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Reviewed Paper

METHOD FOR THE EVALUATION OF ECONOMIC EFFICIENCY OF ADDITIVE AND CONVENTIONAL MANUFACTURING

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Abstract

The advantages of individuality and complexity for free are commonly known in the field of additive manufacturing, but, nevertheless, they compete with advantages of conventional manufacturing methods. On the one hand, a small size production can be economically viable through additive manufacturing. On the other hand, conventional manufacturing methods are well known and optimized, so that they have low cost per unit. Therefore, to evaluate the economic efficiency various criteria are needed to compare additive and conventional manufacturing methods. In the following part comparative criteria and influence factors for economic efficiency are identified and described. Besides general aspects personal reasons may influence a manufacturing decision. Therefore, the identified criteria are used to build a method which helps the user to decide on a manufacturing method depending on personal preferences. The structure and use of this method is described in the second part. After this, an outlook and conclusion is given.

Introduction

Due to the progressive individualization of the required products and the resulting product diversity new challenges arise within the production area. This trend towards diversity of variants is evident, for example, in the automotive sector, which has seen a large increase in vehicle variants in recent years. At the same time, the number of pieces shrinks and the production times are reduced. Quality and design are becoming increasingly important. Market needs are therefore changing fundamentally. [Wes10]

The conventional production of products with low unit numbers and high required complexity is not economically advantageous. Additive manufacturing methods have lots of advantages and characteristics: Components are build layer for layer, there are no additional tools or models needed except of support material in some cases. Through this special production method, complex geometry can be realized. This is a great advantage compared to conventional manufacturing. Furthermore, the integration of functions is the second advantage of additive manufacturing. The assembly process can be reduced or skipped because of the integration of functions. Therefore, process time and financial resources can be saved. Still, development time shrink and prototypes can be made easily and quickly. These advantages make additive manufacturing methods to a competitive process to conventional manufacturing methods. Nevertheless, a method to decide about the advantageous production method is needed. Therefore, various decision criteria are defined. As an example for the use of this method four manufacturing methods are selected. These are in case of the additive manufacturing methods the selective laser sintering and the fused deposition modeling, in case of the conventional manufacturing methods the injection molding and the milling of synthetic material. [Arn15], [Geb13], [Gib10]

In the method, the four manufacturing methods are compared concerning different decision criteria which are presented in the part “concept”. Through the decision criteria each manufacturing method reaches a rating. This rating is evaluated considering personal preferences. Various decision criteria are needed because the conventional and the additive manufacturing methods are very different and have special advantages. It does not make sense to compare only the costs of a produced part. The quality for example is an important factor as well. In the following part, the motivation for the topic is described. After that, a short state of the art deals with approaches to evaluate the economic efficiency of additive manufacturing. Next, the detailed concept is described with its structure and functionality. The next part deals with the implementation and validation of the concept. In the end, an outlook and a conclusion is given.

Motivation

The key motivation is the qualitative relation between cost per unit and lot size for conventional and additive manufacturing which is shown in figure 1.

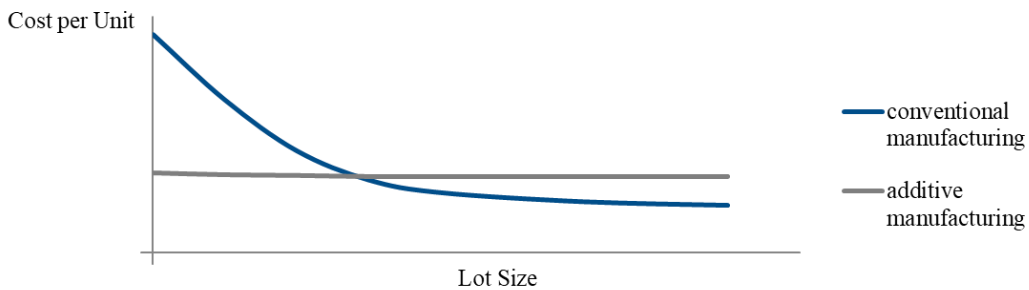

Figure 1: Qualitative relation between cost per unit and lot size. [Vog13]

In the process of additive manufacturing almost all costs of a part are running costs. There are only few or no fixed costs. This is demonstrated in the figure with the nearly constant graph (grey). On the contrary, the graph for the conventional manufacturing (blue) has a falling negative grade. This is caused by the high fixed costs for the injection molding tool or the programming of the CNC-machine. The more parts are produced with the help of conventional manufacturing the cheaper one unit becomes. Besides the grade the figure shows an intersection point, the break-even point. At this point, the costs per unit for conventional and additive manufacturing are the same. This relation is not quantified yet and forms the motivation for the evaluation of economic efficiency of additive and conventional manufacturing with the help of a method.

