Development of a method for evaluating the benefits of using a digital twin

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***Abstract*—The use of digital concepts, such as the digital twin, increases the competitiveness of industrial companies. Various possible applications of a digital twin are described in the literature. However, in order to drive their implementation, it is necessary to quantify the resulting benefits for companies. Therefore, an approach is presented in this publication that allows the estimation of the economic and ecological benefits of using a digital twin for a company. First, possible applications are identified based on the product life cycle and then their use potentials for the company are analyzed. The use potentials are categorized according to direct, indirect, and strategic benefits. After the categorization, models are set up to quantify the direct and indirect benefits. Thus, the presented approach enables an evaluation of the benefit of using a digital twin for a company. Through a use case in additive manufacturing the function of the method was validated.**

***Index Terms*—additive manufacturing, benefits, cost reduction, digital twin, ecological impact, LCC, LCA**

I. Introduction

Due to the two megatrends of globalisation and individualisation, the competitive pressure on companies is growing [1]. Although the increasing competitive pressure is increasing the power of innovation, companies are confronted with more and more cost and efficiency pressure [2]. In addition to economic goals, the importance of ecological goals, such as saving CO2 and the recycling of products, is increasing [3]. In order to meet these challenges, the arrival of digitalisation technology in industry offers new opportunities for companies [4]. One technology with great potential is the digital twin, using this new technology both economic and ecological challenges can be overcome [5].

To quantify this potential, this paper describes a method to support companies in evaluating the benefits that arise from the use of a digital twin. The term benefit describes the degree of satisfaction of a certain need that is caused by the use or consumption of a good or service [6] [7] . Depending on the target system, the satisfaction of the need is assessed differently [8].

In order to better differentiate benefits, they are divided into three categories: direct, indirect and strategic benefits. The direct benefit is defined as a benefit that releases funds, which arises through the generation of additional income and is therefore directly visible in the profit and loss account of a company [7]. Cost savings, for example, represent a fund-releasing benefit [7]. In contrast, the indirect benefit describes a benefit that is quantifiable but cannot be directly reflected in a company's finances [9]. Time savings through process optimisation are an example of an indirect benefit, as employees have more time for other activities as a result, but no new funds are directly released [7]. Strategic benefits are those benefits that are quantifiable but cannot be expressed in the form of key figures [10].

In this method, only the direct benefits are considered. The direct benefit is divided into an economic part, which can be generated in the form of cost savings, and an ecological benefit, which is defined as the reduction of environmental impacts. Before presenting the method, the related work outlines the current state of the art in this research area. In the methodology, the developed method is presented and then validated on a use case. Afterwards, the method is interpreted and evaluated in the discussion. Finally, the results of this paper are summarised in the conclusion and an outlook on further work in this research area is given.

II. Related Work

To assess the benefits of a digital twin, it is first necessary to define the digital twin and outline its potential benefits.

The definition of the digital twin has its origin in Dr Michael Grieves [11]. According to Grieves, the digital twin consists of a real physical product, a virtual image, and a virtual data linkage of these two components [12]. The physical product provides current sensor data, which is supplemented by all historical data of the product [12]. The future behaviour of the product can be predicted by evaluating this data [13]. Klostermeier et al. (2020) interpret the digital twin in a different wording but with identical meaning. They describe the digital twin as the individual, virtual image of a physical object or process, which makes the data provided by the physical object intelligently usable for various use cases [14]. Within the scope of this paper, digital twins are regarded under consideration of the product life cycle. The definition of the digital twin in the context of this work is based on the definition by Riedelsheimer et al. Accordingly, the digital twin is understood here as the virtual representation of a physical product, system, process, or service, regardless of whether the real image already exists or not [15]. This definition ensures the use of the digital twin throughout the entire product life cycle.

To simplify matters, the product life cycle is divided into the following three phases: development design, production logistics and application service. In the following, some examples of possible applications of the digital twin, which can provide a benefit for a company, are presented in the different product life cycles.

