Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing

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Abstract

The costs of additive manufactured parts often seem too high in comparison to those of traditionally manufactured parts, as the information about major cost drivers, especially for additive manufactured metal parts, is weak. Therefore, a lifecycle analysis of additive manufactured parts is needed to understand and rate the cost drivers that act as the largest contributors to unit costs, and to provide a focus for future cost reduction activities for the Additive Manufacturing (AM) technology. A better understanding of the cost structure will help to compare the AM costs with the opportunity costs of the classical manufacturing technologies and will make it easier to justify the use of AM manufactured parts. This paper will present work in progress and methodology based on a sample investigated with business process analysis / simulation and activity based costing. In addition, cost drivers associated with metal AM process will be rated.

Introduction

Nowadays, industrial companies face more and more complex challenges in product development. Customers ask for innovative, individually tailored products with a high product quality for a reasonable price. In addition, the economic lifespan of products decreases which forces the companies to shorten their time to market and their development cycles [SBA02]. Through globalization the competition in fertile markets increases. Imitators from foreign markets make it harder for the companies to maintain achieved market shares [Bu94]. One solution to increase innovation and shorten the time to market is delivered by a new production technology: Additive Manufacturing.

AM, also known as Rapid Manufacturing, is a technology development of Rapid Prototyping, which was established around 1986 mainly based on Stereolithography. Nowadays there exist several different technologies for AM. They all have in common that they are based on 3-D product data and that they manufacture layer by layer. The difference between AM and Rapid Prototyping is based on the product characteristics. While prototypes are used to show special product properties or functions during the product development phase, AM delivers parts with characteristics of a final product [Geb07].

The additive production process allows product designers to create parts with high geometric freedom. Nearly all shapes can be realized by AM, which consequently allows the designer to improve product properties [Geb07]. This groundbreaking technology has the potential to revolutionize the theory of product design. It allows the designers to concentrate on product features instead of manufacturing restrictions given by the existing production technologies. Unfortunately, the knowledge about this technology and the freedom of design is not widely spread among today's engineers [BLR09]. Thus, the potentialities of AM often go unused and the added value compared to traditional manufacturing remains low. Particularly branches dealing with long product life cycles could benefit from weight savings and the integration of several functions in one part without the need to assemble. Within a study [EKW+12a], especially the aircraft production, automotive production and the electronics industry have been identified as very promising to profit from the use of AM. Experts have selected these branches by means of assessing the prospective attractiveness of current application fields [EKW+12a].

But nowadays the process costs of AM are one of the top three critical success factors of this technology [Gaus09]. This seems to be one of the major barriers for the further dissemination of this technology. In order to promote the dissemination of the AM technology the economic aspects and the costs need to be evaluated in detail.

Economic Aspects of Additive Manufacturing

The fast moving markets require a rethink in manufacturing. As products are getting more individual, and at the same time, getting a shorter lifecycle, AM enables the manufactures to fulfill these requirements.

Design / Construction

Compared to traditional manufacturing, the general advantages of AM are the capabilities in design and development of products. Despite certain limitations, companies are using AM increasingly to use the many possible benefits like complexity-for-free manufacturing. In traditional manufacturing there exists a direct connection between complexity and manufacturing costs. A relationship tying cost to complexity does not exist in AM. On the basis of the procedure there's almost no limitation in relation to the complexity of geometry and this without the need to produce any kind of tools (e.g. forming tools). This is why one speaks of "complexity-for-free" [HHD06, p. 9]. Consequently, most restrictions of design for manufacture and assembly are not valid for AM. Designs intended for traditional manufacturing are often heavily limited by high costs in construction and tool-making. The greater freedom of design via AM makes it possible to combine an assembly of parts into one part and, therefore, to reduce the required assembly work and costs. In addition, no compromises regarding the assembly capabilities are necessary [HHD06, p. 5].

Capabilities of Additive Manufacturing

As mentioned above, AM makes it possible to replace several traditional manufactured and assembled parts by one part. Hence, this allows an integration of functions from different parts, which may result in better performance. Even if the requirement on movability of a part in relation to standing parts exists, e.g. ball and socket joint, the production with AM can be done completely as a single monolithic structure. Unlike the applied design rules for traditional manufactured parts, which do not apply to parts produced by AM, design guides for AM processes must be considered. Due to the freedom during the design, the simple assembly moves forward into focus and becomes of higher importance. The fewer number of parts and fewer assembly steps may result in a high impact to production costs. The targeted design of a relieved or decreased assembly may result in a much higher reduction of the production costs than the construction compared to parts designed for traditional manufacturing [BDK94]. A lesser amount of parts provides other advantages as well. For example, fewer parts must be sourced, labeled and evaluated. In the end this also reduces the spare parts that have to be stocked. Since there is no need of tooling for production of spare parts, it is unnecessary to hold legacy tooling in storage. The complexity of the production and the whole management decreases and therefore savings in the entire business can be achieved [GRS10, p. 288f]. As a consequence of the simple way to produce complex geometric structures, the offer of mass-produced individual parts, like it is done for hearing aids, is given.