The value added of this method is created by simple and fast decision making. By comparing different criteria, the advantages and suitability of the manufacturing processes are investigated, since this can be determined only with great complexity in the existing multiplicity of production processes. This effort of comparing manufacturing methods exceeds the possible savings potential, especially in the case of simple components. In the end, know manufacturing methods are used to produce a certain part because this is the easiest and fastest solution for a company. The evaluation method, which is described in the “concept” part, recommends a certain production process objectively and with relatively little effort to the user. From the user’s point of view, he receives a suggestion of the most economical or best suited manufacturing method with the help of the method.

State of the Art

The cost calculation is an essential part of the process and production planning. Furthermore, the calculated costs are often used for extern offers. Companies use for example the machine hour rate to estimate the cost for a part. Concerning the conventional manufacturing methods many costs occur during the preparation phase. For the milling process, a special machine programming is necessary. For producing a part with the injection molding, an additional tool is needed for the forming process. With the preparation costs, the material costs and the machine hour rate a conventionally manufactured part can be calculated.

For the field of additive manufacturing there is no standardized calculation method. Some authors have already developed possibilities for various additive production processes to name the costs involved in the production and to quantify them partially. They perform different depth and accuracy. *Hopkinson and Dickens* (2003) divide the total costs into three areas: the machine costs, labor costs, and material costs. As an example, they use these three cost categories to determine the unit costs for two different parts. This concept is used and detailed by *Ruffo et al.* (2006). The authors use the estimation of the process time and supplement indirect costs such as administrative costs and production costs. *Atzeni et al.* (2010), such as *Hopkinson and Dickens* (2003), focus on the calculation of unit costs by machine costs, labor costs and material costs. *Kraus et al.* (2011) include the entire process chain into the calculations. They subdivide the total costs into the three sectors of the building preparation, construction and dismantling. *Rickenbacher et al.* (2013) look at the whole process and analyze the costs of selective laser melting. They identify the costs of process preparation, the costs of the alignment and positioning of the components, the cost of the machine preparation, the cost of the assembly of the parts, the costs of the removal of the components, the cost of detaching the components from the base plate and finally costs for the follow-up.

Concept

The aim of this part is the development of a concept to compare the economic efficiency of different manufacturing methods based on the manufacturing of certain parts. In the following, the requirements for this concept will be explained. Based on those requirements the comparative criteria are described. After the determination of the total production costs calculation and the assessment of the complexity of the component geometry the overall concept is illustrated.

Requirements

There exist several general requirements. The method for the evaluation of the economic efficiency needs to be user friendly and as a matter of course. Therefore, the user do not need any excessive explanations to use the method. The structure has to be simple and clear which supports the matter of course. The result of the method needs a high expressiveness that the operator can interpret it quickly and easily on his own. The reproducibility ensures the same result with the same initial specifications. Overall, an additional benefit should be evoked for the operator using the method.

Besides the general requirements, there exist specific ones. The specific requirements can be divided in input, output and database criteria. Figure 2 shows the general and specific requirements for the method in an overview.

