4 and fig. 5). The MIM technology is well suited for large quantities of 10,000 or more components and for medium to high component complexity. This tendency can also be observed in the validation component independent of the orientation. For the PBF-LB/M process, highly complex components with a quantity of 1,000 parts are cost-effective manufacturable (compare fig. 4 and fig. 5), and the BJT/M technology is suitable for medium to highly complex components in the range of 10 to 10,000 parts according to <sup>24)</sup>. This observation could not be recognized due to the high assumed material and machine costs in table 1. For the validation of the cost tool, the investigated steering gear bracket was uploaded to an online marketplace for 3D printing manufacturing services as per <sup>25)</sup>. The manufacturing costs for 500 parts are with approx. 180 € per unit in the range of the cost prediction for the PBF-LB/M (SLM) process and meet the prediction with the PBF-LB/M (OCM) process regardless of the orientation.



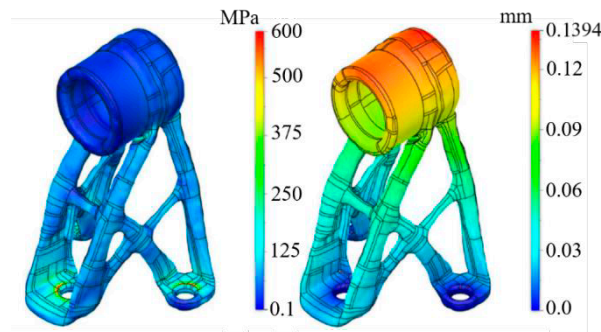
**Figure 5:** Component costs as a function of the number of pieces for the steering gear tab in the upright orientation for the considered process technologies conventional, MEX/M, PBF-LB/M, BJT/M and MIM compiled from <sup>8)</sup>.

Several ways exist to achieve a weight reduction of a component. Changing the material could be one possibility while ensuring the required mechanical and material properties. However, a different material usage can, in the worst case, lead to higher total costs due to increased material prices. Another way to achieve a reduction in weight is to redesign the component. For the MEX/M (Aim3D) process, the weight reduction in the upright direction of 19 component has to be 26 % to be competitive in terms of costs. A design space for topology optimization of the steering gear bracket has been generated. It should be mentioned that the design space is larger than the original conventional part design to achieve a great solution space for the optimization. In topology optimization the density-based Solid Isotropic Material with Penalization (SIMP) approach is implemented and Autodesk Fusion 360 (Autodesk Inc., San Rafael, USA) is utilized. The optimization results are transformed into a volume body. Fig. 6 displays the four step transformation, where in step one the net body as an optimization result is taken and smoothed to avoid sharp edges and thus, to prevent potential stress peaks. The smoothed mesh was then converted with hexahedron elements into a mesh body (3.) using Autodesk Re Cap Photo software (Autodesk Inc., San Rafael, USA) after the grid errors were removed. Applying a T-spline interpolation, the mesh is converted in the last step into a volume body, and the contact surfaces are remodeled (4.).



**Figure 6:** Four step transformation of the topology optimized result into a volume body.

A strength test was performed with Autodesk Fusion 360 and is illustrated in fig. 7. The assumed load on the bolted connection is 2,000 N. The optimization results in the component volume showing stress peaks at the through-bolted connections. These stresses do not occur in reality, as this is an error caused by a simplification of the clamping situation. The analysis of the areas around the hole located under the washer and on the chassis (as bearings) yields a permissible stress with a maximum value of approximately 350 MPa on the component, which does not exceed the ultimate tensile strength as a boundary condition (compare fig. 7 left). Therefore, this region is uncritical. The maximum displacement is approx. 0.14 mm and is therefore within the manufacturer's tolerance limits (see fig.7 right). The original body shell weighs around 196 g. The optimized steering gear bracket with the extended installation space weighs around 133 g (32% weight reduction). The necessary weight reduction of 26 % for 19 components in the MEX/M (Aim3D) process has been achieved by means of topology optimization, and all mechanical properties meet the requirements for the component.



**Figure 7:** Stress analysis (left) and deformation analysis (right) of the steering gear bracket with installation space extension.

Another way to save weight, especially in the MEX/M process, is to use infill structures. Since no loose powder is used in this technology, it is therefore possible to save weight only by integrating infill structures into the conventional design of the part. With the use of ML, as demonstrated in <sup>26)</sup>, the maximum stress of an component can be estimated by selecting an infill configuration. Predicting the maximum stress of an infill-structured part using the algorithm in <sup>26)</sup> yields to the following result. Assuming the same load of 2,000 N and a grid structured infill volume of 74 % (realising a total target weight reduction of 26 %) with a wall thickness of 2 mm and an infill orientation of 0 ° the maximum predicted stress of the applied random forest regression ML model is 347.7028 MPa. This stress is in the same range of the finite element analysis of the topology optimized component and similar deviations of the parts can be assumed. The main advantage of using infill structures is that no redesign of the component is necessary, and the appropriate infill configuration can be found quickly and easily with a prediction. This does not optimize the weight of the component to the same extent but also meets the requirements and saves drastically on computation time. Further consideration for the improvement of the application are the implementation of design guidelines and restrictions for AM processes, as analyzed in <sup>27)</sup> and <sup>28)</sup>, and extending the material input opportunities to further inclusion of multi-material applications, as investigated in <sup>29)</sup>, especially for the MEX/M technology. Additionally, an integration of the component complexity would also increase the reliability of the cost estimation, as was done in <sup>24)</sup>. A more detailed cost tool can be also found in <sup>30)</sup>, which does not use the simplified assumptions in <sup>8)</sup> but carries out a cost optimization depending on the product and the respective process chain. ML will also be used in the future to automate optimization processes there. However, this calculation is much more specific and no longer freely accessible.

## Conclusion

A cost application tool was successfully developed and validated for four different process technologies concerning the calculated costs of an 3D printing supplier. By specifying the dimensions and the material, the total costs consisting of the material, machine, overheads and post-processing as well as the assumed simplifications the costs are calculated as a function of the quantities. Entering a relatively small amount of component information allows an initial estimation to be made for the MEX/M, PBF-LB/M, BJT/M and MIM processes that have been developed. The cost tool has a modular structure and allows changes to be made to machine costs and material prices. Additional systems and processes can also be added. This allows different use cases to be analyzed. The design for additive manufacturing was indirectly specified on the basis of a specific key factor of the necessary weight reduction in percent so that cost parity with conventional manufacturing processes can be achieved. In this way, it is very easy to assess how realistic the weight reduction is without prior experience in AM. Cost-effective quantities could be determined for the investigated process chains using a validation component. The MEX/M process therefore makes sense for small quantities and is only suitable for very small series or prototypes in this case. The material costs have a much greater influence than a more expensive system purchase. With an adapted design using topology optimization or the use of infill structures, 19 components can be produced in the most expensive MEX/M (Aim3D) process chain. The orientation of the component has also an influence on the costs for AM processes. Therefore, there is a potential for savings with optimized orientation and must be taken into account for AM technologies. The cost-effective PBF-LB/M (OCM) alternative is also cheaper than the conventional manufacturing method for 100 components in the observed use case. With this number of units, the system costs have a greater influence, as the PBF-LB/M (SLM) variant is significantly more expensive. As expected, MIM technology is profitable for large quantities. Under consideration it makes sense to use the process for quantities of 500 parts or more. Here, the BJT/M process is only suitable for medium quantities up to approx. 48 parts in terms of costs. The high system costs as well as the larger number of process steps have a significant influence. As the post-processing costs for all technologies are set at the same level due to the assumed factors, they will need to be adapted to the specific applications in future.

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