Economic application

There are key economic criteria in the area of AM, which cannot be directly expressed monetarily. AM helps to shorten the time-to-market-duration. The resulting advantage is not allocable by hard facts in general [Zaeh06, S. 121]. Another opportunity of AM is the increase of diversity of variants, while quantity of variants decreases.

At this point, AM technologies can play out their potential because they precisely support the individualization. Additionally, the development is much faster which makes early market positioning possible. The discontinuation of the need for production tooling is another key factor. Further, the introduction of new products is much less risky than before, due to the elimination of costly production tooling. This has a strong impact on the post-processing of existing products. Changes in the design can be published to the market even faster. With a slight or agile production significant improvements of the operational efficiency are achievable, therefore, the usage of such a technology is a competitive advantage. [Zaeh06, p. 121f] [HHD06, p. 160f] However, it should be noted that customers might not be prepared for higher prices or loss of quality for individualized products. Therefore, new technologies must enable a flexible and inexpensive production. Table 1 summarizes the pros and cons in usage of AM during product lifecycle management.

Table 1: Pros and cons in product lifecycle management [Zaeh06][HHD06][GRS10]

Pros	**Cons**
- More flexible development - Freedom of design and construction - Integration of functions - Less assembly - No production tools necessary - Less spare parts in stock - Less complexity in business because of less parts to manage - No tools for productions need to hold in stock (only digital/CAD data) - Less time-to-market for products - Faster deployment of changes - Offer of individual products	- Available software is a limiting factor - High machine and material costs - High calibration effort - Quality of parts is in need of improvement - Rework of parts is often necessary (support structures) - Building time depends on the height of the part in the building chamber

Additive manufacturing for supply chain management

As mentioned above, with the ability to produce highly complex parts without tools, a decrease of production costs is possible. Since there is no need to produce a high amount of an individual part to refinance the tools, like in traditional manufacturing, AM is predestinated for low volume production. Hence, affordable and high complexity individual products can be manufactured.

To achieve a holistic economical understanding further aspects must be considered. This includes e.g. expenses, logistics, supply chain and other variables. AM with its unique characteristics establishes a complete new business model compared to business models for traditional companies using traditional methods to manufacture [HHD06, p. 159f].

Methodology for accessing lifecycle costs

In this paper we use the definition of the intrinsic lifecycle. Intrinsic lifecycle means all different steps a product passes, from the first product concept trough the production processes and ending with the disposal of the product [PaBe07]. These processes will be modeled and investigated for lifecycle costs. "*Lifecycle costs are the costs associated with* *product users as the sum of all costs due to the purchase and during the period of use of a product (plant, machinery, equipment, apparatus) (product life)*" [EKL07]

AM is capable of cutting costs in a variety of areas. This starts with the reduction of parts and, therefore, a saving of time required to design a part. Tests and tolerances can be reduced in a significant way [DiCu11] as well as warehousing and assembly costs. The integration of an assembly into a single part also means that fewer subcontractors need to be controlled and managed. Digital tooth cap (invisalign®) production has demonstrated the ability of optimizing the whole process chain. The transition from analogue global dental production to digital local production has saved 85% of the logistic steps, reducing the production as well as the energy consumption for production activity by 80 %[1].

But the ability to realize cost-savings and added value does not stop in only the company but also benefits the customer in increased functionality and reduced lifecycle cost for the usage of a product.

Redesigns of sample aerospace parts have shown a weight reduction potential of up to 70 % of the original part weight. If the weight of an aircraft is reduced by 1 kg a year this saves $3000 in fuel annually [Wes11], keeping in mind that an average aircraft has a thirty years' lifespan. This means especially for this sector only the weight savings have an incredible capability of reducing lifecycle costs. But not only weight reduction can benefit the costs of a product.

Considering all these aspects, it is obvious that it is hard to compare the costs of a product simply based upon the production costs per piece. Therefore, a lifecycle based approach needs to be taken. The goal of the CoA²MPLy[2] project is to understand and rate the cost drivers that act as the largest contributors to unit costs and to provide a focus for future cost reduction activities for the AM technology. This will help to expand the applications for additive manufactured parts focusing on Metal Additive Manufacturing (MAM). A better understanding of the cost structure will help to compare the AM costs with costs of the classical manufacturing technologies and make it easier to justify the use of AM technology.

This project focuses as well on the costs over the product lifecycle, starting in the design phase and ending with the spare part supply, which is similar for all AM technologies. By identifying the cost structure, one will be able to understand how much of an economic impact 'design optimization' of part geometry has on unit costs.

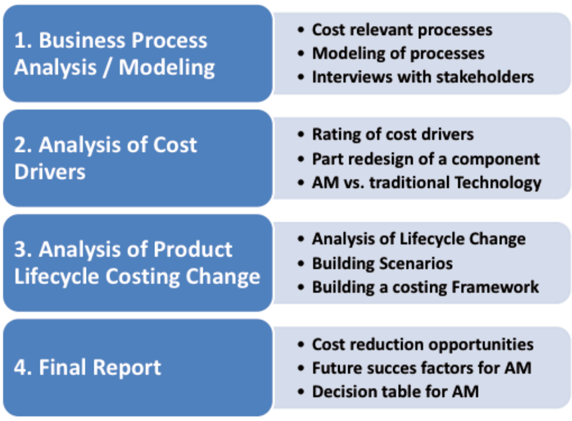

figure 1: Methodological approach

The first objective is to identify the machine rate cost structure relative to current state in AM. The second objective is to understand how conventional machining compares to the MAM machine rate unit cost structure. Therefore, current business processes will be analyzed. An exemplary part will be redesigned to demonstrate the advantage of AM technology and to compare it to conventionally machined part costing and assembly. A list of the major cost drivers will be generated to provide guidance, in which areas of cost reduction will become opportunities for AM. Currently the project is in phase 2 (compare figure 1). Future work will be based on the results presented.

