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Improving sustainability of additive manufacturing processes based on digital twins – a case study

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Abstract

Additive manufacturing (AM) became a key technology in the development of innovative products. Advancements have been made to improve economic feasibility. However, ecological sustainability is still an open issue of AM. To improve sustainability, it is crucial to track, visualize, and evaluate emissions along the lifecycle. This paper presents a novel Digital Twin based approach enabling prediction of the product carbon footprint (PCF) and prescriptive measures to improve sustainability. By improving part and process design, a significant PCF reduction was achieved.

Keywords: digital twin, additive manufacturing, sustainability, sustainable design, product carbon footprint

1. Introduction

Today, ecological sustainability is one of the most critical aspects global businesses must adapt to. Organizations are confronted with the necessity to navigate through emerging regulations and guidelines, such as the UN's sustainable development goals (SDGs) (United Nations, 2015) or the supply chain act of the Federal Ministry of Labour and Social Affairs (2021). Achieving sustainability objectives is recognized as a competitive advantage in the market and is highly valued by customers. A technological advancement to improve sustainability is additive manufacturing (AM). By reducing waste, AM is a meaningful way to improve resource efficiency in production. Further, it enables the use of modern product development capabilities such as generative design or topology optimization, leading to more optimal designs, which result in material and weight reductions as well as quality improvements. Another concept referred to as one of the major trends in engineering design is the Digital Twin (DT). A DT is *"a virtual dynamic representation of a physical system which is connected to it over the entire lifecycle for bidirectional data exchange*" (*Trauer et al., 2020*). Mainly due to its capability to mirror and predict the behaviour of a system over the entire lifecycle, it can be a significant contribution towards sustainable design. For example, it enables companies to meet the requirements of sustainability policies or to create a digital product pass, which is a driver for circular economy. This paper aims to combine the concepts - DTs and AM - to enable sustainable product designs.

2. Methodology

2.1. Literature review

To guide the literature review, a research strategy plan, as shown in Figure 1, was set up, combining the different objects of investigation. A search string consisting of 'AND' and 'OR' operators, in combination with the keywords 3D printing and AM, was entered into Scopus to filter relevant literature in the field of engineering. In the end, 28 relevant publications were identified and reviewed as a foundation for the state-of-the-art section.

AND

OR

Terminology	Investigation Aspect	Subject Area
Digitaler Zwilling	Nachhaltigkeit	3D Druck*
Digitaler Schatten	sustainability	AM Machine
Digital Shadow	Carbon Footprint	3D print*
Digital Twin	CO2 Emission*	FDM
Digital* Model*	Treibhausgas emissionen	Fused Deposition Modeling
PLC management	THG Emissionen	additive Fertigung
product life cycle management	Greenhouse gas emission*	additive Manufacturing
	GHG Emission*	

Figure 1. Literature research strategy for reviewing existing digital twins for sustainable additive manufacturing approaches

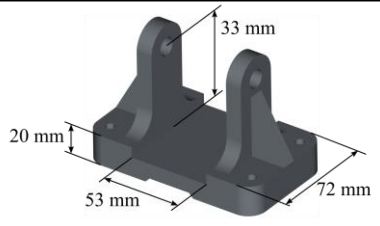
2.2. Digital twin toolbox

This case study was guided by the toolbox for the conception and implementation of DTs by Trauer (2024). The toolbox consists of six elements[1]: (1) a procedure model, (2) a DT business modelling approach, (3) a DT value map, (4) a DT use case template, (5) a DT use case catalogue, and (6) a DT trust framework. In course of this research project, the procedure model was used to guide the activities. The use cases were documented in the use case template, and the use case catalogue was used for the ideation of use cases (UC).

2.3. Emission accounting

To visualize the possibilities of a DT for emission reduction, a bracket is introduced as a reference part. The purpose of the bracket is to maintain another part, a pulley, in position. The mounted pulley creates a vertical load of 150 N. A deflection of 0.03 mm in load direction shall not be exceeded. Also, deflections orthogonal to this shall be small to prevent jamming. The part and use case are a modified version of the pulley assembly from Kumar (2023).

