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Evaluation of Cost Structures of Additive Manufacturing Processes Using a New Business Model

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Abstract

The individualization and customization of products is one the most important trends for industrial companies. New technologies like additive manufacturing (e. g. 3D-printing) are enablers for the further development of this trend. Companies offering production systems for those technologies are more and more required to embed Industrial Product Service Systems (IPSS) to assert theirselves on the market.
The aim of this research is to develop a business model which evaluates process costs of additive manufacturing technologies. The relevant technologies are Stereolithography, Selective Laser Melting, Fused Deposition Modeling, Selective Laser Melting, Electron Beam Melting and Laser Cladding. Product costs can be calculated easily and the outcome of the evaluation will serve as a valuable decision base for industrial decision makers on how to invest in a special technology. By embedding this service in the production system/ machines software, a big step for a new industrial service is provided.
The paper is structured in four steps. Firstly, based on a detailed description of the state of the art research, an analysis of the most important process steps in additive manufacturing is presented. A new business model for additive manufacturing technologies is introduced afterwards including the implementation of this business model in a software tool. Furthermore case studies for different product types and product quantities are explained and detailed values for process costs are provided. In the last step, a sensitivity analysis is done to find the most important parameters (cost drivers) for those case studies.
The business model and the evaluation of cost structures for additive manufacturing technologies is unique in the field of IPSS. Using a cost and investment calculation, the companies can significantly increase the effort and quality of price calculations for their products. Furthermore cost drivers are evaluated and recommendations for technology related investments are given.

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Keywords: additive manufacturing; business model; sensitivity analysis; cost structure

1. Introduction

Additive manufacturing technologies are all technologies producing components automatically by setting up or joining volume elements preferably in layers. Additive manufacturing technologies are with a growth of 34,9% in 2013 the most increasing manufacturing technology [1, 2, 3]. The current market volume of machinery and services of additive manufacturing is estimated at 3.7 billion euros, equivalent to an amount of 2% of the total machine tool market [2]. Conservative estimations expect a market volume of 7 billion euros in 2016. In 2020 the estimated volume will reach $11 billion [1]. Overall, there is a total market potential of about 130 billion euros [2].

During additive manufacturing processes, quality issues often occur due to operator or machine failures. The rejection rates are high and industry-standard product quality rates can rarely be achieved. In order to produce products of high quality reproducible, companies need to invest in a range of facilities for quality improvement and assurance. “A detailed analysis of the current manufacturing costs and evaluation of expected improvements reveals a cost reduction potential of

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about 60% in the next 5 years and another 30% within the next 10 years” [1]. For that reason there seems to be great potential in those investments. Their usefulness needs to be assessed individually prior to their implementation.

Thus, there is a need to analyze different approaches from a financial perspective and to evaluate the economic efficiency. Especially for small and medium sized companies, it is crucial to be able to assess the possible investments in advance. Therefore this service has to be integrated as a product service system in additive manufacturing.

The focus of this work is the development of a cost model, that is applicable for various generative manufacturing processes. The cost model will be used to identify significant cost optimization potentials. In addition, it will be used for sensitivity analysis to identify main cost drivers.

2. Literature review and relevant research work

In recent years, cost models were developed separately for different additive manufacturing processes. In this chapter, the main existing cost models are presented and briefly discussed in order to gain an overview of the current opportunities for cost estimation of additive manufacturing processes.

2.1. Model by Hopkins and Dickens

Hopkins and Dickens developed their model with the intention of a comparison of additive manufacturing processes (in particular Stereolithography (SLA), Fused Deposition Modeling (FDM) and Selective Laser Melting (SLS)) with a classic production process, the injection molding. The model can be used for different components and batch sizes to identify the specific unit costs in order to accurately identify break-even points. The approach of the authors provides a breakdown of costs into three elements. The machine costs, personnel costs and material costs.

It is important to note that the model calculates the material costs of the SLS without a notification of material recycling of the powder. Even post-processing activities as surface treatments or other forms of finishing are not included in the calculations. This also applies to all types of overheads. [4]

2.2. Model by Ruffo, Tuck und Hague

Another cost model was established by Ruffo, Tuck and Hague to estimate the cost of small to medium batch sizes in the SLS production process. As an extension to the model of Hopkins and Dickens, the authors understand their model as a full cost model and observe more influences than the previously recognized material, personnel and machine costs.