The Development Design phase covers the life cycle stage from the initial product idea to the point shortly before the start of production. Here, with the help of a digital twin, the product can be visualised as a 3D model with its main functions and other data, such as product competition and investment budget [16]. Through the integration of this additional information, the digital twin not only supports product developers in their spatial idea of the product, but also increases the level of detail and generates time savings because the relevant information is available in concentrated way [17]. In addition, geometric variations as well as tolerances can be considered with a digital twin in order to evaluate design alternatives and their effects on product quality [18]. On the basis of the geometric information and loads occurring on the product, which are stored in the digital twin, material can be saved by topology optimization [19]. Through the virtual representation of product prototypes in a digital twin, the required development time can be significantly reduced, and thus the start of production can be realised earlier [17].

Next, possible applications of the digital twin from the product life cycle phase production and logistics are presented. By transmitting production and equipment data in a digital twin, production planners can monitor whether the processes as well as the products correspond to the required specifications [20]. With a digital twin, production processes can not only be monitored, but also optimised on the basis of the generated production data, which is stored in the digital twin [**?**]. On the basis of this data, production alternatives can be simulated and optimisation potential can be identified by comparing simulation data with real-time data [**?**]. In addition, a digital twin enables product quality data to be correlated with the stored process parameters so that production parameters can be readjusted by analysing these correlations [**?**]. The digital twin thus offers a technical possibility not only to determine the status quo in real time, monitor it and intervene in the case of short-term deviations, but also to be able to assess and integrate optimisations by means of data analysis and simulations [**?**].

In the "Application Service" phase, a large amount of data is generated, which can offer great potential through the correct use of a digital twin, as the following possible applications show. An application with great potential is the predictive maintenance, which is based on the analysis of real-time data of a production machine [**?**]. Based on this data, forecasts can be made in the digital twin, enabling needs-based maintenance as well as forecasting of failures [**?**]. When the utilisation time of a component or even the entire system reaches the critical point, the digital twin signals a pending maintenance requirement based on the analysis of the data pool [**?**]. The components to be maintained can be viewed on the 3D model, which makes it possible to carry out maintenance more efficiently and reduce the risk of unexpected machine failure [**?**]. Equally, planning measures for optimising machine availability can be implemented in a timely manner for affected time intervals [**?**].

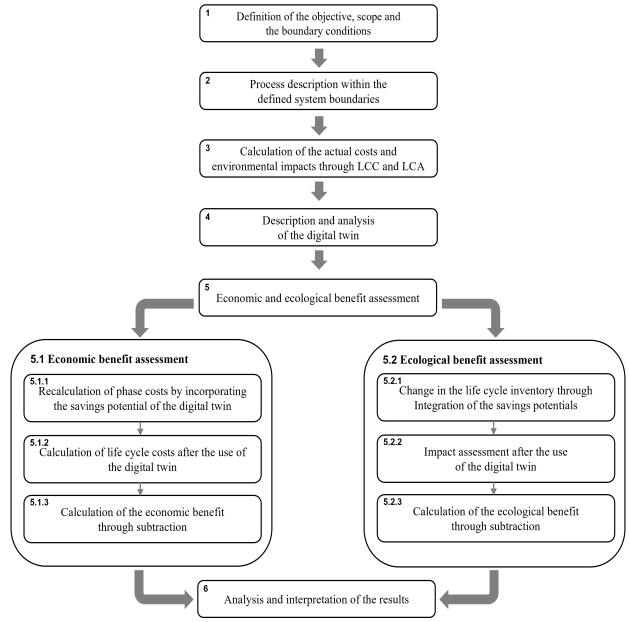

Fig. 1. Process of the Methodology

III. Methodology

Through all possible applications of digital twins in the industrial context it is not transparent which individual benefits are reachable by using them. Therefore, the following methodology is developed as a combination of LCC and LCA adapted to the usage of digital twins. In Fig. 1 the process is displayed. The steps 1 and 2 comprise the basic information to carry out this methodology. Here it is important to set up the goal, the system boundaries, individual conditions, that need to be considered, and the actual status quo of the processes that take place between the system boundaries. In step 3 the user calculates the actual costs and environmental impacts according to the methods LCC and LCA. The costs of a specific phase j of the lifecycle can be defined as the sum of all occurring costs of cost types i.

$$K_j = \sum_{i=1}^{n} K_{ij} \tag{1}$$

The lifecycle costs K_L can be determined by calculating the net present value over the lifecycle. Here the lifecycle costs can be described as the sum of the with the target rate discounted phase's costs K_j per each period t.

