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Method for evaluating the monetary added value of the usage of a digital twin for additive manufacturing

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Abstract

By combining the additive manufacturing (AM)-process with digital concepts, such as the digital twin (DT) or the digital part file (DPF), the competitiveness of additive manufacturing is increased. A quantitative approach to evaluate the usage of a DPF in AM will be introduced within this paper. The focus is set on the production as an early lifecycle-phase, which means that the AM-production process gets analyzed regarding potential advantages of using a DPF. These advantages are transferred into a monetary value with our approach. By calculating the total costs of the DPF, a monetary overall value is obtained.

Keywords: Additive manufacturing; Digital concept costs; Digital part file; Digital twin; Monetary value estimation

1. Introduction

Compared to conventional production processes, such as casting or milling, AM offers an economical production of individualized and functionally integrated products in batch size one due to its layer-by-layer structure [1]. Thus, it represents a useful supplement to conventional production processes in order to be able to react to the accompanying challenges of globalization, such as the increasing demand for individualized products and ever shorter product life cycles, and to be able to continue manufacturing of industrial products in industrialized countries with high labor costs. [2]

The DT is a crucial component for the industrial use of additive production technologies. On the one hand, the quality of additively manufactured components can be improved by evaluating sensor data generated during the production process, which can lead to an improvement in component quality [3]. On the other hand, the use of the DT can facilitate the organizational integration of AM into existing company processes, since the digital linking of data creates increased data transparency [4].

Furthermore, the decentralized production of additively manufactured components can be enabled with the help of a DT [5]. In this paper, decentralized production is understood to mean a local separation of the preparation and design of the production data from the manufacturing of the component.

Since the DT, according to its original definition, has large data and computing power requirements, it is reasonable and sufficient for some individual applications if it is reduced to the relevant functions for a specific use case [6] [7].

Therefore, the DPF for additive manufacturing processes has been developed at the University of Augsburg. The DPF bundles all relevant production parameters in a consistent format which ensures the completeness as well as the correctness of the transmitted data and thus enables the production process to be started. In addition to the target values of the process parameters, quality-relevant data that accrue during production can be stored for each manufactured component as required, for example, in order to carry out verification obligations or process improvements. The DPF can thus be seen as a version of the DT customized to decentralized production with AM technologies and provides a basis for a DT.

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This paper aims to present a quantitative approach that allows estimating the monetary added value of a DPF in AM. Therefore, first literature research on the DT is conducted to map the current state in this research field. In the Methodology, the developed approach as well as the defined use cases are presented. The findings of the developed approach for a suitable example and the implementation in a simulation model are illustrated in the Results. Subsequently the results are interpreted and evaluated in the Discussion. Finally, the findings of the paper are summarized in the Conclusion and an outlook on further research needs in this area is given.

To apply the introduced approach, it is necessary to define a general AM-process chain. The process chain defined for the presented approach can be seen in Fig. 1.

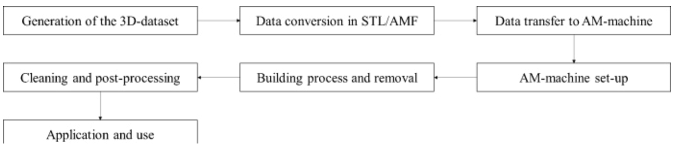

Fig. 1. AM-process chain bases on [1] [8].

In the first step of the process chain, a 3D data set must be generated. This data set can be created either classically by a designer using CAD software or by means of a 3D scan [1]. In the second step, it is necessary to convert the generated data set into STL or AMF format so that it can be processed by the AM-machine [9]. In the next step, the formatted data set is sent to the AM-machine and the system software is used to position the components on the build platform and slice the component geometry [8]. Then the AM-machine is set up and the process parameters, such as recoating time, are defined [1]. After the AM-machine is set up, the build process is started and the component is automatically created by a layer-by-layer build until its completion and can be removed [1]. The component is then cleaned and, depending on the requirements, mechanical, chemical or thermal post-processing of the component takes place [8]. After post-processing is finished, the component is available for its intended application. To collect and use the product data that are generated during the process chain the concept of the DT has been developed.

There are various definitions of the DT in the literature; its original general definition comes from Grieves [10]. Grieves defines the DT as the virtual linking of data from a real physical product with its virtual image [11]. The real physical product provides the sensor data that is generated in the production process, which is supplemented by historical data of the product, and thus enabling predictions about the future behavior of the product by analyzing the collected data [12]. Reference [13] provides a corresponding definition, which sees the DT as a virtual image of a physical object or process, which intelligently uses the data provided by the physically existing object or process for various applications.