The cost model schema follows the principle of the allocation of cost-relevant activities to direct and indirect costs, giving a detailed overview of the structure of the printing costs. The identified cost-related activities are material, software, hardware, personnel expenses, equipment purchase and maintenance, as well as production and management. [5]

2.3. Model by Gibson, Rosen and Stucker

The costs of additive manufacturing are separated in four main categories by Gibson, Rosen and Stucker. They relate to the cost of the machine, production costs, material costs and labor costs. The sum of these cost categories represents the total costs.

The production costs are mainly depending on the time of printing. In this model the print time is calculated more accurately than in any other cost model. As well as the print time, Gibson, Rosen and Stucker designed the calculation of material cost applicable for several additive manufacturing processes. This calculation is based on the mathematical approach that the machine has to measure vectors to build up the product. This means that all kind of processes can be modeled that build products in single layers e. g. by the use of nozzle, laser or welding torch. [6]

2.4. Model by Ingole et al.

The cost model by Ingole et al. was developed within a study trying to improve the rapid tooling – making it faster and cheaper using the FDM process. The cost model was used to evaluate the degree of process changes or investments.

The costs in this model consist of the machine costs, material costs , labor costs as well as pre- and post-processing costs. In the calculations, however, a fundamental difference in comparison to the other models is presented. The calculation of the individual cost items is based on dimensional, homogeneous equations, which already include the benefits of the use of rapid prototyping in the calculation itself. It is exclusively a cost-benefit model. The model and the equations in particular are less suitable to perform solely cost considerations. [7]

2.5. Model by Lindemann et al.

Lindemann et al. choose a time-driven activity-based costing approach for the design of the cost model. To identify the cost-relevant processes, initially all activities are divided into four main process steps. These main process steps are preparatory activities, the printing process, the post-processing and the material treatments to improve the material properties. [8]

2.6. Implications of literature review

In all the presented cost models, there is consensus that some specific cost elements in additive manufacturing exist. However those elements have a great variation in their weighting. In some models, single cost elements were not taken into account at all. Other models strive for the recognition of all costs to reach a full cost model. Most of the existing models try to represent costs completely and realistically.

The process-based approach seems to be more and more important because of the usually small economies of scale and the focus on just one single order. This approach collects the set of all job-related activities that are valued in monetary terms.

Summarizing all the requirements of the different models, it can be mentioned that a cost model for the evaluation of cost structures of orders from different additive manufacturing processes should have the following characteristics:

- Integration of recycling and waste of material
- Integration of support structures of products including a general appraisal for different additive manufacturing processes
- Calculation of the printing time
- Maximum possible number of products that can be printed simultaneously in the workspace (differentiation between 2D and 3D disposal of products)
- Level of complexity of the product
- Duration of the post-processing
- Integration of modern quality management methods for the protection and monitoring of product and process quality

The discussed research shows that there have been some approaches from different perspectives to address cost models for special additive manufacturing processes. Due to the diversity of perspectives different models have been developed. None of the approaches provides detailed assistance for an analysis of cost structures including quality related aspects. There are no specific recommendations for action, which are based on the models' calculations for different additive manufacturing processes. Furthermore, none of the existing models fulfills the mentioned characteristics to the full extend.

3. Methodology

For the development of a business model, which is used for a Product Service System application, the time-driven activity-based costing is used, because costs of the processes are mainly driven by the required processing times [9].

Such a process cost system is generally build up in a three-step procedure [10]. In the context of an activity analysis all applicable individual activities are first identified and collected. In the next step, intercommunicating activities (action/ activity bundles) are combined into logical sub-processes. Lastly, the sub processes are condensed to meaningful main process steps. In that way costs will be consolidated in cost elements with detailed sub-activities (Fig. 1) [10].

In this work, the first step, the analysis and identification individual activities, is based on two information sources. On the one hand, relevant literature was used [e. g.: 4, 5, 6, 7, 8, 11]. On the other hand, a consortium of 12 different small and medium sized companies was identified. All those companies use different additive manufacturing technologies and have enormous product and process experience. 14 expert interviews and 7 researcher interviews provide a valid collection of all relevant activities, which are described as the main process in chapter 4.1.