$$K_L = \sum_{t=1}^{n} \frac{\sum_{j=1}^{p} K_{jt}}{(1+1)^t} \tag{2}$$

In the context of determining the actual environmental impact, firstly it is important to set up the life cycle inventories. That means, that the user must define which inputs and outputs come into and leave the system. After setting up the life cycle inventories the environmental impact can be calculated by the multiplication of matrices and vectors. Vector $\vec{x}$ defines all inputs and their values. In the matrix B all emission factors are displayed, so which and how much of a specific emission occur by using the inputs of vector $\vec{x}$. This multiplication creates the new vector $\vec{b}$ as the number of outputs. The multiplication with the matrix C, defined as the characterization matrix to transform all outputs to a chosen impact category such as climate change as CO_2-equivalent, gives you the environmental impact as the vector $\vec{c}$.

$$\vec{c} = C \cdot \vec{b} = C \cdot B \cdot \vec{x} \tag{3}$$

Based on the actual economic and ecological status quo, possible applications of the digital twin must be chosen in step 4. Here it is important to describe in detail the specific application and the place of action of the digital twin to determine its arising effects. The effect of improving an affected factor can be described as the reduction potential E_d. The reduction potential is the difference of the value of an affected factor X before and after using the digital twin (DT), in relation to the value before its usage.

$$E_d = \frac{X - X^D T}{X} \tag{4}$$

With all calculated reduction potentials, you can go over to step 5 to determine the economic and ecological benefits. First, the way of determining the economic benefit will be explained. In step 3 the actual costs for all specific lifecycle phases and of the whole lifecycle has already been calculated. Based on these values the costs after using the digital twins will be determined by using the reduction potentials. The costs of a specific phase j after using the digital twin can be described as the sum of all cost values of the appearing cost types i, but decreased by its reduction potential E_d. The reduction potential E_d can be assigned to a cost type i in the phase j, if it is part of its cost structure.

$$K_j^{DT} = \sum_{i=1}^{n} K_{ij} \cdot \prod_{d=1}^{m} (1 - E_{dij}) \tag{5}$$

The lifecycle costs after using the digital twin can now be described as the sum of the with the target rate discounted costs of all lifecycle phases after using the digital twin per each period t.

$$K_L^{DT} = \sum_{t=1}^{n} \frac{\sum_{j=1}^{p} K_{jt}^{DT}}{(1+1)^t} \tag{6}$$

The economic benefit is now the difference between the calculated costs before and after using the digital twin K_L and K_L^{DT}. For the whole lifecycle, the benefit N_L can be calculated then as follows:

$$N_L = K_L - K_L^{DT} = \sum_{t=1}^{n} \frac{\sum_{j=1}^{p} K_{jt}}{(1+1)^t} - \sum_{t=1}^{n} \frac{\sum_{j=1}^{p} K_{jt}^{DT}}{(1+1)^t} \tag{7}$$

The calculation of the ecological benefit uses the status quo values of step 3 as well. Here a new matrix needs to be inserted as the reduction matrix D to make the ecological benefit calculable.

$$D = \begin{pmatrix} e_{11} & \cdots & e_{1m} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nm} \end{pmatrix} \begin{cases} n = m \rightarrow e_{nm} = \prod_{d=1}^{z} (1 - E_{dn}) \\ \text{otherwise: } e_{nm} = 0 \end{cases} \tag{8}$$

In this matrix all reduction potentials will be displayed across the diagonal that has a relation to a specific input of the vector $\vec{x}$. With this matrix and the multiplication with the actual vector $\vec{x}$ the new inputs after using the digital twin can be calculated. Here it is important, that not the number of inputs decreases, the value of the inputs will be reduced instead by its reduction potential displayed in the matrix D. Therefore, the new input vector after using the digital twin will be described as the vector $\vec{x}^{DT}$.

$$\vec{x}^{DT} = D \cdot \vec{x} = \begin{pmatrix} e_{11} & \cdots & e_{1m} \\ \vdots & \ddots & \vdots \\ e_{n1} & \cdots & e_{nm} \end{pmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} = \begin{pmatrix} x_1^{DT} \\ x_2^{DT} \\ \vdots \\ x_n^{DT} \end{pmatrix} \tag{9}$$

With this new vector, the multiplication process of matrices and vectors can be repeated, as already explained to determine the actual environmental impact.

$$\vec{c}^{DT} = C \cdot \vec{b}^{DT} = C \cdot B \cdot \vec{x}^{DT} \tag{10}$$

The ecological benefit regarding to a chosen impact category of using a digital twin is now the difference between the actual impact $\vec{c}$ and the reduced impact $\vec{c}^{DT}$.

$$N_{\vec{c}} = \vec{c} - \vec{c}^{DT} \tag{11}$$

The last step of this method is to analyze and interpret the results. Here it is possible to draw conclusions from the calculation process to find out which application of a digital twin has the most important economic and ecological impact to the business.