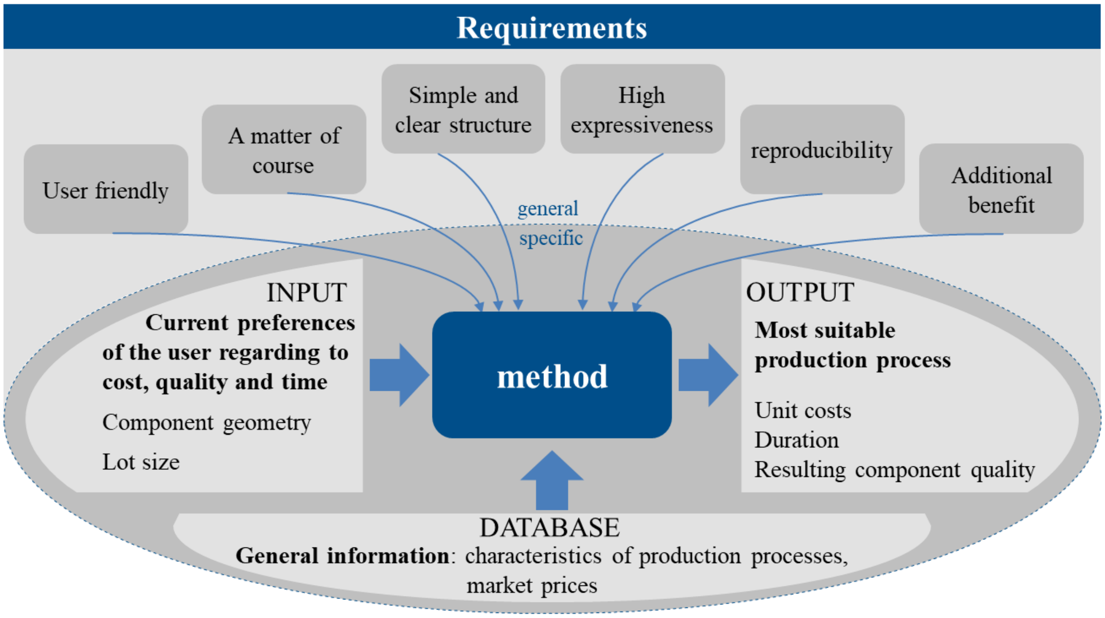

Figure 2: Requirements on the method in an overview.

The main objective of the method is to determine the most suitable production process and to evaluate the advantages with regard to the four production processes. In addition to these imprecise information, the unit costs, the duration of the order and the resulting component quality are presented to the user as a concrete output as well. General and specific information are needed to generate the output. The general information is in a database and refers to the characteristics of the production processes, such as machine data and costs, which forms a decision-making basis within the method. In order to reflect the decision in a realistic manner, market prices are also included through offers for engineered components. This collected data basis is integrated in the method, these information are independent of the user. The special input, however, is inserted directly by the user himself when using the method. It reflects the current preferences with regard to the quality and order time of the user. The desired component geometry also serves as an input and is an important decision-making factor. The lot size act as an input as well.

Comparative Criteria

Based on the requirements, there exist six comparative criteria. The main aim of the method is to enable the user to integrate his personal preferences and to decide with the help of information and preferences, which manufacturing method is the most suitable one for the manufacturing of a certain component. The comparative criteria contain the most important information concerning the component and the manufacturing methods. Figure 3 shows the six criteria.

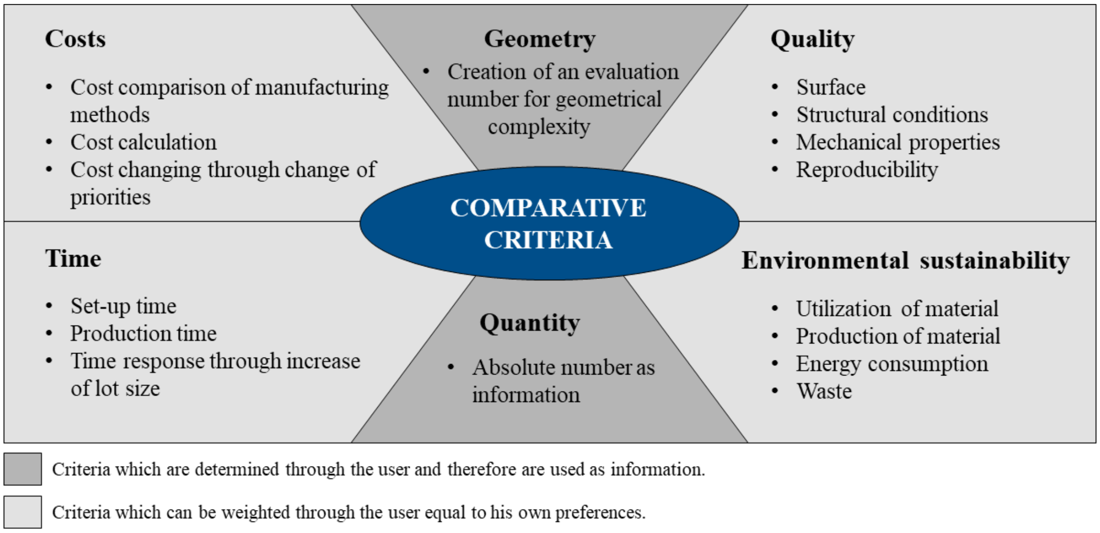

Figure 3: Comparative criteria in an overview.

The classic trio of cost, quality and time is supplemented by the comparative factor of environmental compatibility. The costs can be determined as a quantitative value, whereby a direct comparison between the production processes is possible. Besides the cost calculation for the different manufacturing processes real bid prices are invited for explicit parts.