The use of a DT in AM can lead to several benefits. One possible advantage resulting from the use of a DT is the increase in reliability of the build process, as the DT provides a standardized method for storing and analyzing the sensor data generated in the build process, and thus higher requirements for quality assurance and reproducibility can be achieved [3]. In addition, by evaluating the sensor data using various methods, defects can be proactively avoided, which saves both time and cost [14]. Reference [15] proposes a machine learning-based approach that uses the data stored in the DT during the construction process to reduce the effort required to qualify components. Combined with the blockchain technology, the DT can enable secure data transfer to meet, e.g., aviation's stringent certification requirements for component production [16].

Moreover, there is the assumption that a decentralized production of spare parts can only be realized if a DT or a DPF is applied within this use case. This assumption can be verified in literature [17]. Decentralized production allows a reproducible product to be manufactured at several production sites with the same input parameters [18]. This can lead to reduction in the overall costs of the value-added chain [19]. For the concept of decentralized production, it is necessary that no specific knowledge is required and that the components can be manufactured directly from the digital files [20]. To meet these requirements, the DPF has been developed at the Chair of Digital Manufacturing at the University of Augsburg.

Although quite a few authors have addressed the possible uses of the DT in AM and the opportunities it creates, there is so far no quantitative approach that attempts to determine the monetary added value of using digital technologies in AM. Hence, this paper presents a possible approach to estimate the added value of a customized version of the DT for AM.

2. Methodology of the evaluation approach

To evaluate the monetary added value, first the utility of the DPF and second the costs of the DPF are calculated. The monetary overall value is the result out of the utility calculation minus the costs of the DPF:

$$Overall\ value_{DPF} = Utility\ value_{DPF} - Costs_{DPF} \qquad (1)$$

2.1. Derivation of the use cases

Three use cases for evaluating the benefits of a DPF are identified from the literature review: First, the use case production with the potential benefits of quality and process efficiency of the DPF; second, the use case decentralized production, which offers a standardized data exchange; thirdly, the use case certification, for which the DPF provides data to simplify the certification of components.

The logic for calculating the utility of the use case production is referred to the avoidance of additional production costs. It is assumed that by using the DPF or the DT higher quality and a faster process time can be reached because the processes are optimized by using the additional information and data provided by the DPF/DT. For example, reject can be minimized and workers finish faster, resulting in lower costs. To calculate the utility in this use case, the production costs if the DPF is not used are compared to the production costs if the DPF is used. The difference from this is interpreted as the savings by using the DPF.

As literature shows, decentralized production of spare parts can only be realized, if a DPF or a DT is used for information exchange between the different production sites. Therefore, the valuation principle for the use case decentralized production is based on an additional functionality provided by the DPF. For evaluation, the value of realizing a decentralized production is taken from another paper [18] [19]. This value is also assumed as the utility of the DPF because the DPF is the prerequisite of the decentralized production.

Within the use case certification, the valuation principle refers to the avoidance of costs. By using the DPF, it is no longer necessary to physically store analog files of production data anymore, because they can be stored digitally.

2.2. Calculation steps of the approach

Utility calculation

The overall utility for each DPF is the unweighted sum of the utilities of each of the three use cases, which means that the calculation is structured modularly. Depending on the individual application of the valuation approach, each use case may or may not be considered.

As Table 1 shows, the utility of each use case can be further divided into hypotheses. There are the first eight hypotheses, which describe the use case production and one hypothesis for the use cases decentralized production and certification, resulting in total 10 hypotheses to be evaluated. For the identification of the hypotheses of the use case production, it was necessary to orientate on a process chain of an additive technology. For this purpose, the SLS process was selected as an exemplary additive process chain and divided into its sequences. This was followed by an analysis of the steps, in which a concrete benefit can be achieved, considering the two main benefit areas of quality and process. For these concrete benefits, a calculation rule was developed.

Table 1. Overview of the Hypotheses.