TABLE I
STATUS QUO OF THE USE CASE

Phase	$t = 0$	$t = 1$	$t = 6$	Total
R&D	1676400 €	-	-	1676400 €
Production	1507121 €	1530037 €	-	3037159 €
Recycling	-	-	39360 €	39360 €
SUM	**3183521 €**	**1530037 €**	**39360 €**	**4752919 €**
LCC				**4701958 €**
LCC / part				**235 €**

TABLE II
GWP OF THE STATUS QUO

Process	GWP [kg CO_2-eq]	GWP [%]
Aluminium production	11.884	25.39
Laser beam melting	34.917	74.61
Total	**46.801**	**100.00**

IV. EVALUATION

To validate the methodology, an already existing study to the costs and the environmental impact of the additive manufacturing is used [?]. In this use case, it is the goal to analyse the actual costs and the environmental impact of producing 20,000 shafts for the automotive industry by using additive manufacturing processes and their reduction potential by implementing digital twins to gain more experience about their benefits. In this use case the life cycle phases research and development, production, and recycling, which takes place after seven years, are considered. In the production phase the laser beam melting (LBM) is used as the additive manufacturing process. For that, eleven machines are available that run simultaneously. To define and calculate the different costs and emissions, the study delivers already existing factors and machining values, such as power consumption or machining time. The analysis of the actual status quo shows that the production phase is the phase with the highest occurring costs which is displayed in Table I.

Here, especially costs of idleness according to machining downtimes are very cost intensive. Also, the material costs are an expensive cost type regarding to the high prices for the additive manufacturing powder. For the analysis of the actual environmental impact just two processes are relevant for the global warming potential (GWP) as the chosen impact category. For this use case the two processes are the general production process of the aluminium powder and the machining process according to laser beam melting, which are displayed in Table 2. To define the inputs and outputs a database is used to set up the life cycle inventory. Due to that inventory the impact results show that the laser beam melting has a higher global warming potential than the production process of the aluminium. This can be explained by the high amount of needed energy and the actual used energy mix, which does not consist in total out of renewable sources of energy.

To reduce the actual costs and the environmental impacts, applications of digital twins shall be inserted and analysed on their reduction potentials and effects. The first digital twin is the use of topology optimization (DT1), the second one is the optimization of machining parameters (DT2) and the third and last digital twin describes the application of predictive maintenance (DT3). These digital twins cause some optimization and reduction effects on different factors that result in cost and environmental impact reductions. These affected factors with their old and new values per part are shown in Table 3.

The use of a digital twin to optimize the topology of a product can reduce the amount of needed material from 1.33 kg to 1.19 kg per part, which includes the needed powder which gets lost during the manufacturing process. Another application that has been analysed was a digital twin to optimize the machining parameters, in this case the laser path has been optimized due to simulation that results in reduction of machining time. A digital twin to applicate a predictive maintenance is able to reduce the downtime of the LBM machine from 7.09 h to 6.74 h per part. The values are used to calculate the specific reduction potentials E_d according to formula (4). After considering and inserting the reduction potentials into formula (5) and (6) the benefit can be calculated referring to formula (7). The actual costs, the reduced costs after using digital twins and the resulting benefit is shown in Table 4. Because of applying digital twins a benefit of 13.82 % based on the life cycle costs is reachable according to the highest cost reduction in the production phase.

The calculation of the environmental impact showed that digital twins are also able to gain a positive effect. In this use case the effects onto the global warming potential (GWP) have been examined. After setting up the actual lifecycle inventories consisting of all inputs and outputs, the reduction matrix D has been created.