Table 1. Product rule for future comparison of the reference part and improved part

<table>
<tr>
<td>
</td>
<td>Estimated quantity: 1000 parts
Functionality: Positioning and fixation of a pulley
Estimated duration of usage: 5+ years
Additional condition: Easy mountability in an overhead position
Production procedure: Fused Filament Fabrication
Material: PLA
Printing parameters: Fixed</td>
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</table>

The product carbon footprint (PCF) of the reference product is calculated according to the Greenhouse Gas (GHG) Protocol product standard. For this example, material and energy flows are observed throughout the development and production phases. A so-called product rule (Table 1) is established inside the GHG protocol to allow comparison between the reference part and an improved part.

[1] The elements of the toolbox can be found online: https://www.mec.ed.tum.de/en/lpl/topics-and-software/dittid/

According to the standard, the functional unit and the reference flow are defined to enable a comparison. In this case, the same production method, material, surroundings, and production parameters are chosen. (World Resources Institute, 2011)

3. State of the art

3.1. Digital twins

The concept of DTs exists since the early 2000s (Grieves and Vickers, 2017). Accelerated by the fourth industrial revolution, DTs became one of the major engineering trends (Isaksson and Eckert, 2020). The different associated technologies, e.g., big data and AI, enable detailed digital representations of physical systems (Posada et al. 2015). However, not all digital representations can be called DTs. According to Trauer *et al.* (2020), the following characteristics must be fulfilled: (1) *"The Digital Twin is a virtual dynamic representation of a physical artefact or system", (2) "Data is automatically and bidirectionally exchanged between the Digital Twin and the physical system", and (3) "The Twin [includes] data of all phases of the entire product lifecycle and is connected to all of them"* (Trauer *et al.*, 2020). This vision of a DT is very ambitious. Subtypes of DTs were introduced. According to Kritzinger *et al.* (2018), a DT without bidirectional automated data exchange can be called a Digital Shadow, without any automated data exchange it is called a Digital Model. According to Trauer *et al.* (2020), DT use cases can further be categorized by the lifecycle phase they contribute to the most, i.e., Engineering Twins, Production Twins, and Operation Twins. By now, DTs are applied in various disciplines such as manufacturing, product development, and healthcare (e.g. Attaran and Celik, 2023; Fuller *et al.*, 2020).

3.2. Digital twins for additive manufacturing

In AM, cost and time are challenges in the production of mechanical components with a satisfying quality. To ensure a smooth production, the process parameters must be improved experimentally, thus adding to the challenges. In AM processes, a DT can be used to find a suitable set of parameters to ensure the desired product quality (Zhang *et al.*, 2020). With DTs helping to improve the printing quality, they can also play a role in the validation, certification, and optimization of a printed part (Phua *et al.*, 2022). Stark *et al.* (2019) also adds that the DT can be used to reach a better understanding of the system and optimize products and services. Those advantages are also summarized by DebRoy *et al.* (2017). According to Zhang et al. (2022), the development of DTs for AM is still in an early stage. In their study, they primarily identified applications of DTs to improve printing quality by simulating and adjusting printer parameters.

3.3. Digital twins for emission reduction

Emission reduction in AM. Literature lacks instances of DTs for emission reduction in AM. Previous research already analysed the impact of process parameters in fused filament fabrication (FFF) printing on energy as well as material consumption and thus carbon emissions (e.g. Kumar *et al.*, 2022; Harding *et al.*, 2023; Hopkins *et al.*, 2021). The review of Alfaify *et al.* (2020) showed that there are also efforts made to tackle topics like cellular structures, part consolidation, support structure strategies, and product sustainability for AM in general. However, research has yet to investigate the impact of part design on the sustainability of AM directly.

DTs for emission reduction. Popescu *et al.* (2022) underline the limitations of current product lifecycle management systems while facing environmental regulations, thus highlighting the need for more agile systems. A possible approach was mentioned by Metallidou *et al.* (2022) introducing a DT that generates multiple virtual scenarios based on energy consumption. Edrisi and Azari (2023) investigated how DTs can be used for sustainability assessments and policy evaluations. Tzachor *et al.* (2022) showed the impact of DTs on contributing to the UN's sustainable development goals by improving resource allocation efficiency and facilitating monitoring and reporting of progress towards achieving the SDGs. Zhang and Ji (2019) showed in their work an architecture for a DT driven, low carbon control manufacturing job shop. This architecture includes the physical and virtual world and adds two additional modules. First, the evaluation and prediction of emissions, and second, the control methods to enable low-carbon production. It becomes clear that, the data collected by the DT, needs to be further analysed and embedded in evaluation/prediction models before enabling carbon reduction efforts.