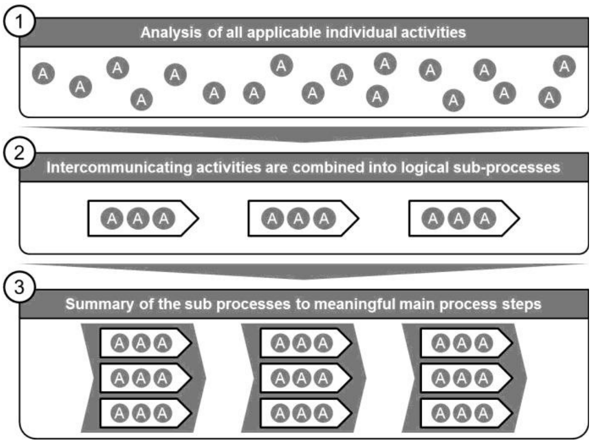

Fig. 1. Procedure for a process cost system.

After the three-step procedure, all applicable individual activities have to be described via cost functions. Those cost functions are parameterized through expert interviews, technical data from different additive manufacturing processes and technical information about additive manufacturing machines. In the end, costs for all process steps can be calculated. The aggregate cost method us used. The costs of all process steps can be add together to get total costs.

4. The business model

4.1. Process steps

Figure 2 shows the seven identified main process steps: design & planning, material processing, machine preparation, manufacturing, post-processing, administration as well as sales and quality. All main process steps have different sub-processes. Each sub-process has its own cost function.

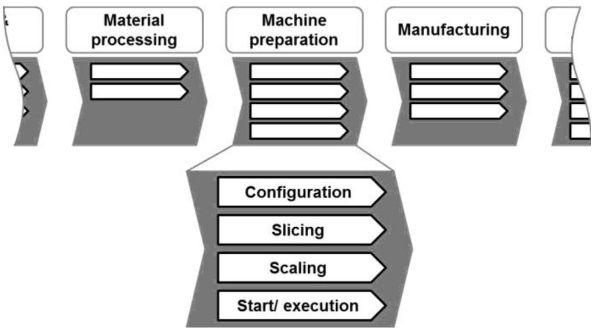

Fig. 2. Main process steps.

Because of the high amount of different implemented cost functions, one example will be given in the next section just to show the functionality of the method. The example shows the scanning time, which is an extract of the printing time calculation of a special order. The printing time is one of the most important characteristics for the main process step "manufacturing". Multiplied with the hourly rate for machine (operation), the printing time strongly influences the manufacturing costs (see also chapter 5). The model is sensitive to the most important technology factors (machine type, speed, thickness of layers, distance between parts, …). There is a fist differentiation in technology, machine and material. For each case there are special calculations which take all relevant factors into account.

4.2. Example for a cost function – the scanning time for the Laser Sintering process

The printing time (Z_P), as already introduced, is divided into three parts: first, the scanning time (Z_S), indicating the duration of a laser or a nozzle to trace contours on all the layers, thereby applying or melting the material. Second, the re-conditioning time (Z_R) of additive manufacturing processes using a powder bed, specifying the duration of the smooth down of the fresh material on the platform. Third, the time lag (Z_T), the start time of printing, which takes the time of the engine heating and the cooling-down period after the process into account.

$$Z_P = Z_S + Z_R + Z_T \quad (1)$$

Z_P = printing time [h]
Z_S = scanning time [h]
Z_R = re-conditioning time [h]
Z_T = time lag [h]

The scanning time (Z_S) is determined by the following equation:

$$Z_S = \frac{N_{max} * SL}{SS_{Avg}} \quad (2)$$

N_{max} = maximum product quantity per print
SL = scan length [mm]
SS_{Avg} = average scan or printing speed [mm/h]

The product quantity per print job is determined by the workspace of the machine if enough equal product have to be processed. The machine and process configuration define the scan or printing speed. Lastly, the scan length is calculated by different factors. Especially the geometry of the product and the thickness of the layers and the hatch between the scan lines affect the scan length as shown (Fig. 3).

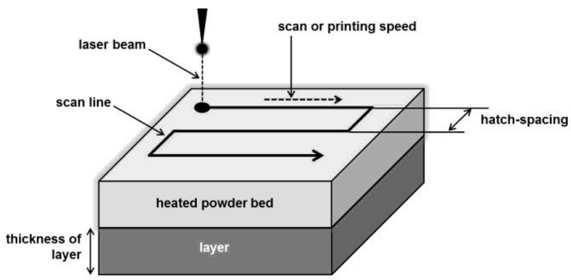

Fig. 3. Selective Laser Sintering process scheme [12].

