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A Systematic Review

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Review

Quantitative sustainability assessment of metal additive manufacturing: A systematic review

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ABSTRACT

This paper presents a systematic critical review of quantitative sustainability assessment studies on metal additive manufacturing (MAM) with a life cycle perspective. Potential benefits and present challenges of MAM are also discussed. MAM showed the potential to reduce overall environmental impacts and be more cost-effective for parts with complex designs, high value and low production volumes, particularly for automotive and aerospace components. However, currently, conventional manufacturing appears to have a better sustainability performance than MAM for simple parts in industrial applications. Overall, MAM technology is still in development, even if there have been optimizations and method consolidations.

1. Introduction

Use and production of metals result in both direct (e.g. mining) and indirect (e.g. electricity use) emissions and thereby contributes to several environmental impacts. Moreover, multiple metals are of toxic concern if they end up in the environment and food chains. Even metals that are essential to human health (e.g., Zinc), can become toxic at high levels [1]. At the same time, in the last 100 years the demand for metals has risen [2,3] which could potentially contribute to metal scarcity [2]. For example, the manufacturing of aircraft requires large energy input and elevated buy-to-fly ratios (from about 12:1 to 25:1), which leads to high waste volumes and environmental footprint [4]. Thus, there is an urgent need to re-think the metal manufacturing sector and improve technologies in order to counterbalance the increasing energy need and the descending ore availability [2]. Recently, there has been increasing attention to additive manufacturing (AM) as a potential way to address some of these challenges [5–7]. AM is commonly known as 3D printing or rapid prototyping, and it is a disruptive technology to fabricate products. It starts from a digital model to produce relatively rapidly a physical three-dimensional object by depositing, solidifying, or fusing layer on top of layer [8,9]. AM was first defined when, in 1986, Charles Hull and Calif Arcadia fabricated a 3D part using stereolitography, and received a patent [10]. Several studies stated that AM has potential to contribute to lean manufacturing and shorten manufacturing lead time [11–13]. For instance, [14] estimated a reduction in lead time from 12% to 60% relative to machining of an injection mold once AM technology is optimized. Moreover, several studies have underscored that additive manufacturing (AM) presents notable advantages in terms of complexity, flexibility, enabling customization of spare parts' designs without the need for traditional tooling, such as forging dies. This technology also facilitates lightweight design, ultimately resulting in reduced material consumption and enhanced sustainability benefits, even during the product's usage phase [15,16]. The potential of AM has already been recognized. In particular, from 2013 to 2015 the average annual market share growth rate of AM was 31.5%, and its global revenues, including desktop 3D printers and industrial apparatus, has reached $5.1 billion [17]. More recently, in 2020, the annual growth rate decreased to 7.5% but it resumed somewhat with 19.5% in 2021. This is majorly ascribed to a steady worldwide recovery from the COVID-19 pandemic [18].

According to the ISO/ASTM 52900:2015 [19] existing AM techniques can be classified into seven categories: material extrusion, material jetting, vat-photopolymerization, sheet lamination, binder jetting,

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Nomenclature

AM	Additive manufacturing
BJ	Binder Jetting
CM	Conventional manufacturing
DED	Directed Energy Deposition
EoL	End-of-life
FU	Functional unit
GHG	Greenhouse gas
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
LPBF	Laser Powder Bed Fusion
MAM	Metal additive manufacturing
ME	Material Extrusion
PBF	Powder Bed Fusion
S-LCA	Social Life Cycle Assessment
SDGs	Sustainable Development Goals
SLM	Selective Laser Melting

directed energy deposition, and powder bed fusion. Currently, the latter is the most commonly used for fabricating metallic parts [20,21]. As concerns materials applied, a report from [22] lists the main metals used since metal additive manufacturing (MAM) has become commercially available (see Figure S.1 in the Supplementary Information). Nickel, Steel and Titanium are the most used metals and alloys, followed by Aluminum, Copper, and Cobalt [22–26]. Due to the growth in the use of MAM for manufacturing, it is important to understand and quantify to what extent it can potentially contribute to manufacturing for sustainability. Numerous definitions of the latter are available in the literature [27]. The majority refer to the fundamental definition of sustainable development, introduced by the Brundtland Commission through the report "Our Common Future" [28]. Here sustainable development is defined as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".

One of the most frequently used tools in decision-making to quantify the environmental impact of a product is Life Cycle Assessment (LCA) [29]. LCA is standardized in the standards ISO 14040/44 [30,31] and the International Life Cycle Data system (ILCD) guidelines [32], and takes into account the life cycle of a product (i.e. raw materials, manufacturing, use and disposal of it), and covers multiple environmental issues. Thus, it is a holistic methodology, which supports identification and avoidance of burden-shifting between stages of the life cycle and among environmental impacts. It can be employed in comparative studies, in which it is possible to compare alternative products or systems that offer the same functionality. When considered together with Life Cycle Costing (LCC), which has the core goal of quantifying all costs over the life cycle of a product, and S-LCA (Social Life Cycle Assessment), which aims to evaluate the social impacts associated with a product over its life cycle, LCA supports evaluation of product sustainability over the triple bottom line, considering environmental impacts, together with social goals and economical aspects in what is referred to as a Life Cycle Sustainability Assessment (LCSA) [29].

2. Research methodology

This study focuses on quantitative sustainability assessment of MAM with a life cycle perspective. The aim of this research is to identify drivers of environmental, economic, and societal impacts of MAM in the product life cycle based on state-of-art published scientific literature. To the best of the authors ́knowledge previous studies offering a systematic literature review on MAM from a life cycle perspective focus on one or two aspects of sustainability [6,7,21,33,34]. Nevertheless, they do not concurrently cover environmental, economic and social impacts all at the same time. The leading research questions were: "To what extent has the Life Cycle Sustainability Assessment perspective been applied to metal additive manufacturing, what are the drivers of its impacts, and how does it compare to traditional manufacturing processes?".

2.1. Data collection

To answer the research question, a systematic literature review was performed. Initially, relevant quantitative sustainability assessment studies were identified and extracted, followed by categorization according to predefined criteria. To minimize the risk of bias in the retrieval, collection and classification of data from the systematic literature review, the authors followed a predefined methodology [35,36], consisting in the following steps: (1) review planning; (2) review execution; and (3) results analysis (Fig. 2). At first, during the review planning, a systematic literature review protocol was formulated to report the review ́s objectives, and inclusion criteria were identified. Secondly, in the review execution, all studies were assessed and scrutinized against the criteria established in the protocol. This corresponded to a search in Scopus and Web Of Science using a combination of keywords in the search strings with Boolean operators. However, no specific fields were selected; instead, all relevant metadata was considered. These are reported in Fig. 1. All the shortlisted papers were evaluated according to the protocol defined by [35]. The steps to analyze the papers were: (1) "Title and no repetition analysis", (2) "Abstract and conclusion analysis", and (3) "Full paper". To avoid multiple studies presenting the same research findings, it was carefully checked that there were no conference papers connected to journal article with the same case study, approach and conclusion. In this process, two iterations of the so called "snowball technique" or cross-referencing [37] were performed (see Fig. 2). All of this led to a final number of 115 publications considered in the literature review. The last step of the systematic literature review approach was the "Results analysis" by which, the extracted data from the selected papers were analyzed and classified according to groups of criteria presented in the next subsection.