Hypotheses		Assessment intention
H1	Higher process-efficiency for data preparation	Using the DPF for data preparation results in a more structured way of work, which leads to saving of time and less errors during data transfer and entry.
H2	Process reliability for material preparation	By using the DPF for material preparation, optimized powder settings can be realized, whereby powder-related errors can be avoided.
H3	Optimized machine setup by using a simulation of the building process	By choosing the optimized machine parameters and setup, a smooth machine operation can be ensured and thereby a higher quality of the parts can be achieved. To identify these optimized values, a simulation of the building process is necessary. Now the assumption is valid, that such a simulation is only possible if the target and input data in form of a DPF are available.
H4	Consistent quality by monitoring the process parameters	The target data from the DT can be used to continuously check, if the actual data correspond to the target data. In this way, errors can be detected and avoided actively.
H5	Process reliability by applying Predictive Maintenance	Due to a broad digital database, maintenance intervals are strategically planned and unexpected process interruptions are avoided.
H6	Process reliability for removal of the parts out of the building chamber	A recorded position in the construction chamber defined in the DPF avoids process interruptions during component removal
H7	Process reliability for post-processing due to default parameters	Correct selection of parameters of the post-production proactively prevents process disruptions or damage to the part.
H8	Simplified detection of defect-reasons due to individual process data	A broad digital database enables the causes of errors to be identified more effectively and efficiently. For future processes, these errors can be eliminated.
H9	Enabling of decentralized production of spare parts by using digital data transfer	The availability of all production data enables decentralized production and its advantages of less transportation costs and time.
H10	Simplified certification with EN9100 for the aviation industry	The digital verification of production can simplify processes and save costs, as analog storage of documents is no longer necessary.

Use Case: Production

The approach is constructed in such a way, that for each of these 8 processes steps a modular utility is calculated. By summing up these values, the utility for the use case production results. The productions costs, which would result by using the DPF and those which result of not applying it, are calculated. The difference of these two values yields to the utility, which can be achieved by the DPF. By running the calculation with example values (see chapter IV), hypothesis 3 is identified as the most influential hypothesis regarding in terms of the amount of benefit. Since it is interpreted as the most important hypothesis of the use case production, it is presented below.

Table 2. Calculation steps of Hypothesis 3.

Calculation step	**Costs in case of using the DPF (which means using the simulation of the building process)**	**Costs in case of not using the DPF (which means not having the possibility of using the simulation of the building process)**	
Application of the parameter values	Set point	Distribution function (normal distribution)	
Resulting delay from the parameter value	Deposited function (oriented at [21]	Deposited function (oriented at [21]	
Percentage deviation from the reference delay	0 %	= Resulting delay / delay target value (of the individual parameters)	
Deviating total delay	0 %	Addition of the distortion values of the four parameters	
Total delay > critical delay	no	yes	no
Probability that the component is considered as reject	0 %	100 %	Linear function depending on the total distortion
Additional production costs	0	= Manu-facturing costs * probability of reject	= Manu-facturing costs * probability of reject

By using the DPF, which means that a building process simulation is used, there are no additional production costs, because the required machine settings are predetermined. In case of not having the DPF, the workers must select the parameters based on experience and trial and error. This yields to non-optimized settings and therefore to an unsmoothed process with a higher probability of defects. For the calculation of the production costs, the optimization and avoidance of the delay of an AM part is consulted, based on a paper of [21]. In the first step of the calculation, a normal distribution determines the "chosen" value of the parameters. Depending on this value, a resulting delay of the part is calculated based on a function of [21]. Dividing this delay by the resulting delay if the set point was used, gives a percentage deviation. This procedure is repeated for four process parameters, which have an impact on the delay of a part. The total percentage delay is the unweighted sum of these single delays. If the total delay is higher than a critical delay, a different probability of reject is calculated, as can be seen in Table 2. This results in different additional production costs, which can be interpreted as reject costs.

For each of the eight hypotheses of the use case production, there is an individual evaluation approach, which can differ of the approach for hypothesis 3.

Use Case: Decentralized Production

As the DPF enables decentralized production, as can be seen in the literature review, the benefit which can be realized out of decentralized production will be charged as the benefit of the DPF. The authors of [18] and [19] identify a cost advantage from using a decentral hub-configuration for spare-parts supply of additive manufactured parts. To calculate the benefit of the DPF, these savings are multiplied with a parameter of an equal distribution in order to ensure a general transferability of the value of this related paper.

Use Case: Certification

Within this use case, the benefit of the DPF is derived from the fact, that analog documentation of all process parameters is no longer necessary. On the one hand, this means that the employees no longer must invest as much time in document management. On the other hand, there are savings in material costs and storage of documents. The algorithm of the evaluation approach calculates the costs for storing analog documents, as can be seen in Table 3. These costs represent the benefit of the DPF.

Table 3. Calculation Steps of Hypothesis 10.

Calculation step	Calculation rule
Loss of productivity per employee due to analog document management	Distribution function (equal distribution)
Personnel cost savings	= Loss of productivity * number of employees affected * hourly rate (employees) / number of components
Material cost savings	= Number of copies * Printing costs * scaling
Storage cost savings	= Storage costs * Retention period * scaling / number of components
Fluctuation parameter	Distribution function (equal distribution)
Benefit of the DPF	= Fluctuation parameter * (Personnel cost savings + Material cost savings + Storage cost savings)

Table 4. Overview cost categories.