4.3. The cost calculation tool

The basis of the evaluation of investments in an additive manufacturing technology is the clear knowledge about all costs of each relevant process step. The cost calculation tool calculates the costs of all main process steps (see 4.1) and additionally some important key figures. All cost functions for each process step are implemented in the tool. The tool has two main areas: the data input area and the data output area.

For a detailed cost calculation, an overall of 77 input values is needed. Because of this high amount of values the input area is divided into a process-specific information which can be preset, and order-specific information.

4.4. The input area

The process-specific area includes quality-related investments, process relevant cost rates and machine and material settings. All those values have been established within the framework of presets for different process types. Users can adjust these preset settings, for instance through proprietary process times and cost rates, according to the necessary accuracy of the cost calculation. The most important order-specific area is separated in 4 sections as shown below (Fig. 4).

Fig. 4. Data input form for general order information.

In the first section, the kind of manufacturing process is selectable via dropdown. Available methods are SLA, SLS, FDM, Selective Laser Melting (SLM), Electron Beam Melting (EBM) and Laser Cladding. Moreover, the corresponding machine for the job, the product and the support material are chosen. The selection of machine and material refers to databases which are implemented in the tool as well. The database entries (machines and materials) can be adapted to specific company requirements. For instance, a company can create its machine park initially and maintain the dataset over time.

Furthermore the required product quantity of the order has to be inserted. As the last point, the machine running time has to be set, meaning the available machine time per week for the considered order.

The second section is the input area for product-specific information. This means that all information which is required to characterize the product for the processing has to be provided adequately. Especially information about the product volume and its enveloping body is needed.

In the third section, process-related information has to be prompted. First, the specification of the layer thickness is important. It determines the number of layers the component is decomposed to. This has a direct impact on the calculation of the required printing time. The most commonly used layer thicknesses are from 0.016mm to 0.1mm. This does not include machines producing micro parts, where thicknesses can be decreased to about 5nm. In order to shorten the manufacturing period, some machines can print with 0.2 mm thickness, but this often leads to a deterioration in quality [11].

Many additive manufacturing companies have to handle high rejection rates. The rejection rate is defined in the range of values from 0 to 1. 0 means no rejected products, 1 means that all products do not fulfill the requirements. Depending on the procedure, the complexity of the component and the material used, the rejection rate is moving. According to the survey and the interviewees of the project consortium, the range of the rejection rate usually differs between 0.05 and 0.5. Thus, the rejection rate constitutes a critical factor in additive manufacturing especially because its substantial impact on manufacturing times and material utilization.

The fourth section has four important input possibilities.

As already described, the tool contains databases for machines and materials. The databases for machines and materials can be edited in this section. Additionally, there is the possibility to adjust measures of process-specific preferences like labor costs or process times. The user can edit these preferences once for all kind of processes to increase the accuracy of the calculation. The preferences which are set standardly are preset on the basis of expert interviews, the survey and technical information about additive manufacturing machines.

4.5. The output area

The results of the cost calculations for each main process step are given in the output area. There is a "graphical summary" for a quick identification of cost drivers illustrated by cost curves and cylinder charts (figure 5). In addition, a separated "production cockpit" shows particularly important production figures.

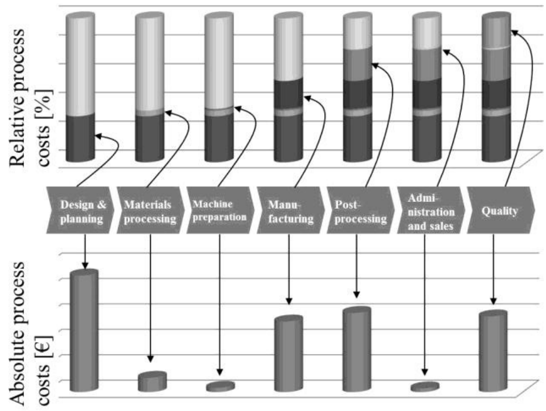

Fig. 5. Data output section (extract).

In the graphical summary, both, the relative and absolute costs per order are shown. The relative costs represent the proportion of each process phase to the total order costs. All information can also be displayed both in terms of unit costs or order costs.

