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Sustainability Assessment of Products manufactured by the Laser Powder Bed Fusion (LPBF) Process

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Abstract

Assessing the sustainability of a product is dependent on considering individual product life cycle data. Based on the information on material, energy and information flows, evaluation tools such as the life cycle assessment (LCA) or the calculation of the cumulative energy consumption can be used. Especially the methodology of LCA according to ISO 14040/44 allows a selection of alternative analysis and measurement cycles as well as a combination of impact assessment indicators that have a direct and significant influence on sustainability. The comparison of various manufacturing processes allows the identification of relations between the applied evaluation tools and the product- as well as process-specific parameters during the production phase, and throughout the entire product life cycle. Within the various case studies considered, a distinction can be made both between the definition and the indicators of sustainability and between the ecological, economic or social dimensions within the motivation formulated. This paper describes the results of the literature review on the sustainability assessment of additive manufacturing processes in general as well as the Laser Powder Bed Fusion process as an example. A research map shows which phases of the product life cycle of an additive manufactured component are considered and which methods can be used to assess their sustainability. The result is a summary of the state of the art regarding the methods of sustainability assessment of additive manufacturing processes. In addition, an outlook can be determined on how the different phases of the product life cycle can be evaluated with tools that currently receive less attention.

Keywords: Sustainability Assessment; Additive Manufacturing, Laser Powder Bed Fusion, Systematic Literature Review

1. Introduction

Following the movement of Industry 4.0, the production process of additive manufacturing technologies enables a possibility of linking the interests and producibility of highly complex components and products [1]. In this context, various approaches, methods and limitations can be identified within the wide-ranging current literature and can be linked to the increasing demand of standardisation [2].

When assessing the sustainability of additively manufactured products and the associated processes, the question arises as to whether and to what extent standards, such as the ISO 14040 series of standards, should be used as a comprehensively applicable method or be modified for additive manufacturing or more specifically metal additive manufacturing like the laser powder bed fusion process.

Not only the divergent interpretations of the multi-dimensional sustainability definition and the identification of the process chains and process parameters to be examined are problematic [3].

Therefore, as a result of a systematic literature review (SLR), this paper aims to provide information on the phases of the SLR investigated in the existing topic-specific publications, the methods applied and the limitations identified within the investigations.

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2. Methodology: A Systematic Literature Review

In this paper, the SLR method was used. The aim of SLR is to capture and evaluate the current research findings in a specific area of knowledge by means of this methodological approach [4]. According to Xiao (2019), a research gap identified is only valid if the boundaries of the knowledge which is already available can be clearly and consistently delimited [5]. Defined as "A systematic literature review aims to comprehensively locate and synthesize related research using organized, transparent, and replicable procedures at each step in the process" it becomes clear how an SLR differs from a traditional literature review - by being able to combine systematic, transparent, and replicable values [4, 6].

Following Kitchenham's assumptions, an SLR can be classified into three fundamental phases in planning, execution, and review [7]. The phases are extended by Mengist (2020) via the PSALSAR method, which includes a set of six different stages [8].

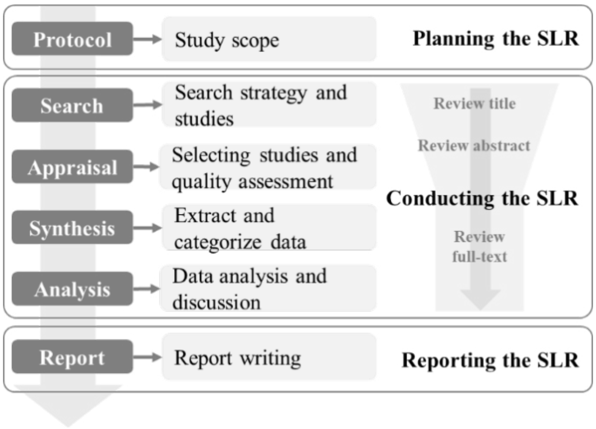


Fig. 1: Phases of a systematic literature review according to [5,8]

These different stages, as well as the included duties, are shown in Figure 1. In addition, these assumptions of Mengist (2020) are connected to the process flow of a SLR according to Xiao (2019) and extended in order to be able to use the highest possible detailed approach for a SLR in the following. Based on the formulated research questions, the following section describes in more detail the scope of these various steps by using the example of the literature research in order to identify and evaluate all available influencing factors [4]. To provide a comprehensible framework for the implementation of the SLR, this illustrated methodology is used as a basis for the further proceedings according to Mengist (2020) (cf. Figure 1) [8].

3. Results

The following sections present a summary of the procedure and the resulting (intermediate) findings generated in the phases of the linear process of SLR shown in Figure 1. To enable a formulation of an overview of the currently available literature in the field of sustainability studies and its orientation, the primary focus is to provide an overview that is as up-to-date as possible.