To calculate the new input vector $\vec{x_1}^{DT}$ for the reduction of material usage from 1.33 kg to 1.19 kg, the matrix for the reduction potentials of using the digital twin for optimizing the product's topology needs to be multiplicated with the actual vector $\vec{x_1}$.

$$\vec{x_1}^{DT} = \begin{pmatrix} 1 - \frac{1.33-1.19}{1.33} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 - \frac{1.33-1.19}{1.33} \end{pmatrix} \cdot \begin{pmatrix} x_{11} \\ x_{12} \\ \vdots \\ x_{1n} \end{pmatrix} \tag{12}$$

After determining all new inputs and outputs according to the multiplication of matrices and vectors, the environmental impact before and after using the digital twin can be compared. Due to the usage of digital twins, the emissions for the aluminium production can be reduced by 10.53 %, for the laser beam melting process by 15.09 % and in total by 13.93 %. The results of the global warming potentials as the environmental impact before and after using digital twins are shown in Table 5, separated to the aluminium production process, the LBM manufacturing process and both processes in total.

TABLE III
IMPACTS OF THE DIFFERENT DIGITAL TWINS

No.	Digital Twin	Affected factor	Old value X	New value X^{DZ}
1	topology optimization	material quantity	1.23 kg	1.10 kg
		loss of powder	0.10 kg	0.09 kg
		machining time	7.09 h	6.34 h
		energy demand	39.50 kWh	35.33 kWh
		compressed air demand	183.99 m^3	164.54 m^3
		cooling water demand	1.09 m^3	0.97 m^3
2	machining optimization	maching time	7.09 h	6.74 h
3	predicitive maintenance	Downtime	0.088 h	0.0044 h
		Maintenance time	0.0055 h	0.0044 h

TABLE IV
ECONOMICAL RESULTS OF THE USE CASE

Phases	Costs w/o DT	Costs w DT	Benefit[€]	Benefit[%]
R&D	1676400	1558882	117518	7.01
R&D / part	84	78	6	7.01
Production	3037159	2497654	539505	17.77
Production / part	152	125	27	17.77
Recycling	39360	29700	9660	24.54
Recycling / part	2	1	1	24.54
Total	4752919	4086237	666682	14.03
Total / part	238	204	34	14.03
LCC	**4701958**	**4052080**	**649878**	**13.82**
LCC / part	**235**	**203**	**32**	**13.82**

TABLE V
ECONOMICAL RESULTS OF THE USE CASE

Process	GWP w/o DT [kg CO_2-eq]	GWP w/ DT [%]	Benefit[%]
Aluminium production	11.884	10.633	10.53
Laser beam melting	34.917	29.647	15.09
Total	**46.801**	**40.280**	**13.93**

The analysis of the economic and ecological results shows that each application of digital twins had a different effect on affected factors. In the economic context it gets visible that factors that result in high cost also produce high reduction potentials if they get effected by using a digital twin. Fig. 2 shows the difference of reached reduction potentials by different digital twins over the lifecycle phases research and development, production, and recycling. The highest reduction potential and with it the highest impact onto the cost in total results in using DT3 in the production phase, which is the use of predictive maintenance to reduce machining downtimes. Other digital twins have also reached a positive effect, but not as much as DT3. The impact potential of DT3 can be explained by the high costs that result through having a huge number of downtimes. A significant impact is reachable by affecting factors that are part of creating huge costs.

The analysis of the ecological results shows that factors, which are responsible for big emissions, need to be affected to get better results in emission reduction potentials due to the global warming potential. Fig. 3 displays the comparison of the digital twins for the topology optimization and the optimization of machining parameters, here the laser path. DT1 achieves in this use case a bigger impact than the machining parameter optimization, because it reduces the amount of needed material and the machining time per part because of less material for the layering of laser beam melting. The parameter optimization reduces just the machining time.

Due to this analysis, it becomes obvious that different digital twins can be used to achieve a positive potential due to cost reduction and to have a better environmental impact, but they are different to interpret and depend on the actual status quo.

V. DISCUSSION

Through the development of this methodology and its validation, there are a lot of advantages and possibilities that this methodology can deliver, but also some more points need to be mentioned that require further research demand.