2.2. Criteria for systematization of the papers

A relevant set of classification criteria for the analyzed publications was identified with an iterative approach. The following groups of criteria were considered:

- *"Background information on the literature"* (see Subsection 3.1) involved: (1) year of publication, (2) geographical location of the publication, (3) type of publication, (4) triple bottom line focus, (5) type of metal additive manufacturing technique (i.e. Powder Bed Fusion, Directed Energy Deposition, Binder Jetting and Sheet Lamination), (6) feedstock types (i.e. powder, metallic sheet, and wire), (7) metal alloy group and (8) industrial sector investigated;
- *"Approach of quantitative sustainability assessment"* (see Subsection 3.2) comprehended: (1) life cycle stages included, (2) functional unit definition, (3) indicators assessed in the study, (4) comparative assessment against conventional manufacturing, (5) sensitivity analysis, and (6) potential design achievable through AM;
- *"Sustainable Development Goals (SDGs) targets addressed"* (see Subsection 3.3);
- Meta-analysis of scores for 1 kg metal alloy converted into product using conventional or additive manufacturing and quantifying (1) *electricity use*, and five midpoint impact categories: (2) *Climate Change*, (3) *Human Toxicity*, (4) *Terrestrial Acidification*, (5) *Ionizing Radiation*, and (6) *Marine Ecotoxicity* (see Subsection 3.2).

The outcome of data systematization by selected criteria is illustrated in detail in Section 3 *Results and discussion* (see also Supplementary Information).

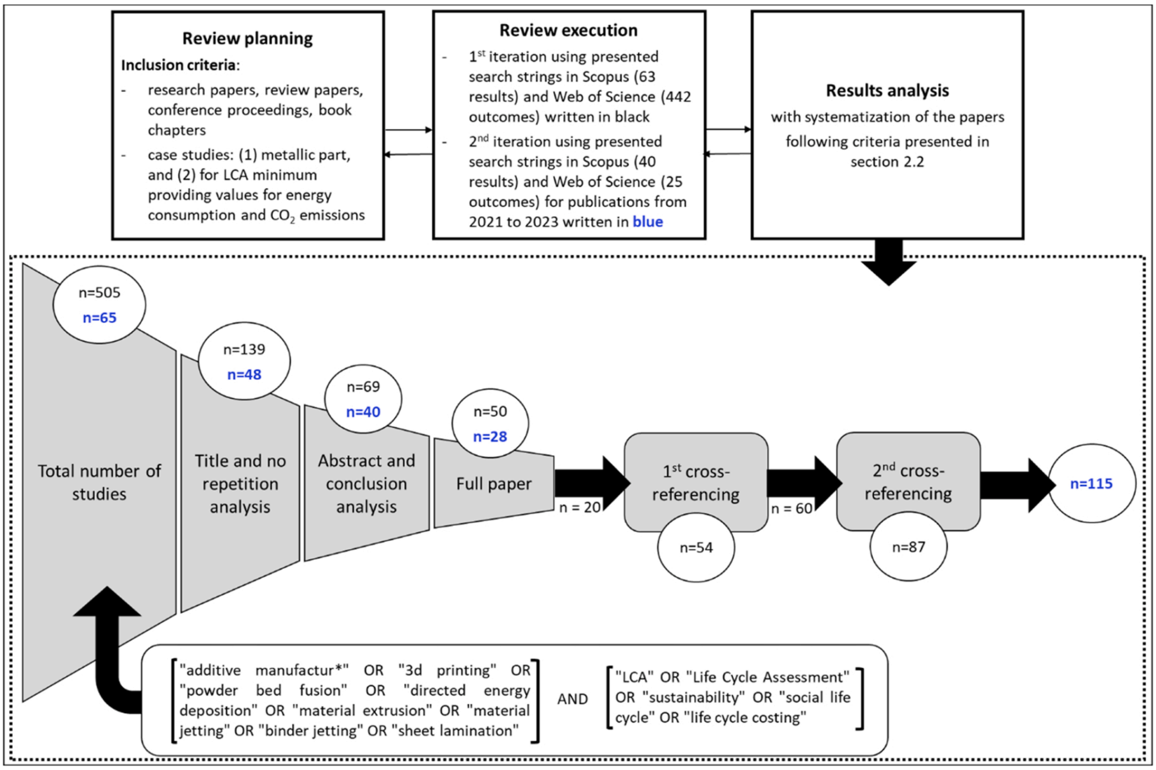

Fig. 1. Schematic overview of the approach taken in the systematic literature review.
Adapted from [38].

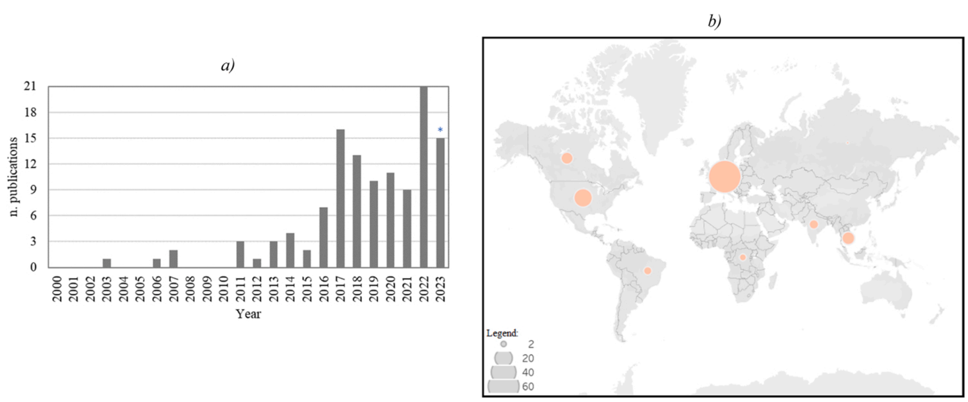

Fig. 2. a) Publications per year from 2003 to 2023 (*additional studies may have been published after July 2023 after this review was carried out); and b) location of publication.

3. Results and discussion

This section presents the results of the systematic literature analysis considering the criteria mentioned above in Subsection 2.2. Review papers were generally excluded from systematic and quantitative considerations, with exceptions made in Subsections 3.1 and 3.3, and mainly employed to validate our findings with other studies. Additionally, Subsection 3.3 highlights the main drivers of the sustainability impact of MAM of products.

3.1. Background information on the literature

The assessed papers were published mainly in the last 8 years, from 2016 to 2023, see Fig. 2a. Fig. 2b illustrates that most of the studies were performed in Europe, followed by USA.

In the Supporting Information, it is reported that the majority of the case studies were published as journal articles (about 50% of the total), followed by 31 review papers ([39–42], etc., for further details, please refer to SI 2). Only 3 studies out of 84 analyzed (excluding review papers) consider all three sustainability dimensions in parallel [43–46]. The majority assessed environmental-related sustainability aspects (i.e., 79% of the studies), followed by the economic characteristics of the technology (i.e. 33% of the total), as also identified in another bibliographic analysis [7]. Overall, the most adopted MAM class according to [19] was Powder Bed Fusion (58%) and concerned powder-based AM (85% of these studies, see Supplementary Information). This is in line with the results from the other systematic literature reviews [6,7,11,47], and reflects that this is the most commercially diffused technique [48]. In case the same study analyzed two techniques, they are both counted. The systematic review illustrated that the majority of studies involved ferrous alloys (i.e., 50%) followed by titanium and aluminum alloys (i.e., 25% and 15%, respectively, see Supplementary Information), which is in accordance with the market trend [22]. The automotive and aerospace sectors represent a bit more than one third of studies (see Supplementary Information). However, it should be observed that many products did not have a specific application in any sector (approximately a quarter of the total).

3.2. Approach of quantitative sustainability assessment

A cradle-to-gate assessment was performed in 43 out of 84 studies (excl. the 31 review papers), and just a few of them justified this delimitation by the study being comparative and having system equivalence of the compared products systems (see Supplementary Information). The dominant approach was to focus on these life cycle stages because the authors reckoned it to be more relevant for their research scope. This is in line with findings from other review papers (e.g., [7,47,49]). However, the functionality and performance of the product related to the use stage should be considered, particularly when quantifying the potential fuel or energy savings during the product utilization due to lightweight design achieved through additive manufacturing (see Subsection 3.5.1). Inclusion of all life cycle stages of a product in the assessment helps reveal and avoid burden-shifting. Therefore, taking a cradle-to-grave approach is encouraged by the authors of this paper. The functional unit (FU) used in the studies was very often not explicitly defined or considered one unit of the finished product (in 37 and 34 papers out of 84, respectively, see Supplementary Information), and this is line with observations from another review [47]. This is problematic in a comparative LCA of a component produced with 3D printing or conventional manufacturing processes as it does not support a fair comparison that also considers the potential benefits due to an improved product functionality over the total life cycle. Solely 10 publications defined the FU based on the delivered service of the product according to [30,31]. For instance, in [16] the functional unit was defined as *"Ensure the closure of an aircraft door throughout the aircraft's lifetime (35 years)"*. Finally, Fig. 3 below illustrates a schematic product system overview of the life cycle processes of metal additive manufacturing (MAM) considered in the quantitative sustainability assessment (QSA) of the reviewed studies that took a full life cycle perspective.