1.1. Protocol:

During the first phase, the preparation of the protocol, various questions preceding the actual research have to be answered for limiting the context of the research. Most importantly, it is the validly formulated research question that determines the direction of the SLR. The three research questions have been formulated according to the CIMO model by Briner et al. (2009), which assesses the quality of research questions according to four different aspects. The context (C) refers both to the systems under consideration and their interrelationships, while the aspect of intervention (I) focuses on the effects or actions investigated. In addition, the mechanism (M) aspect under study forms an explanation of the relationships between the resulting outcomes (O) and their interventions [55].

For this paper's case, these are:

- "Which phases of the product life cycle are examined in sustainability assessments of additive manufacturing processes?" (RQ1)
- "What research work has been done in publications in the field of sustainable additive manufacturing, and what methods are used in it?" (RQ2)
- "Which outstanding questions and limitations can be identified as a result of sustainability assessments conducted within the additive manufacturing field?" (RQ3)

The aim of answering these three research questions is to create the most comprehensive picture possible of the state of the art regarding sustainability analyses for the use case of the LPBF process.

To further limit the pool of literature to be analyzed, the focus will only be on metal additive manufacturing. The aim is to create a picture of the current situation that is as holistic as possible, to identify statements regarding the hotspots within this research area as well as future questions and research gaps.

1.2. Search:

In the second phase, the "search" itself, the applied strategy has to be formulated in the beginning. The question to be answered in this phase relates both to the choice of keywords used and their combination in the form of search strings. Since this research focuses on metal additive manufacturing, keywords in this field are "LPBF" or "Laser Powder Bed Fusion" to specify the publications referring specifically to these types of powder bed based processes. Also, since the expression was mixed in the earlier years of research, "SLM" or analogously "Selective Laser Melting" is defined as well. Moreover, the publication should be filtered out, dealing with sustainability-related evaluations or assessments. In order to address these investigations by keywords, these keywords were defined as "Sustainability" and "Assessment" referring the range of methods used.

To be able to filter out publications that are relevant to the research questions within a database by using these keywords, a searching string was used:

- ("Sustainability" AND "Assessment" AND “Additive” AND ("LPBF" OR "SLM")).

Both of these searching strings were applied to two different databases to generate matching results. The first one is Scopus by the scientific publishing company Elsevier and the second one is Google Scholar.

As a result of these first searches, there is a pool of publications of different types, which has to be filtered in the coming phase of the "Appraisal". The quantitative structure of these results is shown in the following table 1 according to the matches of the search terms in title or abstract.

Table 1. Quantity of searching results by database

Database	Results
Science Direct	522
Google Scholar	1.520

Based on a first search with the predefined searching strings, a large pool of especially english-speaking publications can be identified, which match with the titles or abstracts stored in the database and have to be considered in the further steps.

1.3. Appraisal:

The third phase, "Appraisal", involves decisions regarding the criteria that will be used to include or exclude publications from the subsequent analysis. Each of these formulated criteria can lead to the exclusion of publications and consequently to the reduction of the pool to be analyzed.

Current time of publication:

A first exclusion criteria is the time period in which the publications were published. Since the actuality of the publications to be analyzed is essential for a high quality capture of the state of the art, the range to be analyzed was reduced to recent publications of the last six years. The resulting breakdown of the remaining publications in terms of quantity over this period is shown in Figure 2.

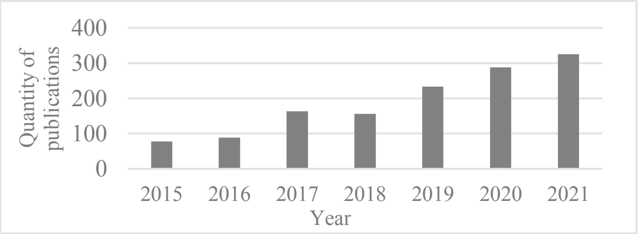


Fig. 2. Spread in time according to the year of publication

In relation to the publications published each year, an increasing trend is evident for the examined range of the last six years. The number of publications whose title or abstract matches the search string has increased by a factor of 4.167 compared to 2015. The continued attention and interest in possible potentials of metal additive manufacturing for sustainability is therefore obvious.

Limitation in accordance to the first 100 publications:

As no significant reduction in the number of published papers can be observed despite the temporal restriction, the pool to be analyzed is restricted in the following to an upper limit of 100 publications per search iteration. The resulting pool of a total of 136 publications can now be analyzed regarding the hotspots of the most research intensive regions. Based on the premise that an increased research activity in this area can be assumed from a number of two publications and above, the result is a global research map as shown in Figure 3.

It is noticeable that the focus in the European area is on the one hand on the KU Leuven (3) and the Universidade NOVA de Lisboa (5).