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[1] www.melotte.be

[2] CoA²MPLy: "Costing Analysis for Additive Manufacturing during Product Lifecycle"

Costing Models for Production

To date few approaches have been taken to calculate the production costs of AM. Most of them have been looking at the Laser Sintering (LS) and Fused Deposition Modeling (FDM) processes and have compared them to injection molding or similar. The most important will be presented in this section. Some of the most influencing authors were Augsburg, Hopkins/Dickens (HD), Ruffo/Tuck/Hague (RTH) and Gibson/Rosen/Stucker (GRS).

A comparison of the models shows that all authors have chosen a similar approach for the calculation of costs in their models. Each of them has set a specific emphasis on a certain topic. The model of Augsburg for example describes manual process steps (e.g. removal of support structure, machine preparation), which helps to assign the labor costs directly to the product. The model of RTH is the only model showing the composition of the indirect costs and the composition of the cost rate for the build time. The Model of GRS shows advantages in the estimation of realistic building times, as no other model is as detailed in this section, as well as in the estimation of the powder usage for the production process.

In summary, one could say that each of the existing costing models has advantages and disadvantages, but no model meets all criteria satisfactory. Thus, there is a need to combine the strengths of the existing models without including their weaknesses and to develop a new costing model that is suitable for the calculation of today’s AM. A model considering the whole production process completely and correctly will be the basis for research how to include for instance development and lifecycle costs.

Development of a costing model

Prior to the development of a cost model, all cost relevant processes of the AM production process have been investigated and modeled with Event Driven Process Chains (EPC).

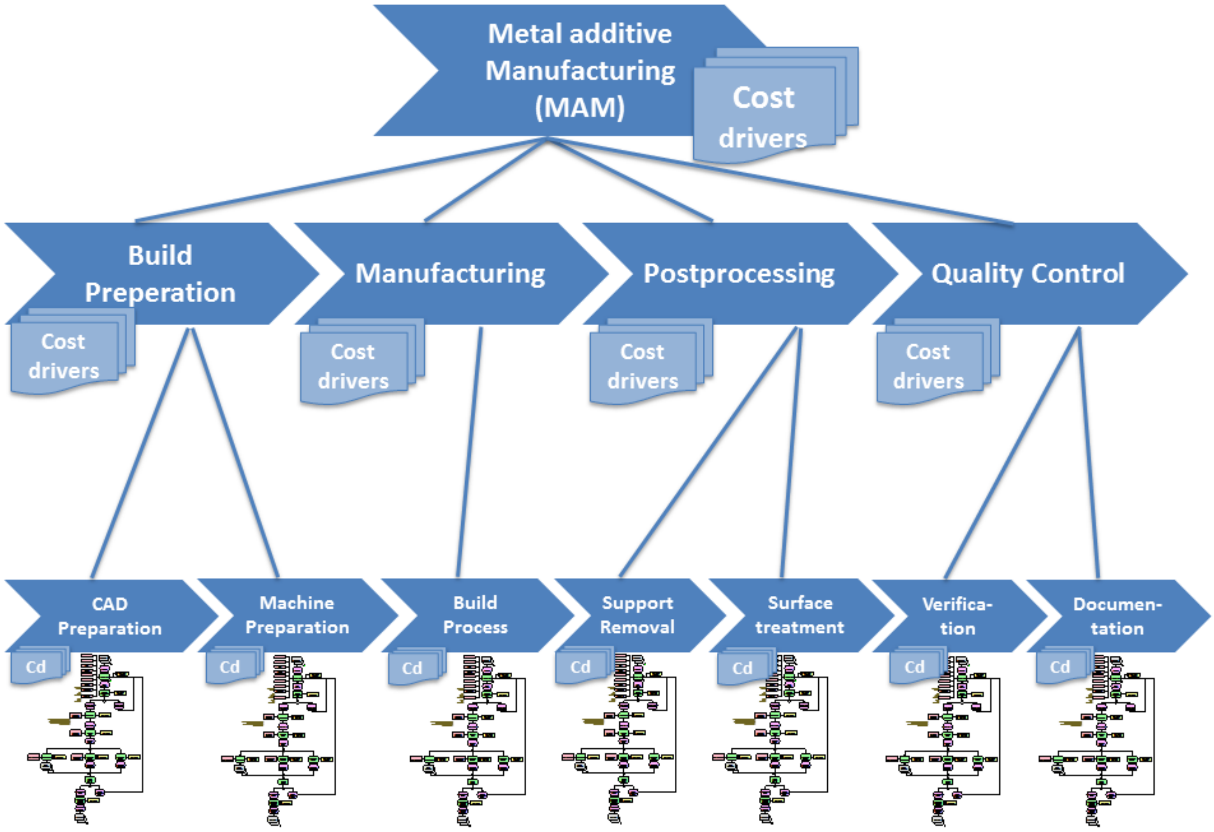

figure 2: rough Production model

Business process models, especially EPC's, have been proven in the past that they are capable to represent knowledge. They are the basis for an aggregation of different types of information [LPK10]. This should help to understand the processes in detail. Important process data has been captured. On this basis simulations of the production process have been performed in order to estimate the different influences of the cost drivers of the model. This helped to simplify different processes, as a cost model may not become to complex.