There was considerable variation in the choice of environmental sustainability indicators in these studies. For example, 25 papers solely analyzed CO_2 or GHG emissions in combination with cumulative energy demand or embodied energy. Thus, those studies resemble more Carbon Footprint Analysis than LCA as they only investigate one environmental impact category (e.g., [4,13,14,50–54]). Nevertheless, the outcome of those studies was taken into account in this systematic literature review as they contributed with relevant information. However, overall, the majority of the studies considered several midpoint or endpoint indicators for the LCA (42 publications, see Supplementary Information) as supported in another review [25]. The goal of the majority of the studies was a comparative assessment with conventional manufacturing such as casting or injection molding (i.e., 57 out of 84 papers, see Supplementary Information). A few studies considered a comparison between different MAM techniques (e.g. [43,55,56]). A sensitivity analysis was performed in roughly half of the studies (see Supplementary Information). The main tested parameters were product weight or use of consumables (e.g., electricity use, process gasses) during manufacturing (e.g., [55,57–61]). The dominant scenario in sensitivity analysis was about the product's current and optimized design for additive manufacturing [16,62].

3.3. Sustainable Development Goals (SDG) targets addressed

In order to get an alternative overview of the triple bottom line coverage of the reviewed studies, we performed a semi-quantitative evaluation of the coverage of aspects of relevance to different SDGs for each of the publications considered in the systematic literature review by using the list reported in [63] (see Supplementary Information). Table 1 shows the keywords used in the analysis of the relevance of SDGs targets for each publication. Keywords for SDGs 1, 2, 6, 7, 11, 16, and 17 are not included since no publications addressed these goals (Supplementary Information).

Fig. 4 illustrates the numbers of papers that dealt with topics of relevance for each of the SDGs.

As it can be seen from Fig. 4, the reviewed publications discuss sustainability impacts related to mainly seven SDGs. In order of magnitude they are: 12, 8, 13, 9, 3, 14, and 15. Then, a few papers included some aspects relative to people- and prosperity-related SDGs 4, 5, and 10. The fact that people (SDG 3), prosperity (SDGs 12, 8, 9) and planet related (SDGs 13, 14, 15) sustainable development goals are the most pertinent to the analyzed papers. This is in line with what will be discussed in Section 3.4 and reflects the holistic nature of the current literature on sustainability of MAM. Additionally, the importance of additive manufacturing in relation to SDGs has been recognized and assessed in a few studies in the literature (e.g., [34,64]).

3.4. Overall sustainability performance: triple bottom line

Only three papers investigated all three sustainability dimensions (i.e., triple bottom line) within the same case of study [43–45]. The metrics adopted by the studies was different and it is reported in short in Table 2. None of the studies attempted to quantitatively aggregate across the bottom lines, but included a generic qualitative discussion in regard to the overall sustainability. One of the study performed a predictive sustainability analysis at global level considering the triple bottom line and product life cycle for objects produced with 3D printing by 2025 [45]. The study highlighted the potential of reducing global costs by 170–593

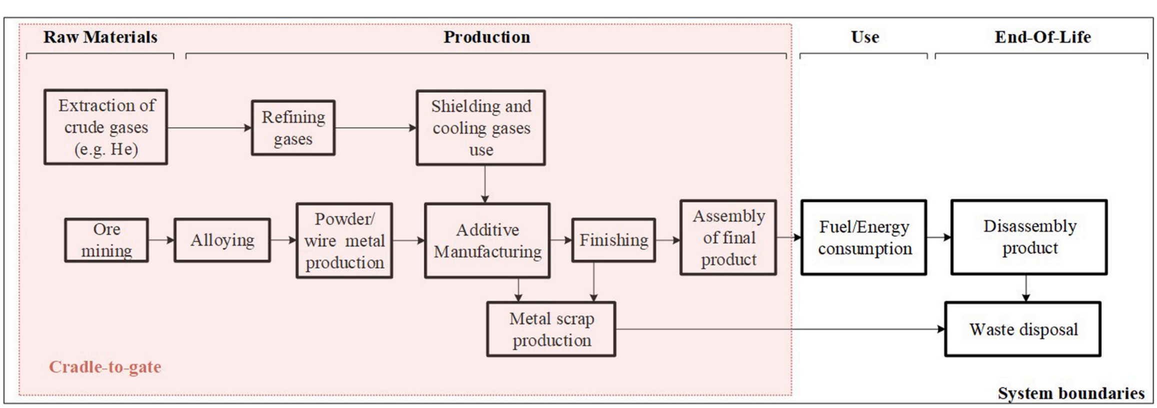

Fig. 3. Generic framework of system boundaries of the product system applied in the systematic literature review. The system boundaries did not include capital goods, electricity use and transportation, but those were included in the modeling of those life cycle processes where they were relevant.

Table 1
Key aspects used in the analysis of the relevance of SDGs targets for each publication.

Sustainable development goals (SDGs)	Key aspects considered
"SDG 3 Ensure healthy lives and promote well-being for all at all ages"	Human health, health safety, human toxicity
"SDG 4 Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all"	Aspects related to labor and inequalities in developing countries
"SDG 5 Achieve gender equality and empower all women and girls"	Ensure women's equal opportunities for leadership
"SDG 8 Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all"	Economic productivity through innovative technology
"SDG 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation"	Innovative technology that can contribute to increase in resource-use efficiency and the green transition
"SDG 10 Reduce inequality within and among countries"	Alleviate disparities between economically advanced and emerging nations
"SDG 12 Ensure sustainable consumption and production patterns"	Sustainable management of resources and applications for circular economy
"SDG 13 Take urgent action to combat climate change and its impacts"	Reported considerations or results related to climate change
"SDG 14 Conserve and sustainably use the oceans, seas and marine resources for sustainable development"	Reported considerations or results related to acquatic / marine ecotoxicity acidification of ecosystems
"SDG 15 Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss"	Reported considerations or results related to terrestrial ecotoxicity acidification of ecosystems

billion US $, the CO_2 emissions by 130.5–525.5 Mt, and the total primary energy supply by 2.54 to 9.30 EJ by 2025 [45]. Social sustainability was discussed in a more qualitative way and based on other literature. One of the main critical points mentioned relates to the increase of automation in manufacturing systems, which can be beneficial in developed countries with a high average age, but critical in relation to unemployment in developing economies [45]. Another work compared the cradle-to-gate impact of an aluminum alloy part produced with Directed Energy Deposition (DED) to milling [44]. The outtakes were that the selling price of DED product becomes competitive to milling when the milled part requires removing 90% of feedstock material, and the main contribution to the environmental impact for both techniques come from the feedstock production. Additionally, the injury rate was extrapolated from the Bureau of Labor Statistics data but, as there was no proven data on that yet for AM, it was estimated to have the same value of other similar manufacturing categories, and resulted that the injury rate is reduced with AM [44]. Lastly, an article investigated the life cycle of an aerospace component manufactured with Directed Energy Deposition (DED) or Selective Laser Melting (SLM) [43]. Overall, the performance evaluated on the triple bottom line showed that DED was better than SLM, mainly due to the fact that the latter has a slow melting rate leading to higher energy consumption and labor costs [43].