DTs for emission reduction in AM. A first implementation of DTs in the context of emission accounting for commercial 3D printers was shown by Winter *et al.* (2023). However, there is still a lack of information about the connection between part design and carbon emissions in FFF printing. On a more abstract level, there is also no existing framework which connects the stages of data acquisition and product development and gives suggestions to reduce carbon emissions in the case of FFF printing.

4. Academic case study

4.1. Use cases

With the use of the DT Use Case Template (Trauer, 2024) a variety of different DT use cases were identified in the context of emission reduction in AM. Out of those, three were classified as especially interesting and impactful. The connection between the use cases is shown in Figure 2.

The first one is the general **identification of emission highs and lows**. With the data collection groundwork of a DT, data analysis methods can be used to gather information about fluctuations in power and material consumption of different components. The second use case of interest is the predictive **estimation of emissions based on the design**. Building up on emission data gathered in the first use case, estimation models can be used to predict the emissions of a specific design early in the design process. When the specific emissions of a part can be predicted via the second use case, **design proposals to reduce emissions** can be made. Therefore, the part design can iteratively be improved to reduce emissions until other part requirements will be in conflict.

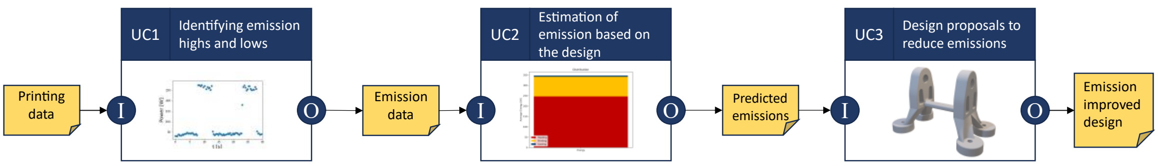

Figure 2. Schematic of the use case connection

4.2. Digital twin architecture

How DTs can be integrated into a system to improve sustainability is shown in Figure 3. The various forms of a DT are the foundation and framework of upcoming processes. The DT instance in this case represents one specific mirrored printer. The DT aggregated combines results of multiple DT instances, which enables a more global data analysis. On the highest hierarchy level of DTs lays the DT system, which combines different types of DTs to allow analysis with the big picture of a whole company, department, or overarching process in mind. This case study focuses on the DT instance. Additional technologies can use the framework of the DT to build up on the database and integrate their functionality in the bidirectional connection. The top layer includes the activities that are using the technologies (Grieves and Vickers, 2017; Soni *et al.*, 2019)

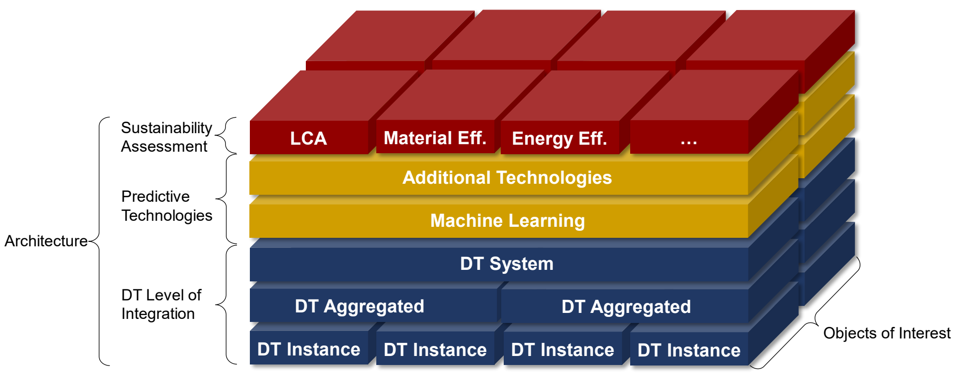

Figure 3. Structure of a digital twin concept for carbon emission reduction

The DT is realized with the help of various sensors and data sources. The measuring equipment captures the overall power consumption of the printer (Ender 3 pro) directly at the outlet. Various data about the printer is accessed through a Print Monitoring System. This includes information about the current printer state, the bed and the nozzle temperature, the feed rate, and more. All sensors and the printer are connected to a Raspberry Pi. The Raspberry Pi gathers the data and writes them into a MySQL database located on a server. Additionally, the slicer and CAD model data are also stored in the database. Figure 4 provides a system overview, including the current and data transfer.