As a calculation method a "Time driven Activity Based Costing" (TD-ABC) approach has been taken. This approach allows the consideration of different influence factors on the basis the use of resources [CFG07]. For the estimation of cost relevant processes, the process steps of the initial model have been simplified into four main processes:

- Preparation of the building job
- Production of the building job
- Manual removing of sample parts and support
- Post processing to enhance material properties

The main processes have been selected in order to be able to represent different cost centers. This facilitates the calculation and makes it easier to adopt the model to different production environments.

The costing center "preparation" includes all steps from the initial CAD data, placement of the parts in the building chamber and creating the support structures. Interviews with engineers have shown that the costs in this step are highly dependent on the complexity of the different parts and the complexity of the building job itself. Therefore, a complexity factor has been introduced in the calculation of this cost center, which is capable of estimating the duration of this task. This is especially important, as this process requires an experienced engineer, whose labor costs represent the main costing factor in this step. Furthermore, this factor allows distinguishing between the variation of an existing building job as well as the creation of a new one.

The costing center "machine" can be seen in detail in figure 3 and is mainly based on the work of RTH and Dietrich [Diet10]. This production model is completely time driven and gets an additional fixed cost rate for the initial gas flooding of the machine as well as a fixed labor cost rate, as the processes are considered constant for each building process. The hourly machine rate consists of an indirect and a direct cost rate and is multiplied with the build time afterwards. Many factors are already available as the energy consumption of different machines (compare[BTL+11]).

$\text{Costs}_{\text{Build}} = \text{Costs}_{\text{Fixed}} + \text{MachineHourlyRate} * \text{Buildtime}$

The estimation of the build time is certainly one of the most important factors in costing models as it influences the costs of the build significantly. A lot of authors have put some effort in the calculation of the building time (compare [MeRe11] and [GRS10]. Therefore, different approaches can be taken. As stated above the model of GRS is the most detailed concerning the estimation of the build time. Hence, the equations from GRS have been adopted for that model. Further research attempts to find a way to simplify the estimation of the building time depending on factors such as standard elements, material selection, part density and part alignment. As material usage is not directly related to the build time these costs will be allocated in an additional step.