It is positive, that this methodology bases on two already existing and validated methods, the LCC and LCA. The combination of these methods provides a stable and functional fundament to calculate and determine the costs and environmental impacts across the whole lifecycle. Due to that, an

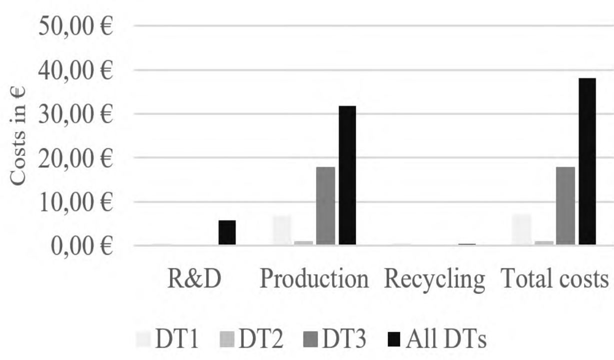

Fig. 2. Economic reduction potential of the different digital twins

increasing transparency of the status quo can be achieved. The calculation of actual costs and emissions gives the chance to show which factors need to be addressed by using digital twins to gain high reduction potentials. It is not necessary to implement a huge amount of digital twins, it is necessary to know which applications will affect my business efficiently and significantly.

Another point that needs to be considered is the scope of application for this methodology. It is not limited to specific areas. Every user can apply this methodology to analyze and optimize his business with numerical and interpretable values.

Next to all these advantages, there are also points requiring further research demand that need to be considered as already mentioned. First of all, just positive reduction potentials are included in this methodology. Upcoming costs or additional inputs that cause emissions by implementing digital twins, are excluded. This methodology delivers just hints and some advice, which digital twin affects the business positively. For investing decisions, also upcoming costs and emissions need to be considered into the economic and ecological calculation and analysis.

Another point that must be mentioned is the assumption and takeover of the implemented reduction potentials on factors of digital twins. In this use case the reduction potential on a specific factor was derived from current research. Reduction potentials differentiate individually. To get approximated results to the individual business, the individual reduction potentials need to be further analysed.

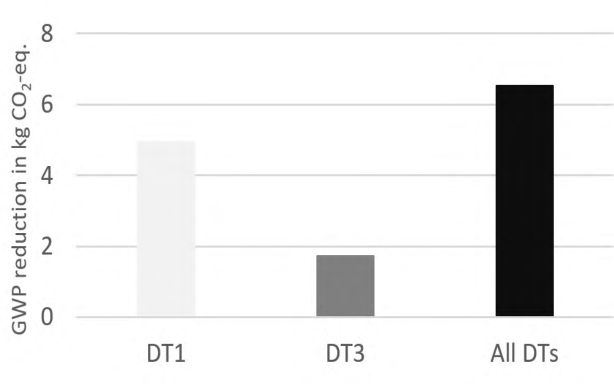

Fig. 3. Ecological reduction potential of the different digital twins

Additionally, it is important to say, that the manual usage of this methodology is complex and time consuming. In this use case, for the calculation and analysis of the environmental impact specific LCA software has been used. A manual usage of the formulas for calculating the environmental impact is not recommendable due to the huge number of inputs and outputs. Because of that, it is also highly recommended to use specific LCA software to reduce the complexity and expenditure of time.

VI. Conclusion

The aim of this paper was to develop a method to assess the benefits of using a digital twin for a company. For this purpose, it was first determined that the benefits are considered to be cost savings as well as the reduction of environmental impacts. Then the digital twin was defined for this work and an overview of different possible uses of the digital twin was given based on the product life cycle. By applying the method to an application example, its functionality has been validated. The Evaluation also showed that each Digital Twin has a different impact on the overall benefit for the company in the described use case. In the discussion the possibilities, advantages, and the limitation of the method were presented. Thus, the method presented here offers a possibility to compare different digital twins with each other in order to filter out the one with the greatest benefit potential. In addition, the implementation of the method increases the transparency of the economic and ecological situation of the company.

However, for a comprehensive functionality of the digital twin it is necessary to expand the scope of consideration. This means that from an economic point of view, not only cost savings through the digital twin should be examined, but also the creation of possible new costs through the integration of the digital twin should be included in the definition of the economic benefit. To this purpose, further research must be initiated to determine at which product and process points digital twins could also be considered as cost drivers. The revenue side must also be investigated. For this purpose, the effects of the digital twin must be researched, how this technology could influence earnings positively, for example by offering new services to increase earnings, or negatively in the form of earnings reductions. Furthermore, the interdependencies of digital twins should be studied more precisely to be able to make detailed and specific statements about their individual effects. Despite these limitations, the method presented here offers the possibility of quantifying the benefits of using a digital twin to a certain extent.

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