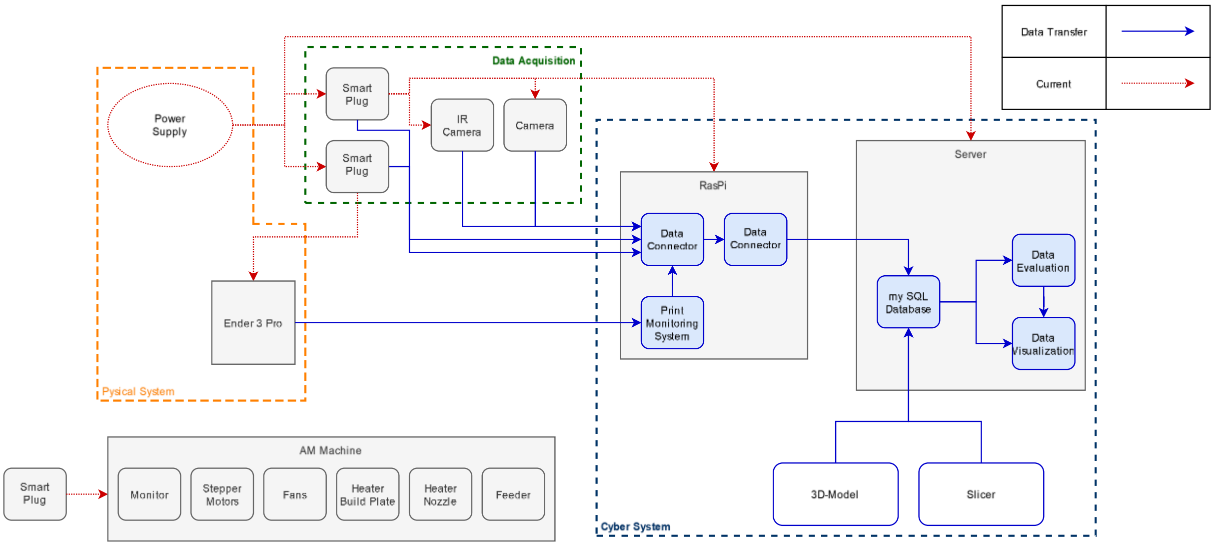

Figure 4. Schematic of the software and hardware interactions

The collected data can be categorized into real-time data, collected throughout the printing process, and static data that depends solely on the corresponding model. Different dashboards are employed to visualize the data. The live dashboard (Figure 5) presents real-time details of the ongoing printing process. The selection dashboard facilitates insights into previously printed parts. The data evaluation module is used to identify correlations between printing parameters, design variables, and emissions. It is also used to detect emission highs within the printing process. Currently the cyber system only evaluates and visualises the collected data without bidirectionality. Therefore, it is called digital shadow.

Figure 5. Excerpt of the live dashboards, displaying the temperatures (yellow, blue) and power consumption (green)

The temperature target is specified in the G-code for the nozzle/bed, while the actual temperature is the current temperature measured by the 3D printer. The difference between the target and actual temperature results in the temperature offset. The collected data and their origin are shown in Figure 6.