The most important production figures like the machine utilization rate (load factor), the machine hour rate, the number of components per print and the expected cost of rework are selected for the production cockpit. In addition, the total cost of the contract and the cost per unit are shown.

5. Sensitivity analysis

Using the cost calculation tool, sensitivity analyses were made to identify special economic effects of additive manufacturing processes. Those effects are the basis for an evaluation of further investments.

For the following sensitivity analysis two typical products were chosen which just differ in size (size ratio: 1:7). All settings in the tool can be kept equal for both processes. In the following, each defined input variable (excluding the product quantity per order) was reduced and increased by 10%. The calculation was made twice in every case using a quantity of 1 and 1,000 pieces of each product. Figure 6 shows the five main effects for a decrease of each factor.

The costs of small quantities can primarily be influenced positively by the costs of manufacturing, respectively the components of the hourly rate for machines. The investment costs of the machine and the average running time of the machine per week have the most influence. Lower prices of investment goods like machines and a better utilization of machines lead to strong cost reductions per unit. For small components, manufacturing costs are the main cost driver with an increasing quantity of pieces. This is caused by post-processing costs, depending on the required post-processing time. For small components the required quality and the associated duration of the post-processing should definitely be taken into account. On the way to a (small) mass production, these costs could be significantly enhanced by measures of automation.

Small product body (enveloping body: 13,5 cm³)

Ranking	Quantity: 1	Quantity: 1000
1.	$AK_{machine}$ (-2,90%)	t_{PP} (-9,62%)
2.	t_W (-2,43%)	$AK_{machine}$ (-0,24%)
3.	T_{end} (-1,39)	t_W (-0,21%)
4.	T_{start} (-1,04%)	$V_{filling\ degree}$ (-0,21%)
5.	a (-0,87)	LT (-0,19%)

Huge product body (enveloping body: 4630 cm³)

Ranking	Quantity: 1	Quantity: 1000
1.	$AK_{machine}$ (-7,39%)	$AK_{machine}$ (-8,03%)
2.	LT (-6,33%)	LT (-6,88%)
3.	t_W (-6,20%)	t_W (-6,74%)
4.	$V_{filling\ degree}$ (-5,12%)	$V_{filling\ degree}$ (-6,11%)
5.	ss_{max} (-4,08%)	ss_{max} (-4,43)

$Ak_{machine}$	Investment costs machine [€]
a	Factor of maintenance costs p.a
LT	Thickness of layer [mm]
ss_{max}	Maximal scan or printing speed [mm/s]
T_{end}	Cooling-down period [h]
T_{start}	Machine starting period [h]
t_W	Average running time per week [h]
t_{pp}	Post-processing time per product [h]
$V_{filling\ degree}$	Volume filling degree [%]

Fig. 6. Results of the sensitivity analysis for two different products and quantities.

Generally, there are high savings in costs per unit if a maximum of products is printed at the same time. If only small quantities are demanded by the customer, different jobs should be combined with each other in order to fully utilize the workspace. Additionally, small quantities should be printed on smaller machines to reduce the hourly rate for machines.

Summarizing the sensitivity analysis, the three main findings are:

- The most cost-influencing factors are the investment costs of the machine and its load factor.
- The post-processing of products with high quantities and small bodies has a big potential for process optimization .
- Economies of scale only exist for small products; products with big bodies are nearly independent from the ordered quantity.

Moreover, it should be remarked that quality related actions do not reach the ranking in figure 5. Possibly a different kind of sensitivity analysis can be done using a percental variation of a realistic range of values of all 77 values to improve the results.

6. Conclusions and outlook

Within this paper, research results of an ongoing research project have been presented. In the first step, a literature review of cost models has been given illustrating the complex field of challenges and elements. Based on a reliable methodology all cost-relevant activities, sub-process and main process steps have been identified. Using these first research results, a cost model with a variety of different cost functions for every sub-process has been developed and implemented in a calculation tool. Main effects and parameters on cost structures of additive manufacturing processes were identified by a sensitivity analysis using the cost calculation tool.

The shown research can be implemented as a Production Service System. It serves as a valuable decision tool for companies using additive manufacturing technologies. Cost structures can be identified and investments can be assessed in advance. All steps are based on information or interviews with a consortium of this research project or analyzed studies.

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