The quality of the components differs in the different production processes. Often, the assessment of the cost-effective production process is not sufficient, since special requirements exist for a component according to the surface or the mechanical properties. A cost comparison without simultaneous consideration of the quality is less meaningful. The time of production can also not be ignored as the four production processes have very different lead times and production times. Another interesting feature is the comparison of the time course with an increase in the lot size. Sustainable and resource-conserving production is nowadays an important factor, which claims more attention through the increasing pollution of the environment and the resource-constrained nature. Above all, additive production methods seem to need a lot of energy during the manufacturing process, which is why the consideration is necessary for a fair comparison of additive and conventional manufacturing methods. For this purpose, the comparative criterion of environmental compatibility is established, which includes the material exploitation, energy consumption, material production and waste. In addition to these four factors, the component geometry and the quantity of components (lot size) are two comparative criteria, which are determined through the user. The geometry is evaluated in a number explained in the following part.

Geometry Evaluation

To estimate the geometry of a component an evaluation number for the geometrical complexity is created. With the four selected manufacturing methods, not all components can be produced in the same way. There exist non-feasible elements or geometric shapes for every production process. Within the method, the deposit of these design limits is important, since it is only then possible to ensure that the recommended manufacturing method can manufacture the component.

Every component is classified as a simple, medium or complex part. Besides these three classes the geometry of a component can exclude the manufacturing with a certain method. If a component owns an undercut for example, it cannot be produced trough injection molding or milling. If the size of the part exceeds the available space of the FDM or SLS machine, the part cannot be manufactured with the two additive manufacturing methods. The rating of when a geometry is considered complex can not be made generally, it is a subjective assessment. Depending on the working environment, individuals value complexity different. In order to be able to make an estimation of the complexity of the components, the geometry value is calculated by a point system. Geometry structures generate different scores, the sum of these scores lead to the classification as simple, medium or complex. These structures include for example the general shape, component dimensions, material strengths, type and size of holes, type and size of additional bodies, free form areas or bionic structures. The number of points, which assigns a component to a class, depends on the user who can set an individual limit for the classification in simple, medium and complex.

Cost Calculation

The costs are allocated to the three areas of pre-processing, manufacturing and post-processing. This triple division allows first statements on the behavior of unit costs when the lot size increases. Figure 4 shows the three parts.

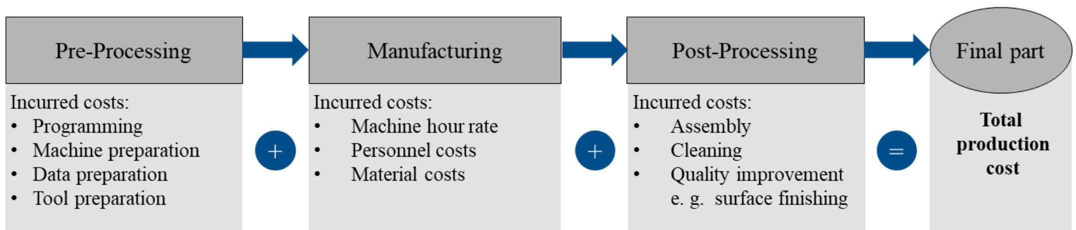

Figure 4: Integral parts in the cost calculation.

The pre-processing involves costs that only arise once in the production process at the beginning, such as the costs for tools or programming. The higher these pre-processing costs are, the lower the unit costs become with an increase in the lot size. The costs of the manufacturing contain the machine hourly rate, personnel costs and material costs. If the number of items increases, the total cost of production increases as well, because additional machine hours, additional material and more operating personnel are required. It must be noted that it is not necessarily a linear connection. In the case of the SLS with the powder filling of the construction space, for example, the production of several components is possible within one production process, since these can be arranged simultaneously in the available space. In some cases, process-specific activities and costs can be incurred in the manufacturing step, such as the removal of supporting structures from the FDM. The costs of the post-processing include all measures that cannot be included in the machine cost rate but are made for a specific characteristic of the final component. It is important that these activities do not have to follow the production process, but can be carried out selectively. These include, for example, additional post-processing for improving the surface structure or measures for improving the structural conditions.

Overall Concept Structure

The overall concept structure unifies the comparative criteria, the possibility to import personal preferences, information concerning the manufacturing processes, costs, quantity of units and geometry of a component. Figure 5 shows the structure of the whole method.