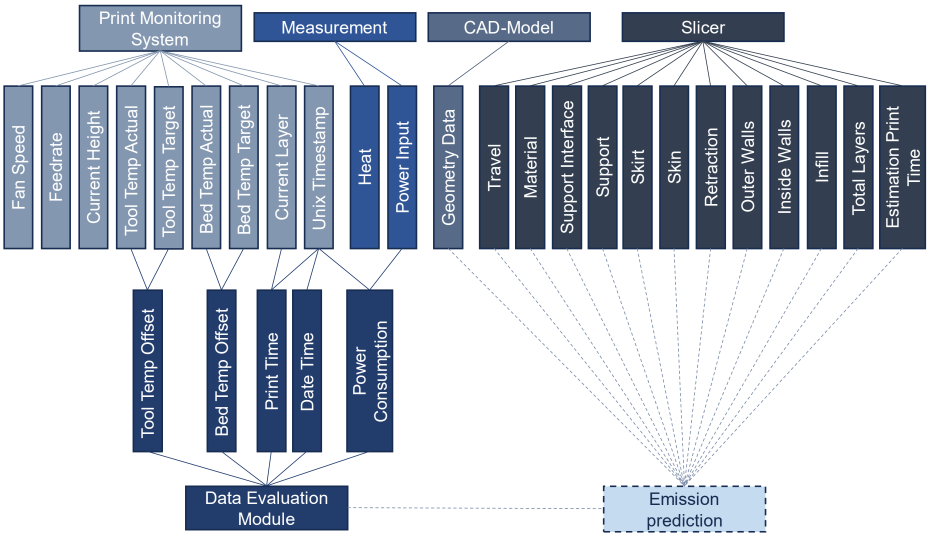

Figure 6. Connection between collected data and data sources

5. Results

5.1. Data analysis

In this section, we conduct an analysis of the experimentally collected data, with a primary focus on understanding power consumption during the AM process. The Pearson coefficient revealed correlations between power consumption and other printing parameters. Notably, the strongest correlation can be found between power, the actual bed temperature (0.47), and actual tool temperature (0.17).
For identifying emission highs, an upper bound higher by 1.5 times the standard deviation than the mean of all datapoints was defined. Statistical comparisons between values over and under the upper bound highlight interesting patterns. Bed temperature actual, bed temperature offset, and feed rate exhibit average differences for emission highs, while other variables show no significant distinctions.
Examining the temperature control during printing, the bed temperature ranges between 59.41 °C and 60.94 °C, while the tool temperature ranges from 195.37 °C to 202.19 °C. A closer look at temperature maintenance during printing reveals varying power consumption for both the bed and tool components. Bed power ranges from 3.39 W to 226.86 W, with a consumption of 61 Wh over 20 minutes. Tool power ranges from 20.28 W to 31.61 W, with a consumption of 25 Wh over 20 minutes. The difference in power consumption is displayed in Figure 7. Due to better readability, only every fifth datapoint is displayed.

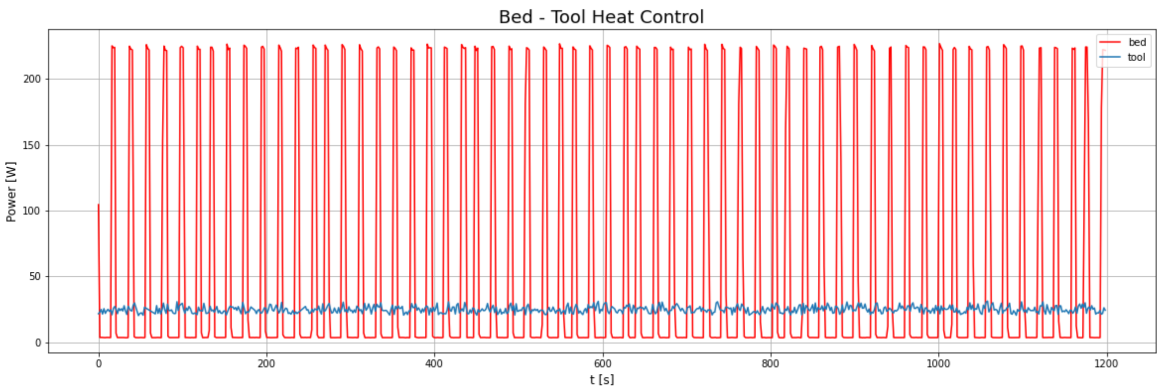

Figure 7. Power of the printing tool (blue line) and the printing bed (red line) illustrating the impact on the overall power consumption

Comparing the printing process between a hollow cylinder consisting only of outlines and a cylinder of the same size containing infill reveals insights into manufacturing dynamics. The mean feed rate for outlines is 1278.14 $\frac{mm}{min}$. In contrast, the mean feed rate for the part with infill is 7396.32 $\frac{mm}{min}$.
Lastly, parts with different overhang scenarios show variations in print time and energy consumption. Notably, the print time for scenarios with an overhang that needs a support structure is higher, accompanied by increased energy consumption.