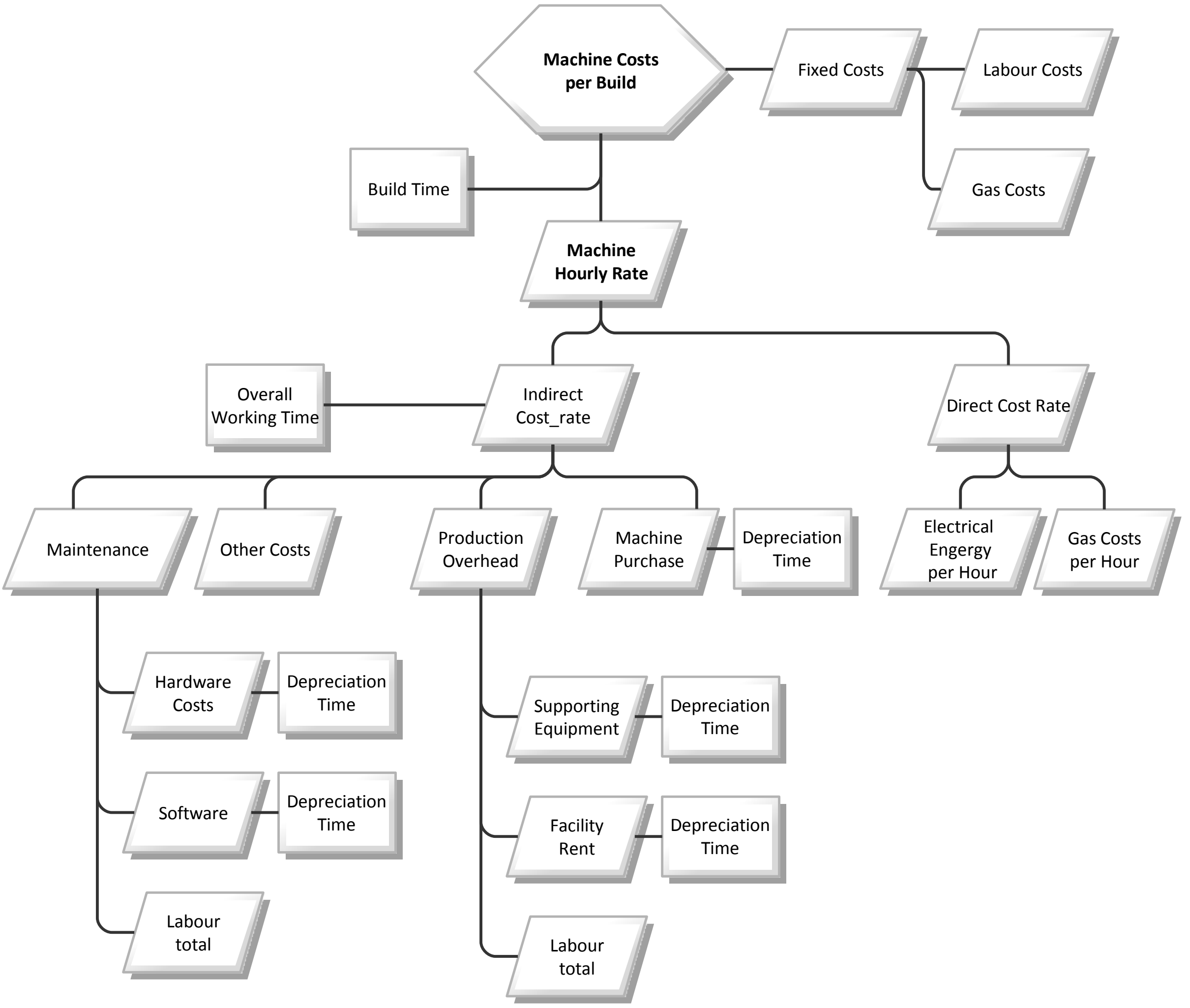

figure 3: Machine Costs per build

After the building process, the costing model allows different treatments to enhance the mechanical properties of the build. This process step can be considered additionally because it depends strongly on the product requirements if a pre treatment is necessary. As heat relief treatments or hot isostatic pressing (HIP) have proven to improve material properties significantly this was found useful by the authors to estimate total part cost for AM. An hourly machine rate, which consists of direct and indirect costs, is multiplied by the processing time.

The last costing factor sums up all necessary manual processing steps. These include steps like support removal, polishing and quality control. An average value for the processing time has been taken which is multiplied with the labor costs per hour. These can be estimated lower than in the preparation phase because only a minimally skilled worker is needed to perform the tasks. The whole processing time will be multiplied with a complexity factor capturing the different efforts that it takes to remove support structures.

As the material costs have not been part of the machine costs per build, they need to be added to the costs of the other cost centers. The formula to calculate the material costs is the same as used by GRS as it is suitable for the FDM, SLM and LS processes.

$$\begin{aligned}\text{MaterialCost} &= \text{Supportstucture} * \text{Wastefactor} * \text{Number of Parts} * \text{Partsvolume} \\ &\quad * \text{MaterialPrice} * \text{MassDensity}\end{aligned}$$

Calculation of a sample part and interpretation of results

As more research and parts are needed for a generalization of the results, this paper will discuss AM-production-costs on the basis of a sample part. For the calculation one of the sample parts used by Augsburg will be benchmarked. Its initial use can be found in the automotive industry.
As a first evaluation of the costing model the cost of this sample metal part has been calculated. The considered processes started with the data preparation followed by manufacturing and post processing. The sample part has retrieved an additional heat treatment afterwards to increase mechanical properties.

Figure 4 illustrates the cost breakdown for the sample part calculated with the aforementioned model.
Some major parameters for the Model were:

- AM-machine utilization: 4500 h/year
- Depreciation time: 5 years
- Investment costs: 500,000€
- Costs for maintenance 21,666 €/ Year
- Build rate: 6.3 cm^3/h
- Build Material: Stainless Steel 316L
- Material Price 89 €/kg
- Part Volume: 1cm^3
- Layer thickness 0.3 µm

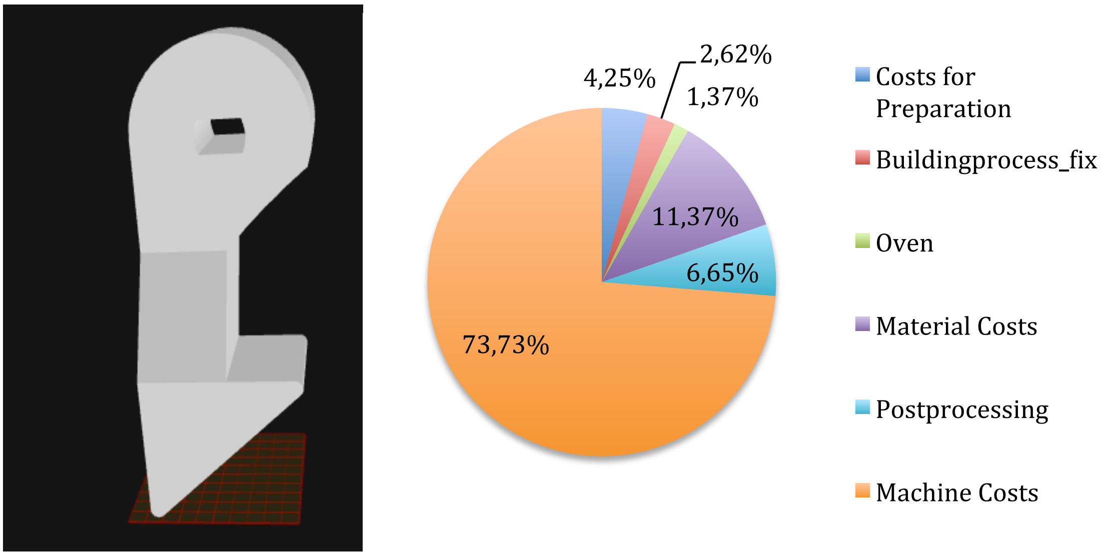

figure 4: Sample Part from Augsburg and the given cost breakdown structure by a batch size of 190 parts per build