Figure 3. Geographical mapping of the publications

Meanwhile, in North America, McGill University Montreal (3) and Texas Teh University (3) show a high level of research activity.

Screening by title:

With the following screening of the titles it is also determined regarding possible inconsistencies in the orientation of the publications, such as the investigation of purely conceptual or construction-oriented approaches. In the course of this criteria, a further 7 publications can be filtered out.

Screening by abstract:

Analogous to the screening of the titles, the reading of the abstracts can provide information about the content of each paper. In this specific case, a further 16 publications can be excluded for further investigation.

1.4. Analysis:

The results of the SLR can be structured and presented in the following section according to the initially formulated three questions. The aim of this procedure is to concentrate on three topics only, although a large number of other relevant and interesting aspects have been elaborated and formulated in each of these publications.

RQ1: “Which phases of the PLC are examined in sustainability assessments of metal additive manufacturing processes?”

Considering the LPBF process, the authors consider a widely varying number of product life cycle phases in the models, methods or case studies developed. In the following table 2, the correspondences of these examined processes, phases and steps have been listed according to the frequency of consideration.

Table 2. Examined phases of the product life cycle (a) as well as process-specific analyzed process steps of the LPBF process (b) (RQ1)

a.

Extraction of material	[10, 11, 17, 22, 30, 36, 37]
Product development	[10 43, 25, 26, 44, 27, 31, 42, 37, 41, 39]
Pre-Processes	[10], 18, 20, 21, 46, 31, 34, 35, 36]
In-process	[9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39]
Post-processes	[45, 10, 16, 22, 23, 46, 34, 35, 37, 38, 39]
Packaging	[17]
Transport/ logistics	[1, 12, 13, 14, 15, 22, 23, 25, 27, 28, 31, 42, 35, 37, 38]
Usage	[11–13, 14, 15, 16, 17, 22–24, 27, 28, 29–31, 35, 36, 37, 38, 39]
Maintenance	[34, 37, 38]
End of life	[11, 14, 16, 22, 25, 27, 28, 30–32, 33, 36, 37, 38, 41, 39]

b.

Powder production	[9, 10, 12, 40, 15, 16, 17, 18, 20, 22, 23, 26, 30, 2, 31, 35, 36, 38, 39]
Inert gas production	[40, 21, 26, 28, 31, 33, 34, 38]
Material-/ powder recycling	[11, 15, 18, 34, 35, 37, 39]
Compressed air supply	[28, 40, 31, 33]
Energy supply	[10, 40, 28]
Machine production	[20, 42, 37]
Waste treatment	[12, 37, 38]
Melting	[9, 2]
Slicing	[10, 20]
Hydraulic fluid production	[40]

As shown in Table 2 a., current sustainability assessments focus on "cradle-to-gate" processes, which do not allow a comprehensive analysis regarding the use phase as well as the end-of-life from a product development perspective. Therefore, the investigation of the interactions between the challenges of product development and the resulting impacts during the use phase forms one research question to be considered in the future, namely how the production process and the associated product design impact the gate-to-grave processes [30].

RQ2: a) "What research work has been done in publications in the field of sustainable additive manufacturing?"

The examined publications can be classified according to their own contribution to the research. In addition to variously orientated case studies and summaries of the resultant findings, the focus of the majority of the publications is on conducting partly systematic literature reviews and developing methods in the area of AM and sustainability assessment. One example of this method development is with the definition of a generic methodological approach within the examined production processes to characterise data for the entire product life cycle within the LCI [11].

RQ2: b) "Which methods/ models have been used in this context?" (Collection of methods)

The authors used, processed or extended a number of different methods and models, as well as some overlapping ones, during the performance of the individual work.

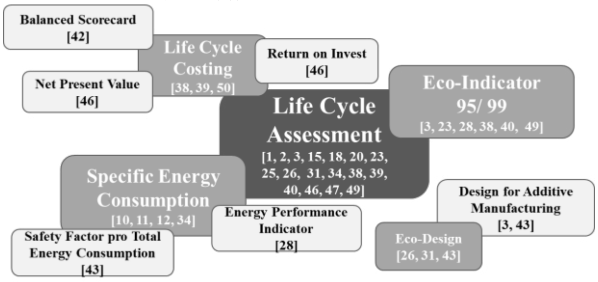
Table 3. Identified own work provided within the publications reviewed (RQ2 a.)

Case study	[38, 37, 34, 30, 44, 26, 23, 43, 20, 47, 40, 48, 13, 22]
Development of methods	[38, 37, 36, 34, 31, 46, 29, 47, 29, 40, 11, 14, 20]
(Systematic) literature review	[39, 37, 34, 33, 32, 46, 2, 26, 49, 50, 1, 9, 17]
Development of frameworks	[39, 34, 42, 31, 2, 44, 25, 10, 21]
Model validation	[38, 36, 34, 18, 21]
Development of a model	[51, 52, 50, 11]
Assessments	[38, 39, 36, 28, 29]
Method application	[42, 48, 16]
Method extension	[15, 45]
Development of a workshop	[37]
Development of metrics	[46]
Development of a research map	[45]

The Figure 4 shows a collection of these methods depending on the application frequency in the examined context.