The following Subsections 3.4.1, 3.4.2, and 3.4.3 present a summary of the most relevant observations from the systematic review of all studies in relation to their separate assessment of (1) environmental, (2) economic and (3) social sustainability performance.

3.4.1. Environmental sustainability performance

Overall, 69 out of 84 papers (excluding review papers and including studies that considered the triple bottom line) dealt with environmental impact of 3D printed products. However, of those only 27 papers provided the information needed for us to calculate the impact scores harmonized to 1 kg of metal product, facilitating a comparison across studies ([13,25,65,66], etc., for further details, please refer to Supplementary Information). Fig. 5 illustrates the cradle-to-gate impact scores harmonized to 1 kg of metal product for electricity use and five selected environmental impact categories: Climate Change, Human Toxicity, Terrestrial Acidification, Ionizing Radiation, and Marine Ecotoxicity. Those indicators were chosen primarily on the basis of data availability from the literature, and were calculated for conventional and additive manufacturing. In particular, the latter considered the four most commonly used MAM techniques groups: BJ, DED, ME, and PBF. It is interesting to notice that the Human Toxicity scores are particularly high for Binder Jetting. More explanations in this regard will follow in Section 3.5. Additionally, the range between the first and the third quartile is limited to one order of difference, except for the average electricity needed for MAM (i.e., 5–162 kWh/kg product). Generally, the average value for electricity use is one order of magnitude higher for MAM groups compared to CM. These differences, along with the observation that conventional manufacturing outperforms additive manufacturing for the majority of the considered indicators, and the presence of outliers in all types of techniques, can be attributed to six critical factors concerning the availability of LCA results and the key challenges associated with the early stages and ongoing development of the technology. Firstly, the level of product shape complexity is not directly reflected in the calculated scores. However, this aspect is

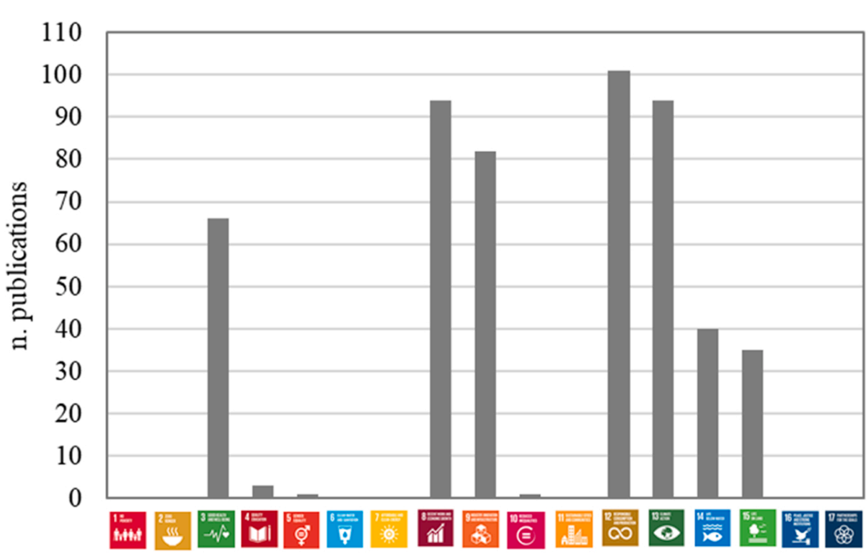

Fig. 4. Coverage of the different Sustainable Development Goals (SDG) in the reviewed literature.

Table 2
Metrics and main findings for reviewed papers that adopted a triple bottom line analysis approach.

Environment	Economy	Society	Source
Absolute change in energy [EJ], or CO_2 emissions [Mt CO_2] calculated based on the total primary energy supply-intensity or CO_2-intensity, AM market potential and the relative change in energy or CO_2 emissions through AM compared to conventional processes. Literature was used as foundation for estimating the parameters values.	Absolute change in costs as result of the multiplication of AM market potential and the relative change in costs through AM compared to CM. Literature was used as foundation for estimating the parameters values.	Social sustainability discussed in a qualitative way and based on other literature	[45]
GHG emissions [kg CO_2-eq/part]	Selling price [€/part]	Injuries [no./part]	[44]
Energy consumption [kWh/FU], and kg CO_2-eq emitted [kg CO_2-eq/FU]	Raw material and manufacturing costs [$/FU]	Number of injuries and illnesses (NOI) based on non-fatal occupational injury rate in the specific industrial segment, and average working hours [NOI/(person x FU)]	[43]

intrinsically considered within the definition of the functional unit (FU) of the studies. For instance, a few authors illustrated that the solid-to-cavity ratio of parts [13,52,67,68], considered as measure of product design complexity [13], has a significant direct correlation with the environmental performance of AM. This is due to the fact that substantial weight savings lead to a decrease of materials needed for the finished product and reduction of the LCA impact score (see Section 3.5.1). Nonetheless, conventional product are designed to minimize cost, and not weight. Thus, to ensure a fair comparison, it is necessary to at least consider how the product might be conventionally manufactured with a reduced weight and what its associated costs would be (e.g., [25, 53,69,70]). Secondly, parts compared are usually designed for traditional manufacturing processes. Therefore, comparing them with MAM produced ones undermines the capability of the process. Thirdly, the sample used to derive the scores was rather limited, and relied on 27 papers in total (see Table S.1 in Supplementary Information 1). Fourthly, a few papers reported the scores for some impact categories only for AM (e.g., [43,52,55,69,71–73]). Fifthly, in many studies the AM system do not have optimized set-ups. In particular, some assessment present laboratory experiments (e.g., [43,52,53,71]), or employed small-size units (e.g., [58,65,66,74,75]). Lastly, many studies did not report sensitivity and uncertainty analysis of the assessed system which is a critical step in carrying out LCA. This examines how robust the conclusions of the study are and increase its robustness [29].

Attempts at performing comprehensive meta-analyses of LCA studies have been limited and mainly focused on electricity use during manufacturing [11,15,47,76]. Overall, the incomplete documentation of key assumptions and methods in the LCA studies of metal additive manufacturing systems prevented a more comprehensive meta-analysis. In spite of that, through alignment of the functional units and reference flows and including only cradle-to-gate studies, it was possible to bring all impact scores on a common scale. The results are thought to provide useful, albeit crude, indications of the range of the published state-of-the-art impact indicator scores for metal manufacturing systems (see Fig. 5).

Generally, it is important to report characterized results from the study in quantitative numbers in tables to have more transparent and reproducible studies (e.g., [55,70]). In particular, this would have been useful in order to calculate a more accurate average score for each environmental impact indicator.

Additionally, it is possible to identify similar tendencies in the 42 studies that took an approach which hindered the impact scores harmonization in the analysis. In the case of cradle-to-grave, or cradle-to-gate & EoL LCAs on MAM highlighted lower total life cycle impact score in comparison to CM due to fuel saving during the use stage of aeronautic and automotive parts thanks to lightweight product design (e.g., [16,77]). Other studies instead demonstrated advantages for product end-of-life in case multi-loops repairs with MAM are considered instead of recycling of the damaged components (e.g., [78]), or serial production instead of one part per build (e.g., [79]). On the other hand, cradle-to-gate or gate-to-gate studies for PBF or DED techniques generally illustrated a reduction of environmental impact in comparison to CM for low solid-to-cavity ratios thanks to a decrease in resources needed during part fabrication (e.g., [80–83]). Additionally, a few studies highlighted the potential of MAM to scale down the supply chain for spare components production [80,82].