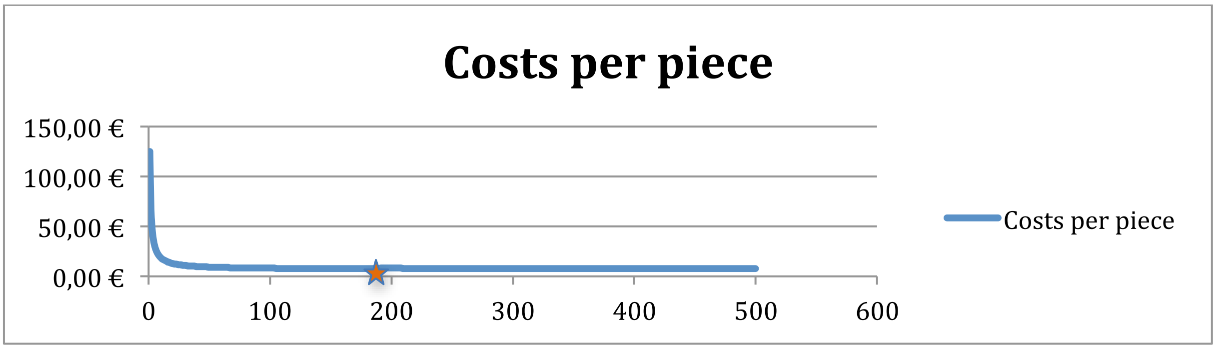

figure 5: Costing Curve depending on numbers of the build

The major cost driver consists mainly of machine costs (73%), as other authors have stated, followed by the material costs, which only make 12% of the total costs. The post processing process, followed with a similar amount, by the preparation process, represents the third largest cost driver.

In figure 5 one can see the relationship between costs per unit and the number of manufactured parts. The star indicates the production quantity, which is used for the following part of the paper. You can see that the initial costs for a single piece rapidly drop as more parts are being placed in the building chamber. The developed costing model does not show the typical chainsaw effect, which can be seen in [RTH05] for example. A slight effect can be noticed after a new production process has been initiated and the building chamber is not fully utilized. Over the time, this effect minimizes as the costs are split on more parts. That means after a certain amount of produced parts the influence of a fully utilization of the building chamber decreases. It has to be stated that the costs of the build are not related to the complexity of the part itself as stated in [HHD06] - meaning that the utilization degree of the building chamber has a small effect on the costs in mass production. As the production capacity increases, the curve converges to a straight line. Figure 6 shows variation of some of the above stated cost drivers.