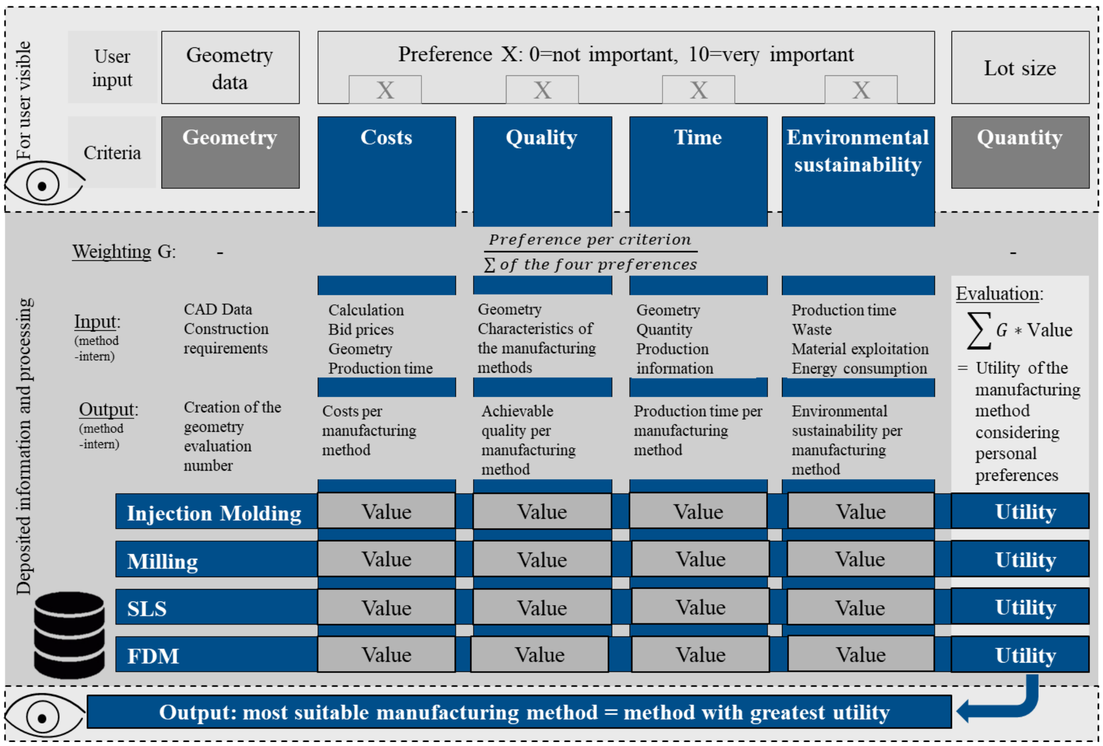

Figure 5: Functionality of the method in an overview.

The first and the last part (light grey) show what a potential user can see. The user can set his preferences for costs, quality, time and environmental sustainability. Therefore, he uses numbers from 0 to 10, with 0 equals not important and 10 means very important. Depending on his preferences and needs, he can configurate the basis for the decision. Besides his preferences, the user evaluates the geometry of the component and quantifies the lot size. After the user concretized his input, the method shows the most suitable manufacturing method for the user with his given preferences. The most suitable method matches the method with the greatest utility for the user.

To determine the most suitable method, the concept is based on a utility or benefit analysis. The preferences of the user are transferred into weighting. Therefore, every preference is divided through the sum of the four given numbers. The comparison and evaluation of the manufacturing methods are made for every criterion. The four manufacturing methods are ranked concerning the criterion from 1 to 4 points with 1 the worst and 4 the best manufacturing method when only one criterion is included. Therefore, the value from 1 to 4 points is set for every single production process in one column. The values in one column are multiplied with the weighting of the associated criterion. The sum of the multiplied values in one line for one manufacturing method result in the utility for the manufacturing method. The production method, which shows the greatest utility, is the most suitable manufacturing method. The output corresponds to the production process with the highest utility.

Prototypical Implementation and Validation

After the explanation of the concept for the method, a prototype implementation follows in this part. Three exemplary components are developed. One can be categorized as simple, one as medium and one as complex. Figure 6 shows the three exemplary components that show the front of a loudspeaker housing. The parts are thin walled, suit the construction space of the additive manufacturing and possess different gradations of complexity.

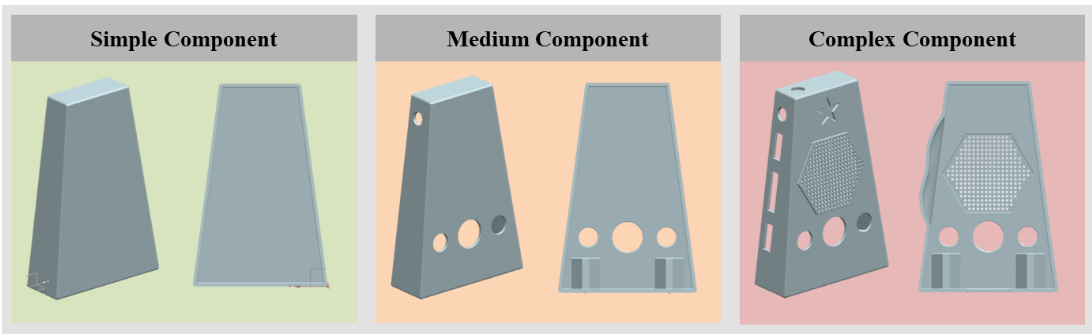

Figure 6: Geometry of the three exemplary components.