3.4.2. Economic sustainability performance

Only 28 out of 84 (excluding review papers) publications investigated the economic sustainability performance of metal additive manufacturing techniques. The striking majority of these papers focused on the material and manufacturing (incl. machinery) cost solely (e.g., [53,67,69,84–88]), only one study considered costs over all life cycle stages from cradle-to-grave [16]. The majority of the studies highlighted that the highest cost is related to the AM apparatus acquisition and operation, but with advancement in the technology development the former will likely be reduced [16,70,86,89,90]. Indeed, AM cost for the equipment declined of approximately 40% between 2001 and 2013 [91]. For example, [16] compared the life cycle impacts of a metallic aircraft doorstop produced with 3D-printing or traditional manufacturing techniques. It resulted that overall, the life cycle costing (LCC) with additive manufacturing (AM) was about 8% more, mainly due to equipment purchase. However, LCC with the optimized design for AM could be further reduced by about 12% respective to conventional manufacturing (CM), mainly due to lower fuel consumption through product lightweight design [16]. The same was also highlighted in the majority of the other studies that focused only on cradle-to-gate costs and consider different economic indicators [14,69,84,87,88,92,93]. For instance, [93] compared the cost of goods sold (i.e., €/part) for binder jetting vs injection molding of a bottom plate for a chemical reactor. This type of cost includes seven aspects: tool, facility, labor, maintenance, raw materials, consumables, and utilities costs. This study showed that the cost per unit with Binder Jetting can be reduced up to 93% due to increased yearly production volume, but injection molding is less expensive [93]. This is in line with Fig. 6b that shows how nowadays CM for large production volume is generally more advantageous than MAM. [62] focused instead on the hourly rate cost per kg of product of laser beam melting (LBM) compared to several conventional manufacturing techniques to produce metallic gear wheel for a car. A very different approach was adopted by [83], who compared the cost for manufacturing (i.e. €/part) of Wire Arc Additive Manufacturing (WAAM) against milling from billets or forged semi-products to produce 3 medium-to-large objects: (i) titanium alloy bracket for civil aircraft, (ii) steel cantilever beam for buildings, (iii) aluminum alloy frame for aerospace. This study performed a multi-criteria decision analysis based on: energy efficiency, manufacturing time and cost; and it emphasizes the significance and intricacy of manufacturing processes and material selection in relation to product applications. In this context, conventional manufacturing for producing steel beams emerged as the most cost-effective option due to its simple design and potential for faster and

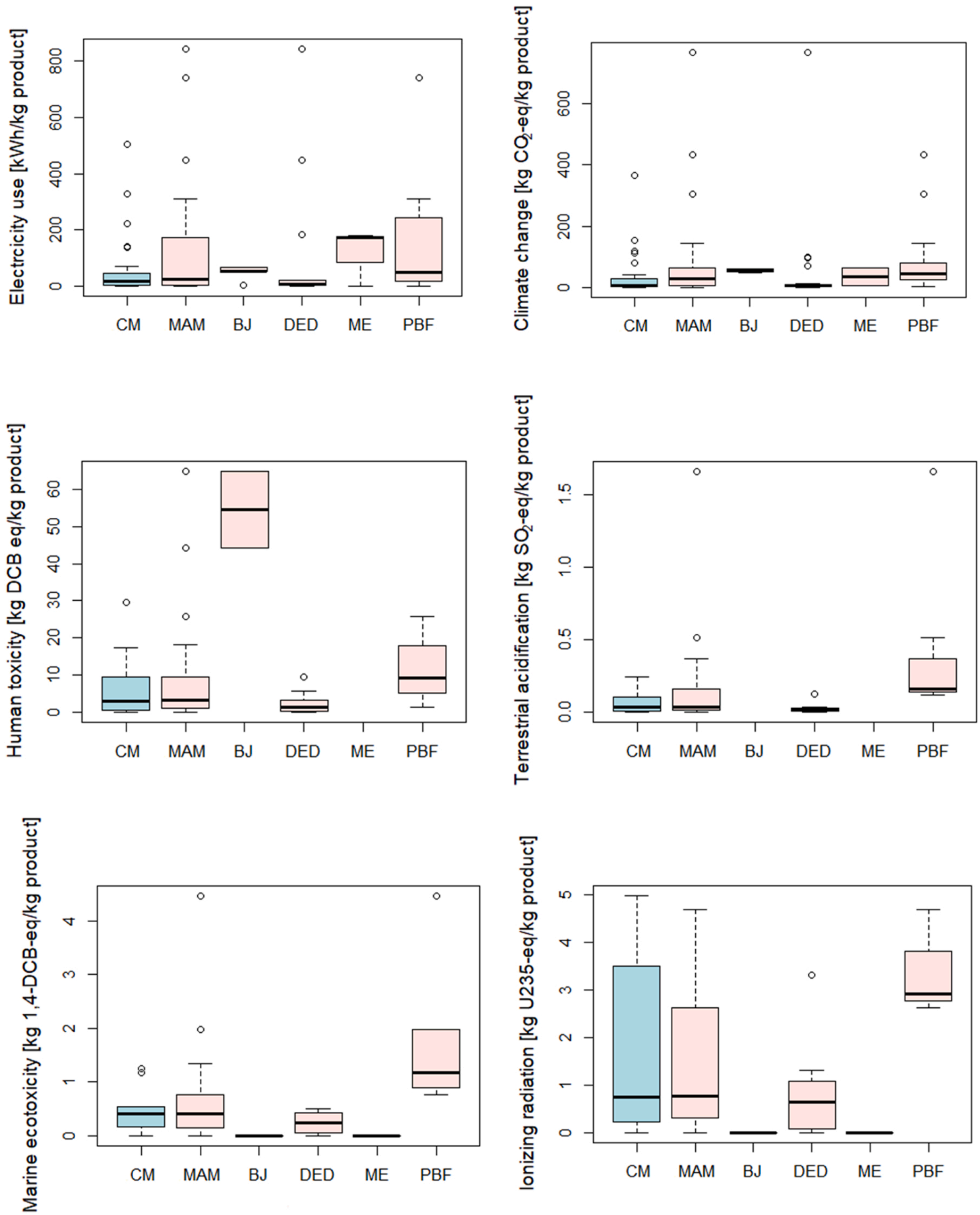

Fig. 5. Electricity use, Climate Change, Human Toxicity, Terrestrial Acidification, Ionizing Radiation, and Marine Ecotoxicity of the life cycle assessment for 1 kg product produced with conventional (CM) or metal additive manufacturing (MAM). Only for electricity use and CO_2 emissions the scores included are from the same cradle-to-gate studies. The boxes and the whiskers are delimited between the upper and the lower quartile and extremes, respectively, and the black solid line in the plots represents the average value of the considered range of values (see Tables S.1 and S.2 in SI 1). Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), and Powder Bed Fusion (PBF).

more affordable production [83]. Furthermore, [53] compared the economic performance of WAAM against machining as estimated costs for producing a steel part (i.e., €/kg part). The costs were correlated to the solid-to-cavity ratio, which can be considered as a measure of shape complexity [13]. The authors verified that for lower solid-to-cavity ratios WAAM is more cost effective than milling, while the opposite is valid in case of high values of the ratio [53]. Indeed, as highlighted by [5], product redesign can allow to achieve optimal strength-to-weight ratio and ability to meet functional requirements while minimizing material volume. This aspect has been further investigated in a study by [88], where they assessed the part cost based on ten different geometries obtained through topology optimization for an aircraft component. [45] estimated that reduced material feed in, tooling, handling, and shorter supply chains can contribute to potential savings of about $113–370 billion by 2025. That can be correlated to the concept of "Complexity for free" which describes the fact that with the increase of product shape

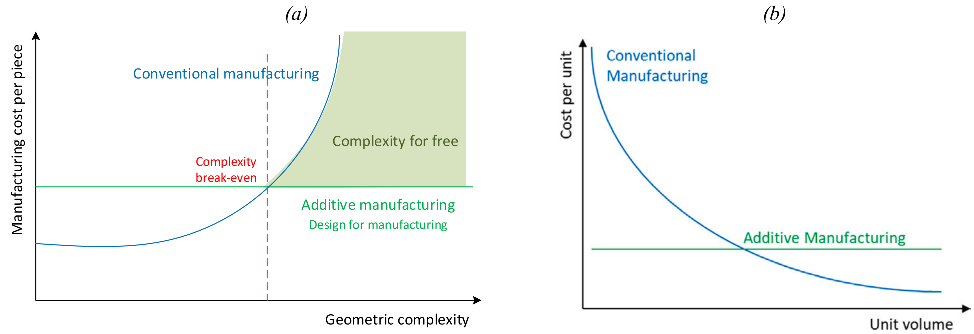

Fig. 6. (a) "Complexity for free" in additive manufacturing adapted from [94]; and (b) cost of conventional or additive manufacturing according to production volume.
Adapted from [96].

complexity, additive manufacturing could potentially become more economically advantageous than conventional manufacturing [94,95]. All of this highlights the fact that superior performance between conventional and additive manufacturing, is product and design-dependent. Fig. 6a illustrates the existence of a break-even point with increasing level of complexity, above which additive manufacturing becomes economically preferable to conventional manufacturing.