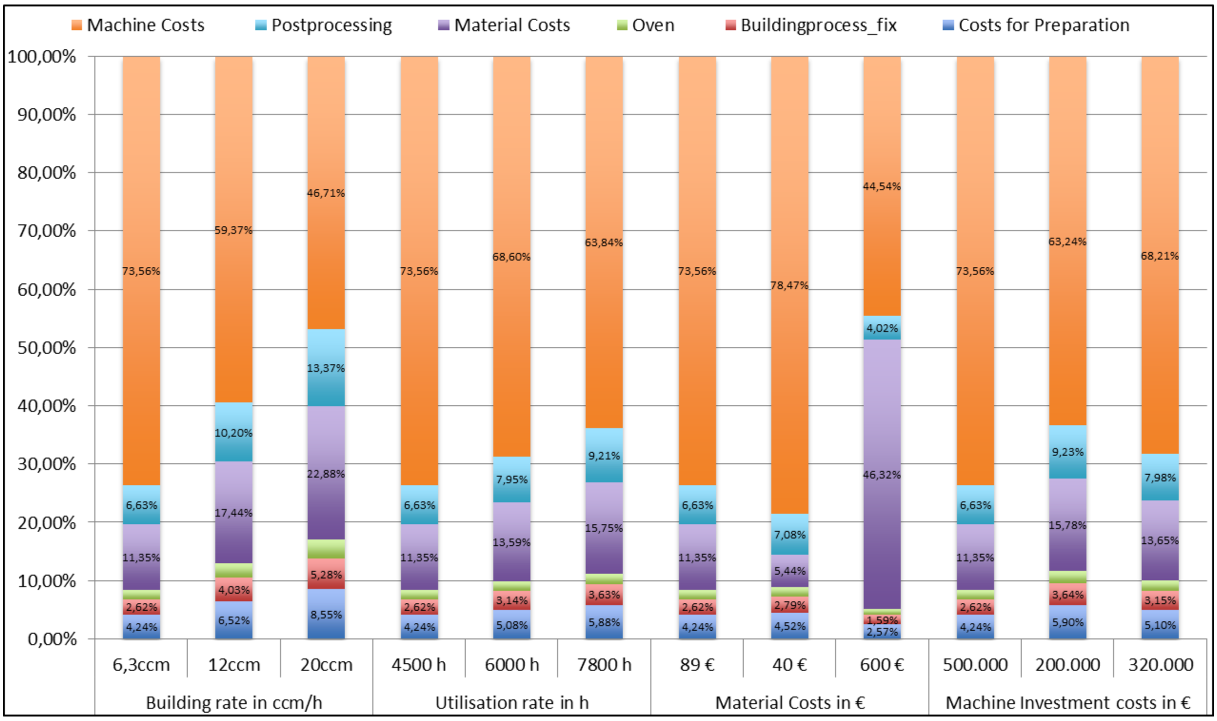

figure 6: Variation on different Influence Factors in %

Therefore, for each column one cost driver has been varied in order to see the effects on the composition of the total costs. Figure 7 shows the total distribution on the costs of the build.

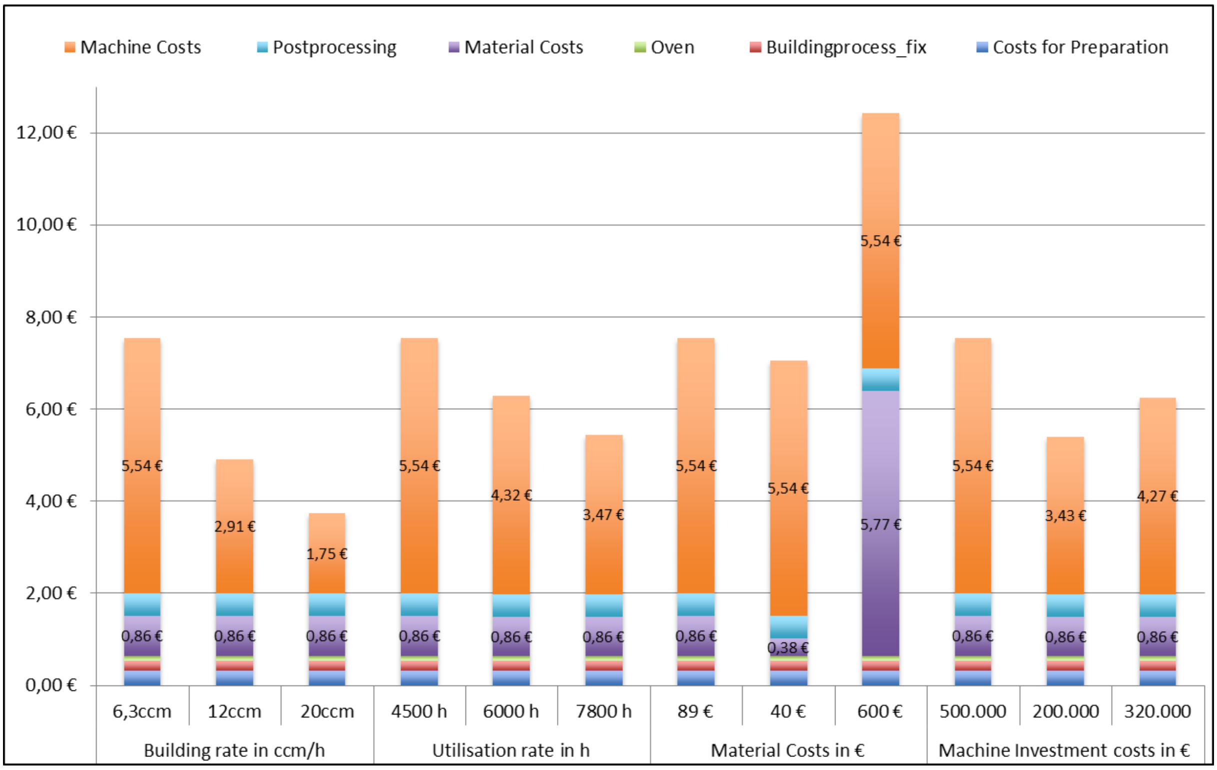

figure 7: Variation on different Influence factors in €

Discussion of Results

The largest contributor for building costs are the machine costs. The variation of influence factors have shown that a reduced machine rate cost can be achieved but will stay one of the dominant factors in the production process. One reason is that the labor costs for the AM building process itself can be reduced to the loading and unloading of the machine, as the production process is a blind process. As the material costs are not considered as a part of the building process, these cannot contribute to a decrease in machine rate costs. As the process is a fully automated and "lights-out" process it is logical that the machine rate costs have the greatest contribution to the total costs of a build. As GRS states, the changing allocation of the overhead costs to the production enhances this effects.

The material costs as the second largest cost driver has a certain influence on the building costs as well. For the sample part this is smaller than for a single piece high volume build. In general, the volume of additively manufactured parts will decrease constantly as the designer is able to construct independently of manufacturing restrictions. Lattice structures as researched in [GLJ+11] have the potential to reduce material volume and therefore the cost of the build. Materials like titanium are still very expensive and can raise costs up to nearly 50% even for low volume parts. As more material is sold every year [WOH12], more manufacturers will enter the market and the costs for the material, which in some cases (e.g. titanium), are approximately ten times more expensive than traditional materials, will decrease in the future. Therefore, the influence of the chosen material on the total cost, especially for low volume parts will decrease even further in the future.