With the help of these three components, the economic efficiency of conventional and additive manufacturing methods can be compared. Bid prices and several information concerning the quality, production time and environmental sustainability are collected. The information operate in the background of the method. The ranking of the four production processes is based on the information that originate from real offers and literature. Besides the generation of information for the evaluation concept the bid prices are used to quantify the initially introduced correlation of the cost per unit and the lot size (see figure 1).

Figure 7 shows the correlation of real bid prices and lot sizes for the three exemplary components for the four manufacturing methods injection molding (green lines), milling (blue lines), selective laser sintering (black lines) and fused deposition modeling (grey lines). The name of the curve for the simple component is C1 for every production process and has a continuous line. The curve for the medium component is called C2 and is long dotted. The name of the complex curve is C3 and is short dotted.

The first chart has an ordinate from 0 to 10,000 € unit costs. The curves of the injection molding fall down with an increase of the lot size. This can be explained through the high costs of the in-mold assembly. Independently of the lot size, the in-mold assembly is needed. Therefore, the costs for the in-mold assembly are fixed costs, which are prorated on the single units. The curves of the injection molding equal the trend of the curve for conventional manufacturing in figure 1.

The second chart has an ordinate from 0 to 1,000 € unit costs, this means it shows the first tenth of the first chart. It is an enlargement of the first chart. With an increase of the lot size the unit costs for components produced with injection molding fall steadily. The blue lines of the milling are nearly constant. It can be seen, that the complex component is more expensive than the medium, and the medium component is more expensive than the simple component. To mill the exemplary components is very expensive independently of the lot size.

Nevertheless, the quality of the component is very good. Even if milling is a conventional manufacturing method, it does not show the typical trend with an increase of the lot size. Besides the CNC-programming, there are not any high additional fixed costs.