5.2. Identification of emission highs

The data collected showed that the FFF printer, with standard speed settings, significantly slows down while **printing surface areas** in comparison to the printing of infill. The reason for this is to ensure a high-quality surface on the outside by reducing ringing - the effect of an uneven layer occurring on the surface. In the example shown in Figure 8, a full-body cylinder is compared with a hollow version. The mass of the hollow version is lower, but the printing time stays the same, resulting only in a small difference of carbon emissions. Other design choices also affect the printing time.
Overhangs over the standard threshold of 45°, suggested by the slicer, need additional **support structures** and are therefore increasing material consumption and printing time. Additionally, the first phenomenon could come into place when two designs are compared with one having an additional increase in the surface structure. An example of different overhangs can be seen in Figure 8.
When the heating process is considered, the **heating of the build plate** shows a significantly greater energy consumption than the heating of the nozzle because of the difference in heating area. In the case of most commercial FFF printers, the whole build plate is heated to a fixed temperature value.
General mass reduction is directly connected with material, transport, packaging, and printing emissions. If other design criteria are not neglected, such as support structures, a mass reduction goes hand in hand with a reduction of emissions.
Another driver for the printing time are **retractions**. Those describe the action of the nozzle stopping the extrusion of filament. This happens when the nozzle moves without printing, like on layer shifts and horizontal non-printing movements.

5.3. Design proposals

Reducing the mass of the part. The mass has a direct impact on material consumption and printing time. Furthermore, the mass of the material used also influences transportation and packaging processes in the upstream value chain. This means lightweight design is a significant measure to reduce carbon emissions. The comparison of both parts is displayed in Figure 8. Applying topology optimization, followed by a manual redesign, a new part was designed, following the Product rule. It maintains both functionalities, the required maximal deflections under load, as well as its ability to mount a pulley. Resulting in more individual geometries, the mass could be reduced by 45% to 16g. Both the conventional and optimized designs, fulfil all requirements on maximum stresses and displacements for the given load cases, as verified in finite element simulations.
Improving the design for a better build plate fitting. Through the open area in the middle of the part, it is possible to use the build plate area more efficiently, as seen in Figure 8. The emissions connected to heating the build plate can be distributed to more parts. The reference part allowed the printing of 15 parts simultaneously, the new design allows 21.
Reduction of surface area. With the mass reduction of the reference part, the overall surface was also reduced. The total surface area was reduced by approx. 26 % from $38000\ mm^2\ to\ 29000 mm^2$.
Reduction of retractions. Because retractions happen when the layer is changed, a wider part design is more retraction-friendly than a higher one. Also, a connected structure means the nozzle needs to lift less and, therefore, reduces retractions, while distributed structures will add more retraction time.
The derived design proposals of our study mainly overlap with established Design for Additive Manufacturing principles (e.g., Lachmayer *et al.*, 2022; Diegel *et al.*, 2019). However, the importance of individual design principles differs when designing for sustainability compared to designing for cost or pure manufacturability. In the end the PCF was reduced from $720\ gCO_2 - eq$ to $476\ gCO_2 - eq$ for a single part, mainly driven by a reduction of mass and surface area. The $CO_2 - eq.$ was calculated

following the product standard of the GHG-protocol, the procedure is shown in Figure 9. The approach in this paper focuses on the manufacturing process, also shown in Figure 9. The figure also shows the attributed process steps, as well as the distribution of emissions and the scope of the life cycle analysis.

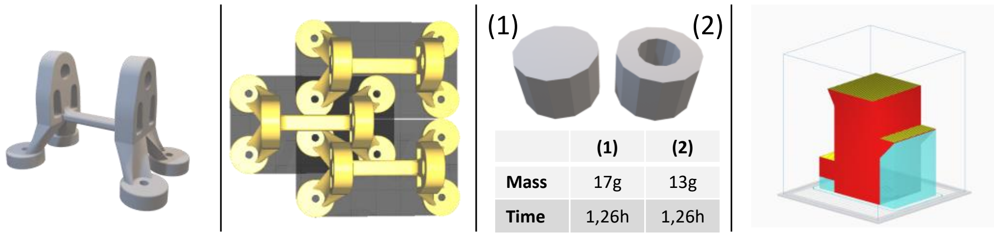

Figure 8. a) Design of the optimized part; b) Improved build plate arrangement; c) Comparison of a full body and hollow part; d) Design space for support structures for different overhangs