It can be concluded that the available MAM techniques can compete economically and environmentally mainly with traditional processes for low production volume of products with complex design and high value [53,93–95]. MAM equipment is expensive, but additive manufacturing will be more cost-effective when it will be possible to reach larger production volumes for a lower cost [5]. However, the potential for technology cost reduction may induce the emergence of a rebound effect, as observed in [14]. Indeed, a greater adoption of MAM could make the fabrication of products cheaper and increase massively the need for new specific equipment to an extent that the potential environmental benefits of the technology could be eroded. This will not be the case if MAM growth occurs with a simultaneous outcompeting of CM methods.

3.4.3. Social sustainability performance

Only three studies of the literature review analyzed and applied social sustainability to the metal additive manufacturing sector [74,97,98]. In their study [97] developed a Social Life Cycle Assessment (S-LCA) following [99] and using twenty-six both quantitative and semi-quantitative indicators. Then, they applied the framework to a British manufacturing company that is specialized in production of heat exchangers using Selective Laser Melting (SLM) and they gathered primary data through a questionnaire. They found that AM had a positive impact in regard to several impact categories such as health and safety, gender equality, fair salary, social responsibility and security, local suppliers, and consumers' privacy. However, even if AM enhanced a local supply chain, employees were not hired locally and had to work extra hours. This is due to the novelty and ongoing research on AM technology, which requires specific qualifications for the workers [97]. Another study analyzed and applied a social sustainability framework to evaluate the impact of a titanium alloy based femoral prosthesis produced with Laser-based Powder Bed Fusion (LPBF) or traditional manufacturing techniques [74]. They identified two social categories (i.e., "Industrial product function utility" and "Product performance") and 10 sub-categories, called social issues, and added them to the life cycle impact assessment methodology IMPACT 2002 + , that they also used to evaluate the environmental performance. The outcome for the social category "Product performance" resulted to be better for AM than CM, as it allows an enhanced biocompatibility and increased shape complexity of prostheses that can be customized for the patient [74]. On the contrary, "Industrial product function utility", intended as effectiveness of manufacturing processes, resulted to be better for subtractive manufacturing because of the presence of leftover powder from the LPBF [74]. In the third study a S-LCA using the Social Hotspot Database (SHDB) [100] was developed by the authors, who performed a survey to obtain a single score for AM and CM through weighting [98]. The case of study regards a first stage nozzle ring produced with Direct Metal Laser Sintering (DMLS) or investment casting. Two main aspects entailed a reduction of impact by the choice of using DMLS: (i) transitioning to in-house production with AM eases social risk management, and (ii) replacing socially unsustainable materials (e.g., cobalt-based alloys) used in traditional manufacturing with more sustainable alternatives [98].

3.5. Sustainability impact drivers of metal additive manufacturing (MAM)

Aspects of MAM that drive the environmental, economic and social impact in a positive or negative direction can be divided into four categories: (i) potential product design alternatives achievable through additive manufacturing, (ii) product lifetime extension, (iii) energy consumption due to layer deposition rate, and (iv) recycling. Table 3 presents an overview of how the aforementioned sustainability impact drivers of metal additive manufacturing affect economic and environmental outcomes in comparison to conventional processes.

Another aspect that has been discussed only in three paper and is not reported as separate factor in Table 3 is how the increase of production volume affects the environmental impact [56,79,93]. A common finding was the serial production has the potential to reduce the impact per part.

The aspects described in Table 3 are further discussed in the following sections by means of relevant literature.

3.5.1. Potential product design achievable through additive manufacturing (AM)

Product design attainable via additive manufacturing potentially allows the fabrication of complex shapes and enables design strategies as light weighting and part consolidation. At the same time, it potentially supports topology optimization, but its feasibility depends on the application, material and AM technique considered [111]. Eighteen of the analysed studies investigated and quantified the benefits of potential re-design for MAM (e.g., [14,16,52,61,65,102]). On one hand, cradle-to-gate studies highlighted the fact that the weight or volume of a product can be hypothetically reduced to about half thanks to topology optimization. This could lead to a 25%–58% reduction of energy consumption during manufacturing and 60% of impact related to climate change [52,62,65,101,106]. For instance, [106] correlated the environmental impact to the buy-to-fly ratios for different part geometries produced with Wire-arc Additive Manufacturing (WAAM). Generally, with the latter environmental impacts decreased approximately of 12%– 47% compared to same parts produced with CNC milling thanks to MAM flexibility of design for complex product geometries [106]. Furthermore, [62] found a 30% reduction of the cost, which could be

Table 3
Sustainability impact drivers of metal additive manufacturing (MAM) and how they compared to conventional product design and process.

MAM class	Potential product design	Product lifetime extension	Layer deposition rate	Recycling
Powder Bed Fusion	Cost per part reduced up to 14%– 30%[62,88], but some studies highlighted overall higher cost for MAM than CM[14,92]. Energy consumption and climate change impact reduced of 31%– 58%[52,101]. Water consumption for the life cycle of a part produced with AM can be decreased up to 80%[101]. Mass for final part reduced 21%– 58%[52,62,81,102]. Reduction of the environmental impact by 11% to 40% thanks to energy or fuel savings during use stage[14,16,57,67].	Extended product lifetime of 33% compared to conventional part can lead to a decrease in the total weighted impact score of 18%– 20%[57]. Remanufacturing using AM can diminish environmental or energy impacts by 36% to 75%[103].	Energy consumption during layer deposition is a main driver of the impact score (15%–70%), followed by Argon gas use (5%-48%)[55,104]. Other studies illustrated evidence of large contribution to the total impact score from the gas atomization step (23%) and inert gas use (19%)[70]. Additionally, a study by[68] showed clear advantages for high deposition rates.	Scrap recycling can lead up to 50% reduction of the score in Abiotic Resources Depletion impact[54]. Unfused powder can potentially be reprocessed up to 30%[105].
Directed Energy Deposition	It is possible to achieve CO_2 emissions savings up to 23% if, thanks to topology optimization, the product mass reduction can be at least 50%[61]. Additionally, thanks to design flexibility of AM it is possible to achieve 40%– 70% materials savings and reduce the environmental impacts of 12%– 47%[106].	Repair with AM can save up to 26%– 45% CO_2 emission, and 32%– 36% of the energy consumption compared to replacing with a new product[78,107]; or reduce up to 98% the impact scores compared to conventional process[108]. Some studies showed that environmental damage can be reduced even up to 90%[109].	Major contributions to the total impact score are from electricity (10%–44%) and shielding gas (10%–60%) use during layer deposition[53,61,66,106,108]. Additionally, a study showed that an enhanced deposition rate from 2 kg/h to 5 kg/h can decrease the impact score further about 20%[61].	Feedstock utilization factors can be quite low like 12% or 32% as the powder is mainly left on the chamber walls of the machine[110]. Additionally, some studies showed evidence of a potential reduction in environmental impacts of roughly 15%–25% if unfused powder is reused for following manufacturing operations[73].
Binder Jetting	Energy consumption and climate change impact reduced by 25% to 58% and 25-58%, respectively[65,75,101]. Water consumption can be reduced of about 80%[101]. All of this is due to the overall reduced quantity of material to manufacture the part with BJ. Human toxicity impact increases of 27%– 49%[65,75] likely because of the use of the binder and cleaner in the process[75] or the alloy employed for product manufacturing[65].	No data	No data	No data
Material Extrusion	CO_2 emissions and energy consumption can be reduced up to 25% and 50%, respectively. Water consumption can be reduced of about 80%[101]. The analyzed part's intricate design and low production volume explain this.	No data	No data	No data