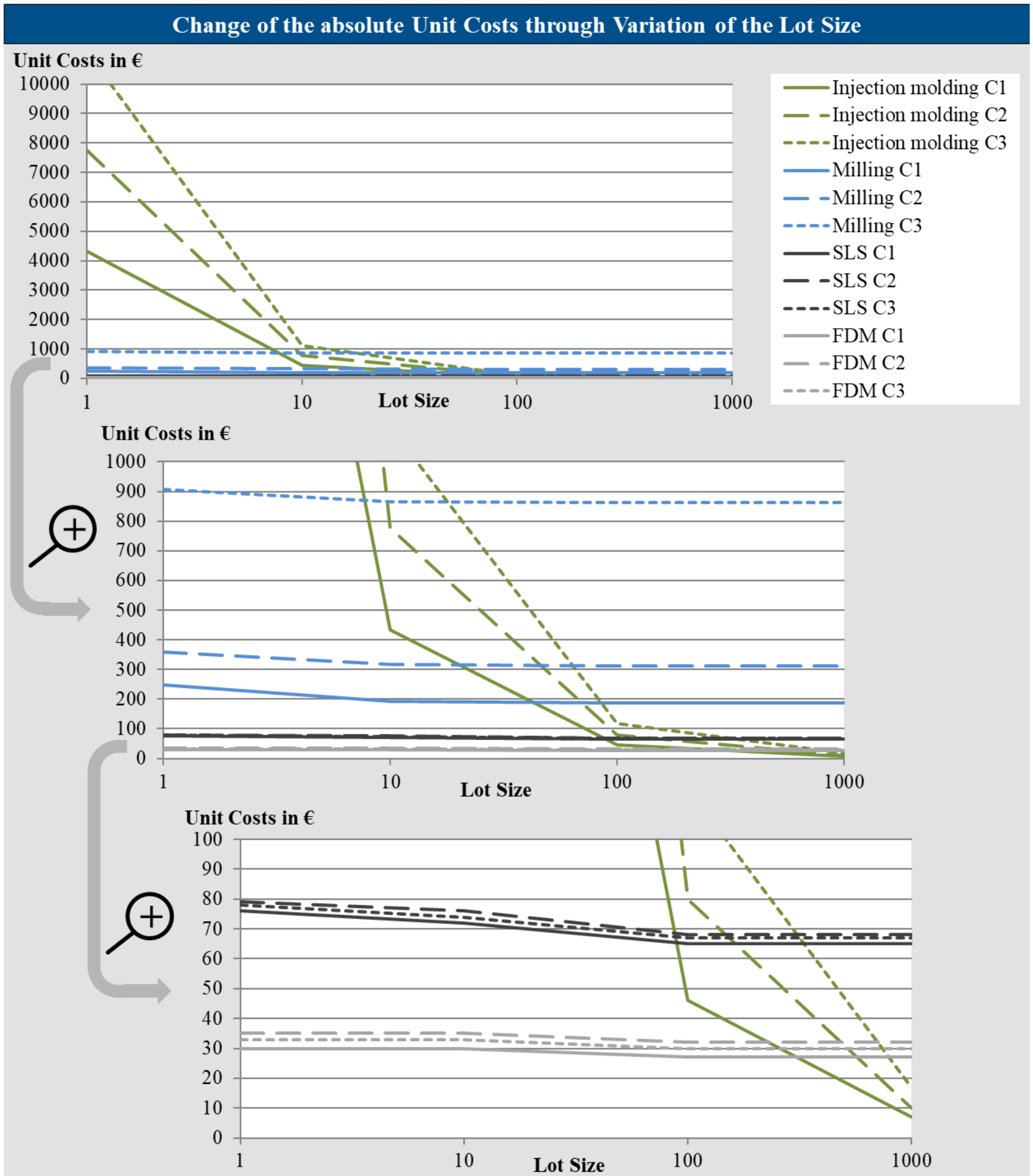

Figure 7: Correlation of real unit costs and lot size.

The third chart is again an enlargement of the second chart and owns an ordinate from 0 to 100 €. In this chart, the curves of the additive manufacturing methods can be seen. Independently of the component complexity, the single curves show a nearly constant course. For the selective laser sintering the unit costs sink a little bit with an increase of the lot size. On the one hand, this is caused by a volume discount, because real bid prices are used for the charts.

On the other hand, in one construction phase several parts might be produced depending on their dimensions and the dimensions of the construction space. Generally, the constant curve of figure 1 for the additive manufacturing can be confirmed with the different curves for selective laser sintering and fused deposition modeling. Producing the components with fused deposition modeling is the cheapest possibility, but the quality of the components are worst. Therefore, the developed evaluation method considers not only costs, but as well quality, time, environmental sustainability, component geometry and lot size depending on the user's preferences.

To investigate the functionality of the evaluation method a validation is conducted. With the help of a new exemplary component, the function of the method can be validated. The geometry of the new part is similar to the three exemplary components in figure 6, but it is not the same. For this component, both the method is used and real bid prices are obtained. The estimated price of the method is allowed to change in a range of ten percent compared to the real bid price. In case of the new part, the two prices differ circa 5 %. Figure 8 shows the prototype implementation of the user interface with the possibility to insert personal preferences. The geometry is evaluated for the validation component and is ranked as complex. The lot size is determined on 50 units. With a high preference in costs, low preferences in quality and time and middle preferences in environmental sustainability, the method recommends the selective laser sintering as production process. The estimated unit costs are circa 75 € with a medium quality and an estimated production time of seven days.