Cost category	Derivation of the cost category
Implementation and introduction of the DPF in the enterprise	It is assumed, that the DPF must be introduced in a company like any new IT-system. Therefore, this cost-category is represented by the costs of a project team responsible for the introduction of the DPF in an enterprise. In addition, the costs of programming the DPF are covered in this category.
License Costs	It is assumed that the software-company that developed the DPF claims license costs for using the DPF.
IT-Infrastructure	For using the DPF, one needs computing power and memory space. It is assumed, that these two elements are provided via cloud computing.
Hardware for production tracking	For generating utility from using the DPF, data from the production process must be stored in the DPF. Therefore, the costs for production hardware, such as sensors or cameras, must be considered as costs for the DPF.
Data entry and creation of every individual DPF	An individual DPF is created for each individual part. This means that specific parameters must be entered into the software. The time taken to provide and enter the data is interpreted as costs for this category.
Simulation of building process	If a simulation of the building process is applied, there are costs for executing the simulation. These are different cost items, such as the implementation of the general simulation model of this product and the individual implementation costs for adapting the general simulation model to the individual composition of the building chamber. In addition, there are hardware costs for special computers needed to run the simulation.
System operation/ administration	It is assumed, that even for running the DPF, there are administrative and cyber security-tasks, as for any IT-system. Thus costs for an IT-administrator need to be taken into account.

For each of the three cost categories of applying an analog part file, concrete costs are calculated based on probability functions of [22] and [23]. The overall costs of the analog part file are equal to the utility of the DPF.

Cost Calculation

There are seven cost categories, which need to be considered for deriving the costs for such digital concepts like the DT or the DPF. These are further explained in Table 4.

Calculation of the overall value

The monetary overall value is the result out of the utility calculation minus the costs of the DPF.

2.3. Design of a simulation-based calculation-tool

Since the algorithms of the evaluation method access the results of probability functions in many points, it can be assumed that each calculation run delivers different results. Therefore, these results are only one possible representation of the real state. To solve this problem and consider several of these possible states, a simulation can be used as underlying method [24].

To implement the algorithms, it is necessary to have on the one hand kind of a material-flow-simulation environment to display the entire production process. On the other hand, one needs a programming environment to implement the calculation steps. For this reasons, Siemens Plant Simulation was chosen to be the environment for the calculation tool.

For one trigger that runs through the material flow simulation, the whole evaluation method is calculated once.

The results are stored in tables. The user of the calculation-tool can choose the numbers of triggers to start, i.e., one can define how many different results for an overall value of the DPF one wants to calculate. This number is also interpreted as the annual production capacity of the exemplary company. The implemented algorithms work with distribution functions and random numbers from Plant Simulation. Therefore, statistic effects can be regarded.

Derivation of the reference scenario

For using realistic input values, a reference scenario was created. As described for the use case decentralized production, the results of external papers were used for our evaluation approach. For this reason, the reference-scenario must be constructed similar in structure to the scenario in those papers. The proposed scenario contains an additive manufactured part, which is used in a plane as part of a cooling system of the F-18 Super Hornet jet. This cooling system contains 100 different parts, for which the total demand is 5000 per year [18].

For the reference-scenario it is assumed, that the company employs 20 employees and holds 25 AM-machines.

Results of the calculation steps

The results of 5000 simulation runs show an overall value 20,81 € and a standard deviation of 40,56 € for the DPF. Due to this positive value, the usage of a DPF is recommended for the reference scenario. It can be assumed that a positive value is also obtained for other companies, hence we suggest using our proposed evaluation method to proof the advantageousness of the use of the DPF for each individual scenario. Then the results for the utility- and cost-calculation are presented in detail.

Utility calculation

As can be seen in Fig. 2, every hypothesis comes to a different value for utility. Since the use case production contains the first eight hypotheses, the use case shows an overall utility of 55,76 €, which corresponds to a percentage share of 88,9 % of the total utility of 62,76 €. Hypothesis 9, which represents the use case decentralized production accounts for about 6,9 % of the overall utility. The third use case, certification, has the lowest share of 4,2 %.

By consideration of the use case production, hypotheses 3 and 4 stand out. This means that the highest utility can be expected for quality-issues, as H3 is to avoid delays by using a simulation of the building process and H4 is to reduce other defects by choosing the right set points for different parameters. With these results, knowledge from the literature can be confirmed, as it is stated that a DPF or a DT supports quality issues in particular.