further decreased by 28% - 30% by using dual laser instead of single laser with Laser Beam Melting (LBM), even though this increased the equipment cost by 17%. On the other hand, the studies that developed a cradle-to-grave LCA and assessed automotive or aerospace parts highlighted potential energy savings during the use stage contributing to a reduction of the environmental impact of 11% to 20% over the life cycle [16,57,67]. That has been assumed to be feasible by means of light weight design. Only one publication assessed the environmental sustainability of an industrial tool (i.e., injection molding machine) manufactured with conventional machining and Direct Metal Laser Sintering (DMLS) [14]. The injection mold design for DMLS allows for approximately 40% energy savings during its use compared to the conventional part [14]. Additionally, two studies highlighted adverse effects on human toxicity for Binder Jetting [65,75]. One of these found that using Binder Jetting for topologically optimized part fabrication leads to reduction of energy consumption and CO_2 emissions compared to CNC milling thanks to potential product weight reduction [65]. However, this method also resulted in a 49% increase in human toxicity impact relative to conventional manufacturing, mainly due to the use of metal powders and solvents in the Binder Jetting process [65]. Similarly, [75] showed a decrease of environmental impact (average 20%) by minimizing assembly operations for consolidated design of a train floor attachment attainable by Binder Jetting. At the same time, an increase in human toxicity impacts relative to the traditional manufacturing process occurs. The latter is due the use of binder and cleaner in the procedure [75].

3.5.2. Product lifetime extension

Six studies in the literature assessed MAM potential to extend product lifetime by topology optimization, and by supporting faster repair or maintenance [57,78,103,107–109,112]. For instance, [103] investigated several repairing and remanufacturing types using AM and showed environmental or energy improvements between 36%–75%. [107] assessed the environmental impact of Laser Direct Deposition (LDD) for a turbine repair. They demonstrated major advantages when there are relatively small defects in the part (i.e., repair volume of 10%). In this case, the carbon footprint improvement is roughly 45%, and the energy savings are about 36% compared to replacing with a new product. [108] investigated the differences in environmental performance of repair of a casting die by Directed Energy Deposition and conventional welding. The die repaired via DED was subjected to testing in the die casting plant and demonstrated an equivalent lifetime to the original die. Furthermore, AM removed the necessity for emergency repairs and unscheduled downtime on the production line, as the DED-repaired dies now endure just as many cycles as the original die before requiring any further maintenance. This was also connected to 12% reduction in CO_2 emissions impact during the fifth repair when using AM, assuming no change in the die's service life compared to CM. [78] investigated the potential environmental impact advantages of multiple repair loops under the assumptions that service life of the repaired mold insert is the same as a new one. In this case, they showed that energy consumption and CO_2 emissions could be potentially decreased of 26% and 32%, respectively [78].

3.5.3. Impact of layer deposition rate

Eight studies in the analysed literature emphasized a significant contribution of energy and process gas usage during the additive manufacturing process to the overall environmental impact [25,53,55,61,66,70,104,108]. One of these compared the cradle-to-gate LCA of two different AM techniques: Near-net-shape electrochemical metallization (NEM) and Electron Beam Melting (EBM) [55]. The study showed that process gas (i.e., Argon) and electricity for NEM contribute to more than 50% to the total environmental impact for two impact categories in particular, Water consumption and Ionizing radiation. Similarly, [108] investigated the differences in environmental performance of repair of a casting die by DED and conventional welding. In the former the major contributions originated from electricity use (about 10% to 40%) and Argon gas use (approximately 10%) during the additive manufacturing process. A comparative LCA study also highlighted the importance of deposition rate due to a major contribution (i.e., 15%−30%) from use of electricity and shielding gas to the total impact score of the MAM technique [66]. Interestingly, a study by [61] elucidated the inverse negative relationship between energy consumption per kg printed part and deposition rates (0.5 to 10 kg/h) with Wire-arc Additive Manufacturing (WAAM) based on [113] work. A similar trend emerged when investigating the connection between impact scores and deposition rates. This phenomenon is likely attributed to the reduction in shielding gas and electricity usage per kilogram of printed material. Additionally, as the investigated application is a steel beam for construction; surface roughness is a non-critical design factor. Consequently, machining operations to refine the WAAM surface are typically unnecessary, and only sand blasting and protective painting were considered for product finishing [61].

3.5.4. Recycling of non-fused metal or new scrap

Depending on the additive manufacturing technique considered, an issue that is often highlighted in the literature is that a significant amount of feedstock is not fused and used for the product fabrication [54,104,110,114]. Through the systematic literature review eight studies were identified as relevant for recycling-related considerations [54,70,73,104,105,110,114,115]. Feedstock utilization factors from literature range from 65% to 99% [114], but some studies report lower factors like 12% or 32% [110]. That depends mainly on the recyclability potential of the feedstock materials and the applied MAM technologies [110], and it should be mentioned that the reviewed papers considered only metallic powder recycling. Some studies highlighted that the unused metallic powder during a manufacturing process might be of lower quality, but it can still be used for the same application multiple times (approximately 8 times) after sieving [104]. On the contrary, in another study the authors highlighted that not all materials can be recycled many times due to reactivity with environment conditions (e.g. Ti-alloys and Al-alloys), and estimated that approximately 20% to 25% of recycled metal powder is lost in the process[114]. In the work by [54] criticalities of scrap recycling with Selective Laser Melting (SLM) or conventional repair of a burner tip with steel and nickel based alloys were assessed. The authors found that with mono-fraction sorting and equal quality recycling the impact for Abiotic Resources Depletion is reduced of 50% and 83% for AM and CM, respectively. Thus, particularly for high-value alloy materials, equal quality recycling has significant benefits. On the contrary, mixing individual scraps, which hinders the scrap reuse for the same application, or down-cycling would lead to an additional need of virgin mineral resources and an increase of environmental impact. Additionally, they highlighted the difficulty to minimize material losses and costs in metal power production. Indeed, metal powder is expensive both to acquire and to dispose as frequently it has to be treated as hazardous waste [54]. In contrast, wire-based MAM allows to achieve higher feedstock-efficiency up to 93%− 98% [116], and the overall waste during manufacturing could be potentially reduced of roughly 30% [70].