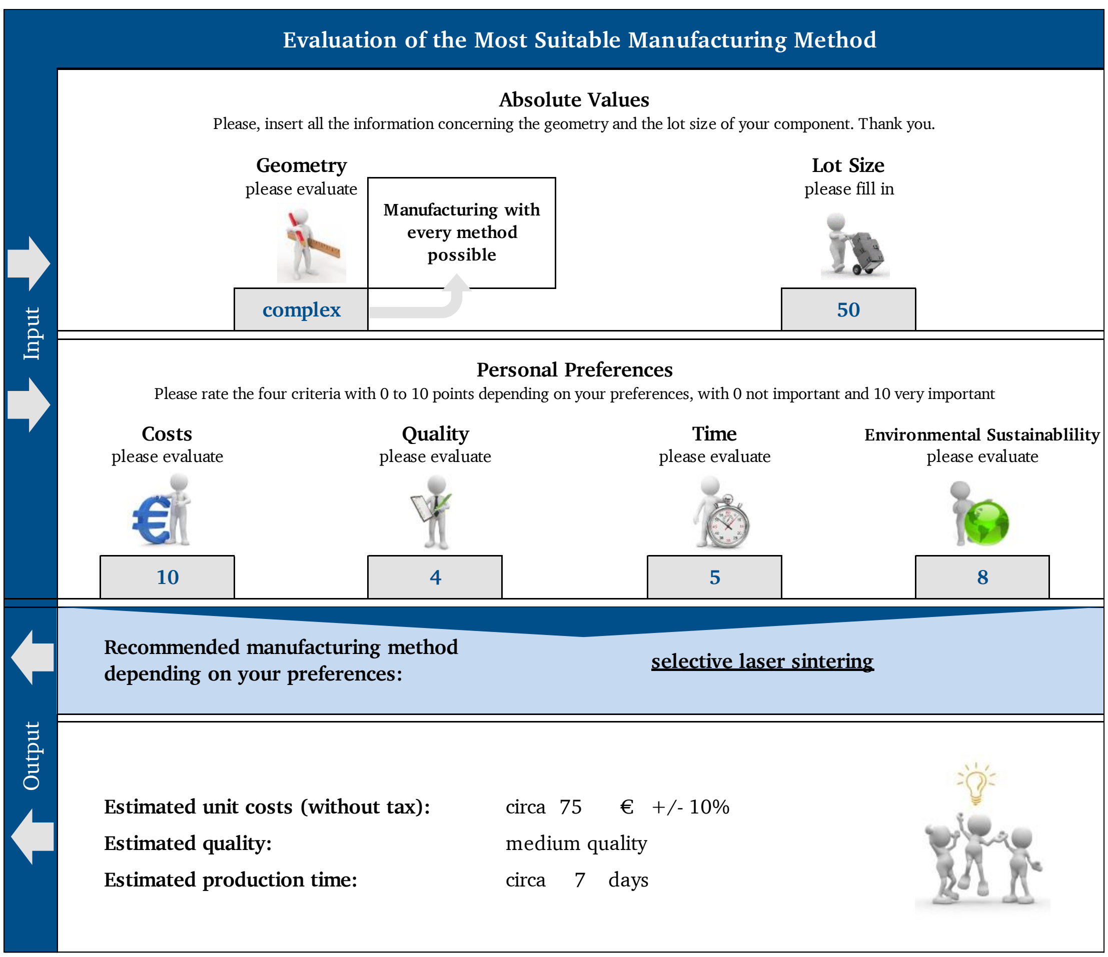

Figure 8: User interface with the validation example.

There is no output information about the environmental sustainability yet, because the preferences concerning this factor and the rating helps to choose the right manufacturing method. The three output factor estimated unit costs, estimated quality and estimated production time serve only as an orientation help for the user.

A screenshot of a real offer shows figure 9. The unit cost amount to 71,32 € with a lot size of 50 units.

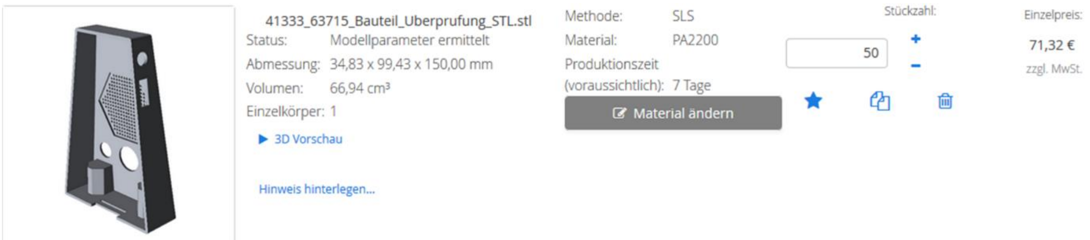

Figure 9: Real bid price for validation component.

With the help of the new part, it can be verified that the method is working well. The more information are integrated in the background, the better the estimated values are. Therefore, the next step is collecting more information concerning different component geometries and their prices – real and calculated – with the corresponding information about quality, production time and environmental sustainability.

Conclusion and Outlook

The prototypical implementation confirms the functionality of the developed concept for the evaluation of the economic efficiency of conventional and additive manufacturing methods. The initially introduced correlation of unit costs and lot size is verified with the help of real bid prices for exemplary components. Beside the costs, the concept of the method and the method itself contain five other comparative criteria. These are the quality, the time, the environmental sustainability, the lot size and the complexity of the geometry. The method enables an integrated consideration of the economic efficiency of the four manufacturing methods injection molding, milling, fused deposition modeling and selective laser sintering. This is important, because the four production processes lead to different qualities for example.

A further step is the integration of additional information. Besides, the determination of the geometry factor needs to be easier to contain the simple use of the method. Components with different geometries can be tested in the method and more bid prices can be gained. Through this step, the prices can be approximated for nearly equal components. Additionally, the information concerning the quality, the production time and the environmental sustainability can be extended. Besides the new information, additional manufacturing methods can be included in the method. A market-ready implementation with a database is then necessary.

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