These two cost drivers are followed by the post and pre processing of the parts. While the production process itself is nearly labor-free, the post processing is not yet automated. In fact, the only two processes in which labor costs are significant, are the data preparation as well as the post processing, because it is necessary to remove the support structures etc. The direct labor costs for the production process are locked in the cost driver "Buildingprocess fix" which amount to a very small portion of the total part cost.

The third largest cost driver is represented by the costs for the data preparation. This influence may be greater than the expected, since only a simple building job has been investigated. For the preparation process a skilled and experienced engineer is necessary. Thus, the main cost driver of the data preparation process is represented by labor costs. Knowledge is necessary to place the parts in the building chamber. Further research will bring more knowledge about the placing of parts and new software will automate this process so that a computer-based placement of parts in the building chamber will reduce the cost driver and make the technology more viable. As the main factor for the preparation is labor costs to place the parts in the building chamber, it only has to be performed once for larger series of parts. This will decrease the costs for the data preparation. Thus, the developed cost model allows a differentiation between mass produced parts (only place parts once) and customized combination of parts in the building chamber. An automated placing of parts in the building chamber on the other hand would make this differentiation obsolete.

In the calculations the main adjustment "knobs" for influencing the cost-driver of the machine rate costs were identified as the working load (or "degree of machine utilization") and the building speed of the machine. New technologies, such as the use of a dual laser concept by SLM[3] will increase building speed in the future. A standardized way to determine the building speed of the machine in combination of different materials needs to be found in order to compare building rates of different processes.

The results show that AM is mainly attractive in terms of additive batch production for suppliers or companies who can reach a high degree of machine utilization. Therefore research should focus on the enhancement of maximizing the degree of utilization as well as on the increase of the build-rates of the machine.

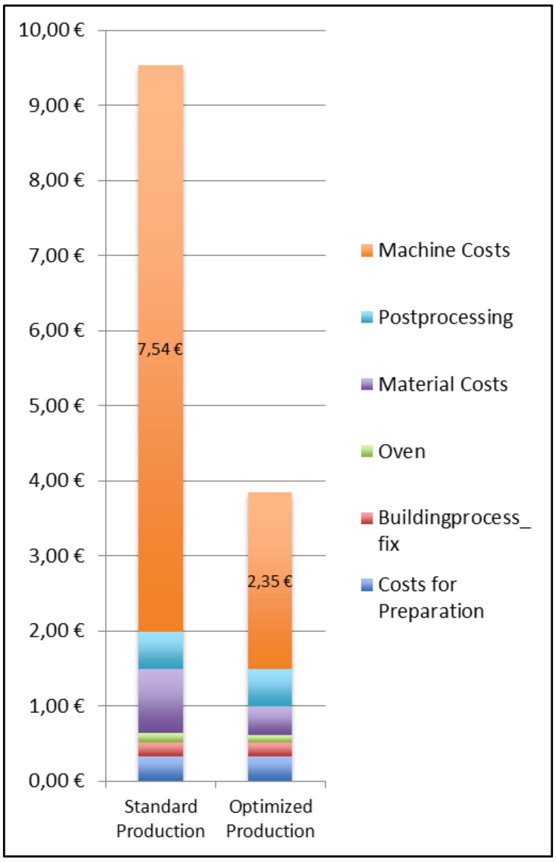

figure 8: Change of Values

Figure 8 shows the comparison of the initial and realistic value setting for the costing calculation and an optimized future production. The following assumptions have been applied to the original costing model:

Assumptions:

- Building rate: 20 cm^3
- Utilization rate: 7800 h/year (that means 90%)
- Material Costs: 40 €/kg (for the same material)
- Machine investment costs: 320,000 €

As you can see in the results the combination of different factors may reduce part costs by over 50% in comparison to the actual market price.

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[3] http://www.slm-solutions.com/de/produkte/slm-anlagen/slm-280-hl/

Conclusion and Outlook

To estimate the benefits of AM a lifecycle-based approach has to be taken into consideration. Otherwise the advantages of this technology will be easily underestimated. The costs of AM builds are very complex but are not the only costs that have to be considered. A first step was taken by modeling the production process. It seems more efficient to work on technological aspects than to only reduce costs of material and the purchase price of the machine.

Further research follows, based on the comparison of an optimized aerospace sample part. These will include the cost estimation based on different standard elements. The rating of the cost drivers so far has shown that there still is a significant cost reduction potential. Still labor costs make a significant part on pre and post processing of a build.

The existing process model will be enhanced by lifecycle processes. Looking for example at the aerospace industry weight reduction provide the possibility to save the customer a lot of expenses during the usage of the product through lightweight constructions. As this example already shows, the costs and benefits of AM strongly depend on the industry of usage. Also quality assurance costs have to be taken into account. These are significantly higher in the aerospace or medical industry compared to other industries. That highlights the need of an industry-specific investigation of AM-costs over the whole lifecycle. The machine utilization rate will be replaced by in the future with the Overall Equipment Effectiveness as a superior, more accurate way to gauge system performance based on customer demands. Influence of the designer on lifecycle and production costs will be part of the investigation as well.

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