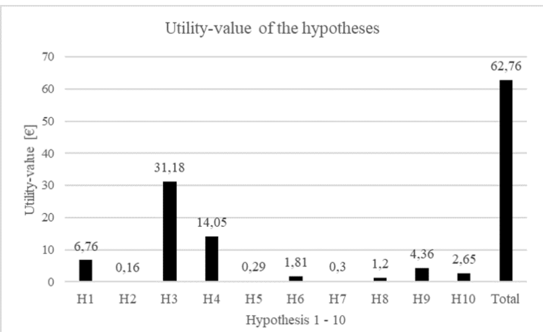

Fig. 3. Utility value of the hypotheses.

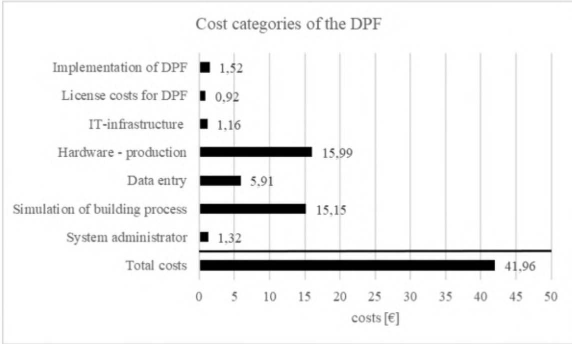

Fig. 2. Cost categories of the DPF.

Cost Calculation

The total costs by using the DPF are about 41,96 €. As can be seen in Fig. 3, there are three main cost-items. First the cost of using the hardware in production in order to collect the data, which is only an indirect cost-position for the DPF. This position is about 38,1 %. The second position can be interpreted as direct cost position, because the simulation of the building-process is an element of the DPF. These costs are about 36,1 % of the total costs. The third position considers the effort for data entry to create an individual version of the DPF. This part is about 14,1 % of the total costs. It can be assumed, that the costs can be reduced in future as data entry can be simplified by further digitalization of documents in a company. Apart from that, we used a very early version of the DPF for our calculations. This version will be further adapted in future and the data entry will be simplified. Another reason for decreasing costs can be a higher number of produced parts. Especially the costs for the hardware or for the simulation can be reduced, if they can be scaled about a higher number of produced parts.

3. Discussion

Overall, it can be stated that the presented approach realistically outlines the manufacturing process of an additively manufactured component and that by linking the findings from physics as well as production technology, the results can be assessed as realistic. In addition, specific added values of the DPF could be determined by using a simulation. In this way, it was possible to show what the actual added value of DPF could look like for an exemplary company. By segmenting the DPF into different use cases, the greatest potential benefits of applying the DPF can be identified.

Nevertheless, the presented approach with its focus on production does not include all life cycle phases of a product. In order to provide a comprehensive result, both the use phase as well as the end-of-life phase of the product had to be included. However, the modular structure of the approach enables the integration of these two phases. Furthermore, the assumption was made that the DPF is the basis for the implementation of construction process simulation, predictive maintenance, and decentralized production, and therefore the added values of these concepts were attributed to the DPF. However, there are several other factors that influence the application of these concepts, which are not considered here. Moreover, it is possible that not all potentials and cost drivers of the DPF have been identified and therefore they are not considered yet. However, due to the extensibility of the approach, there is the option to include these factors.

4. Conclusion

The paper introduces an approach to estimate the monetary added value of the DPF in AM. The background of the development of the presented approach is on the one hand based on the assumption that the potential of this combination is insufficiently recognized and therefore possible use cases resulting from it are not implemented. On the other hand, no comparable approach has been found in the literature that allows the monetary added value of a DT or DPF in AM to be determined.

In order to determine the monetary added value, 3 use cases are first defined and possible potential benefits are identified based on the additive process chain. Thereof, 12 aspects are derived that describe the benefits of the DPF and thereby enable a monetary assessment. Through the cost calculation of the DBA, a possible approach for the cost estimation of digital concepts is shown. For the application-specific determination of the monetary added value of the DPF, the concept is implemented in a simulation-based program. For an exemplary use case, an added value of 20.81 € is estimated.

An enhancement of the DPF to include sustainable information could generate additional added value, which is why future research needs should focus on sustainable aspects, as these will become even more important in the future. For example, by integrating the use and end-of-life phases in the presented approach, an exchange of product data and information could take place over the entire life cycle. This results in higher product transparency for a potential end customer, which could lead to a higher willingness to pay and thus represent a further potential benefit of DBA. In addition, this can enable sustainable courses of action, such as passing on information on the exact material composition of the product to recycling companies. In this way, the DPF can make a contribution to the reuse of raw materials and circular production.

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