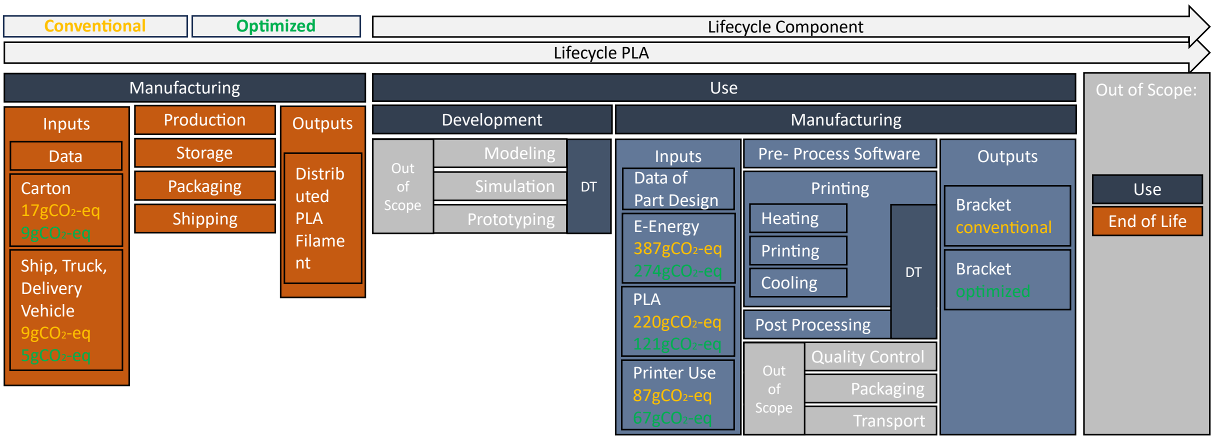

Figure 9. Accountable processes of the investigated bracket for the measurement of emissions (Icha and Lauf (2023), Fonseca *et al*. (2023))

6. Discussion

The comparison of different printing scenarios, such as infill versus outlines and varying overhang types, highlighted key factors influencing printing time and energy consumption. Thus extending the printing parameter analysis of Kumar *et al.* (2022), Harding *et al.* (2023), and Hopkins *et al.* (2021), by also taking the impact of part design into account. However, largely trained emission forecasting models still need to be developed. Additionally, Winter *et al.* (2023) came to the conclusion that 30% of the printing energy consumption can be attributed to the build sheet and nozzle. In the case of the emission-improved part, $82g\ CO_2 - eq$, which are attributed to the heating processes, can be further distributed depending on how many parts can be fit on the build plate, which was not considered in this emission analysis. The presented approach was made for a commercially available small FFF printer (Ender 3 pro). This means the analysis is only partially applicable to industrial printers. Nevertheless, the systematic approach is independent of the production method. It should also be mentioned that, due to the absence of bidirectionality in this work, a digital shadow was developed as the first step towards a DT.

7. Conclusion

Approaches using DTs to reduce emissions already exist. Winter *et al.* (2023) present a concept of a DT for emission reduction in the field of AM, focusing on adjusting the printing parameters. However, there are no publications focusing on the optimization of design parameters as well. Therefore, the novelty of this paper lies in establishing a link between design variables for 3D printed products and the resulting emissions during their development and manufacturing processes. To achieve this goal, a digital shadow was developed to collect data during the printing process and analyse it regarding the impact of design variables on emissions. In an iterative process, the identification of emission peaks and proposals for design improvements were implemented. Identifying design proposals to reduce emissions, as explained in section 5.3, offers actionable insights for advancing the digital shadow toward a Digital Twin (DT). This may involve integrating factors such as the time difference between printing surface area and infill into automatic design adjustments or facilitating the automatic creation of a retraction-friendly design. While the approach is focussing on FFF printing, the general approach for assessing and improving emissions can also be applied to other AM processes. To summarise, this paper shows the potential of DT in AM regarding sustainable design and presents recommended actions for reducing emissions in the design phase of the investigated bracket.

8. Outlook

This study is laying the groundwork for future research of emission reduction in AM. One aspect is generalizing the findings for specific part classes. By exploring different part geometries and their impact on emissions, the presented design proposals can be extended beyond conventional recommendations in AM. Another aspect for future implementation is the development of the digital shadow into a DT by adding bidirectionality through automatic improvements of the part design regarding sustainability. The framework can be further extended to integrate advanced prediction and machine learning models to support decision making in product design, focusing on sustainability at early stages of the product life cycle. Another useful extension is the integration of costs, as their behaviour in many cases parallels or is transferable to emissions. Considering the design recommendations for reducing emissions, there is a possibility that these or other design aspects may be partly contradictory. Accordingly, a multidisciplinary assessment could be necessary. While this paper focuses on FFF printing, the transferability and applicability of the findings to other areas of AM, such as metal AM, should also be considered. By addressing these areas, the outcomes of this case study and future research can contribute to the development of more sustainable products.

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