In this context, it is interesting to mention that besides the implementation of a traditional LCA for additive manufacturing processes, the focus is on the supplementary calculation of other factors, like the "Specific Energy Consumption" or the "Eco-Indicators 95/99" [3, 23, 28, 38, 40, 49].

Figure 4. Collection of primary focused methods/models within the publications reviewed (RQ2 (b))



Furthermore, these indicators are identified, monitored and analysed by means of various parameters defined as "key characteristics" within the process chains, so that a concrete basis for calculating the LCA can be identified [17, 18]. During the product development phase, the focus is also growing on further design developments. Summarised under the keywords "Design for Additive Manufacturing" [3, 43] or extended as "Eco-Design" [26, 31, 43], the aim is to pave the way towards

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standardised recommendations for the development of sustainable products.

RQ3: "Which outstanding questions and limitations can be identified as a result of sustainability assessments conducted within the additive manufacturing field?"

In each of the publications reviewed, open questions as well as limitations can be identified in addition to the insights gained. According to the results of the SLR, these limits can be divided into three thematically separated blocks. On the one hand, a lack of available data (1) is identified, which has a significant influence on the quality of the ecological impact assessments. On the other hand, there are still methodological weaknesses (2), as well as lacks of knowledge (3) concerning the additive manufacturing processes investigated and the associated process chains.

(1) Data availability:

To be able to make significant conclusions regarding future effects of a process or product, it is necessary to generate a varied and complex database for process modeling or simulation. As per Ochs et al. (2021), it is rather a key purpose for the conducted case study to generate data that can provide a knowledge base to support future simulations [53]. According to [31], the previously mentioned insufficient availability of data regarding e.g. costs, environmental impacts or preceding process steps is the reason for the lack of feasibility, reliability and accuracy of these studies [31]. Related to this, only few approaches and findings of conducted case studies can actually be applied [11–13, 1]. There is too little research activity aiming for a holistic sustainability assessment despite the currently very limited system boundaries [49]. Specifically, it is necessary to collect and evaluate data on system-related issues, such as the handling of waste [31] or actual process- and product-specific emissions and their toxicological evaluation [12, 15].

LCA databases already provide a wide range of datasets for conventional manufacturing processes, but such a range of datasets is not available for additive manufacturing processes [54]. Rather, it is only possible to generate data for additive manufacturing processes based on diverse books, journal or conference publications [54]. The uncertainties based on this lack of data availability Van Sice et al. (2021) define at about 40%, making a proper comparison between conventional and additive manufacturing processes in its current form not realistic.

(2) Methodological weaknesses:

Identified weaknesses of the applied methods are both a cause and a consequence of the lack of available data. The number of existing standardised and detailed methods and the resulting guidelines for assessing sustainability in the context of AM is still too limited [49, 52]. The consistent description of process chains as well as the integration of all relevant product life cycle phases is not based on concrete recommendations of action but on the basis of one's own judgement [1]. In addition, there is a lack of comprehensive sensitivity and uncertainty analyses within the existing models to ensure the validity and optimise the quality of the results determined [10].

(3) Limitation in understanding procedures and processes:

Following the methodological weaknesses, the knowledge of the investigated process itself shows limits. This is based, besides other reasons, on the lack of long-term process and process-specific experience [29], resulting, for example, in a high degree of material wastage due to incorrect prints based on inaccurate parameter settings [29]. Furthermore, the question concerning the reuse or continuing use of metal powders and, resulting the potential powder efficiency, has not been completely answered for powder bed-based AM processes [15, 26]. Regarding the powder handling, according to [26], the question arises to how the health risk can and must be assessed and handled [26].

4. Conclusion

This paper shows an analysis of publications published during the last six years regarding the assessment and description regarding the sustainability of products manufactured by the LPBF process as metal additive manufacturing process.

This analysis identified research gaps throughout publications which need to be investigated in following research activities. Those activities need to serve the main aim of overcoming the information gap between conventional and additive manufacturing processes that currently dominates for being able to calculate different scenarios.

The three identified gaps in the analyzed literature refer to data, adaptation of existing methods and the need to build up process-specific knowledge.

Regarding the data needed for calculations, these have to be structured and documented for building up a valid baseline for following evaluations. These data are process-, component- and resource-specific. Therfore, existing methods have to be adapted in order to be able to perform target-oriented calculations. Such adaptations are, the result of accumulated knowledge on processes such as the additive LPBF process.

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