4. Metal additive manufacturing (MAM): future outlook and method consolidation

Several aspects of MAM technology have improved since its advent on the market. Fig. 7 illustrates the sustainability assessment with a life cycle perspective on MAM techniques based on the literature and the historical growth in the sales of metal AM systems from [18]. This upward trend (as depicted in Fig. 7) aligns with a global market valuation of US $ 2.54 billion in 2021, as reported by [117]. It is anticipated that its market value will continue to expand over the next decade. Another significant aspect to consider is MAM process energy consumption. To enhance the latter, it is vital to evaluate pre-planning optimization in

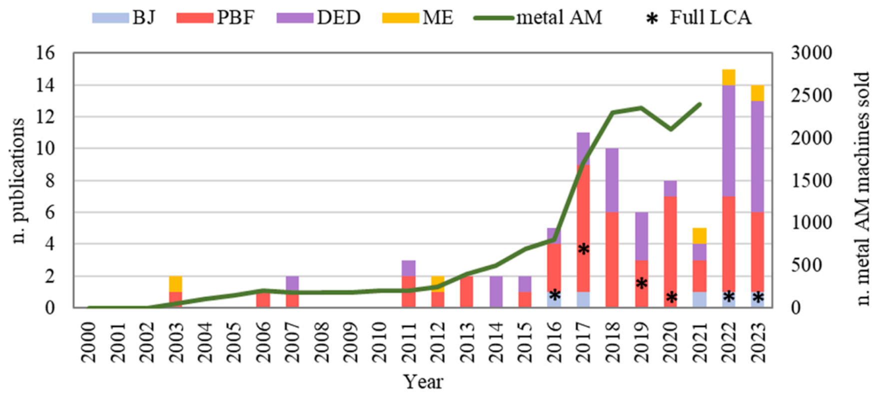

Fig. 7. Analyzed MAM technique in the literature (stacked column referring to primary y-axis), cradle-to-grave LCA studies that consider several environmental impact categories (black asterisks relating to primary y-axis), and number of metal AM machines sold per year (green line connected to secondary y-axis) [18]. Binder Jetting (BJ), Powder Bed Fusion (PBF), Directed Energy Deposition (DED), and Material Extrusion (ME). Additional studies may have been published after July 2023 after this review was carried out.

conjunction with optimal part design [118]. In the study, the energy beam emerged as the most energy-intensive module for a metal AM machine [118]. Additionally, the numerous studies on MAM allowed the creation of life cycle inventories for energy consumption for different techniques and materials per kg printed part [7,119]. Even though that depends a lot also on the specific application [61,106,111]. One more meaningful feature of MAM techniques advancements regards the hardware of some, which now allows to print large build envelope [61, 70,120]. Moreover, AM equipment price for different materials and machine scales declined of approximately 50% or more between 2000 to the present days [121–123], reinforcing the idea that the technology is becoming more diffused and getting more affordable. Nevertheless, its costs are still two or three times higher than for conventional fabrication machines [70]. Other improvements regard software-related aspects such as optimized processing parameters (e.g., reduced height and support material), printing at maximum capacity, application of topology optimization or part consolidation [34,41].

In general, all of that can be called "method consolidation" as the market is converging and some techniques are more becoming favorable than others. This is in line also with the analysed literature (see Fig. 7). Indeed, throughout the years it is possible to notice that the most investigated MAM techniques are belonging to two groups: Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). At the same time, BJ is gaining attention for part consolidation, with recent breakthroughs in industry highlighting its growing significance (e.g., [124,125]). On the other hand, currently, it is possible to notice there are no large scale adoptions of MAM [58,61,65,66,74,75]. Challenges that might hinder its adoption at a larger scale by companies are listed in Table 4, but also discussed in the literature [41]. However, in order to see a change of trend in the medium term, a coordinated and continuous effort from various disciplines both in academia and industry is encouraged [41].

Furthermore, Fig. 7 depicts the studies that have undertaken a comprehensive cradle-to-grave Life Cycle Assessment, taking into account multiple impact categories rather than solely focusing on energy requirements and carbon footprint. It is evident that such analyses constitute a minority, comprising only ten out of sixty-nine studies. Nevertheless, the authors strongly recommend the adoption of a holistic assessment approach when conducting an LCA, emphasizing the preference for a cradle-to-grave methodology. This approach can encompass potential fuel or energy savings during product utilization achieved through MAM and help mitigate burden-shifting effects.

4.1. Potential applications and present challenges of metal additive manufacturing (MAM)

Some of the major potential advantages and current challenges of MAM relative to product sustainability based on the reviewed papers are listed in Table 4.

The aspects illustrated in Table 4 might disregard further potential benefits of MAM as this is based on existing and published scientific literature, and reports were excluded. Additionally, some of critical aspects highlighted previously as the high energy demand for MAM (see Section 3.4.1) have also been discussed in other recently published works [126], and it is in contrast with argumentations provided by other studies [127,128]. Other reports highlight that the knowledge and experience of AM potential advantages is still to be fully discovered in order to best prioritize opportunities and long-term investments based on Life Cycle Assessment [129].

5. Conclusions

Metal additive manufacturing (MAM) appears to have trade-offs in its potential as disruptive technology that to some extent can substitute conventional metal manufacturing processes. On one hand, there are several drivers that could probably decrease its sustainability impacts, such as the re-design for AM. That would allow to obtain: lighter weight products, reduction of the use of consumables, and reduction of energy or fuel consumption during the use of the product. A common finding was that a lighter product due to topology optimization has relevant potential on fuel or energy savings during the product use, in particular in the automotive and aviation sectors. Several studies highlight the relevance of investigating more efficient recycling routes for new scraps and unfused metal during the manufacturing stage, as it represents often a high amount of the wasted material, i.e., from 70% to 90%, that could be recycled. Therefore, it is recommended to consider all life cycle stages when performing LCA on MAM in order not to neglect these potential benefits. It has also potential in reducing number of product components, assembly time, and generally cost and time of production. Multiple studies highlighted that MAM equipment is currently expensive but the overall technology could become more cost-effective than traditional manufacturing once it will be viable to reach larger production volumes. It could also lead to a decrease of transportation and packaging of the finished product due to more local supply chains. More specifically, the capability to shift towards internal production has the potential to mitigate social risks linked to material sourcing, as well as other people-related concerns, including gender equality, human health, and safety. On the other hand, other researchers pinpointed possible adverse environmental, or toxicity impacts caused by the use of auxiliaries or consumables of the technology. Examples for this include binders in Binder Jetting and electricity use in Selective Laser Melting. Another challenge lies in recycling unfused metal internally with a certain quality, making it difficult to use it for new products with similar

Table 4
Main potential benefits and current challenges of MAM relative to sustainability aspects analyzed in the study, and potential overall trade-offs.

Sustainability aspect	Potential advantages	Disadvantages
Environment	• Increase material-use efficiency through near-net shape[52,65]. • Reduce fuel or energy consumption during use stage of product due to lightweight design[14,16,57]. • Prolong product lifetime by topology optimization, faster repair, or maintenance[57,103,107,108]. • Multi-material additive manufacturing showed potential in improving material strengths, possibly extend product lifetime and reduce the use of critical raw materials[112]. However, there is a lack of papers discussing this aspect relative to product sustainability performance. • For large products, e.g., turbine blades, AM techniques is an advantage[107]. • MAM has potential to implement a local supply chain and decrease environmental impacts relative to transportation[11,14,54,98].	• Surface quality and dimensional accuracy are not optimized yet. Thus, further post-processing is necessary[33]. This could cause adverse environmental impact during the EoL phase, and often the recovery rate is lower than 100%[5,33]. • Binder Jetting showed to have adverse effect on human toxicity impacts[65,75]. • For smaller products conventional techniques, e.g., welding, may achieve the same outcome as AM [108]. • Adverse effects due to electricity and process gas use during layers deposition[53,55,61,104]. • Multi-material additive manufacturing, through the combination of diverse alloys, can complicate recycling processes. Therefore, it is important to consider product design for recyclability[112].
Economy	• MAM has the ability to realize part consolidation and thus reduce assembly steps and cost, since it allows to eliminate joints and connectors[114]. • Some studies in the literature claimed to be possible to reach up to 30% cost reduction[62,88]. • Available MAM techniques can compete economically mainly with conventional processes for products with low production volume, complex design and high value[53,93–95]. • Local supply chain and reduced lead time[11,14,54,98] have potential for associated costs decrease.	• For some techniques, e.g., PBF, cost is high due to the need of high-quality powder, inert atmosphere [14,92], and expensive machinery[16,89,90]. • Cost reduction could also lead to the occurrence of rebound effect[14]. • The speed of the AM process and some steps of the post processing, e.g., powder removal, are time-consuming, and, depending on the application, conventional processes are more efficient[5]. • The acquisition cost of AM machines, represents a significant expense, even though it is decreasing[16,70,86,89,90].
Society	• AM contributes to the success of automation efforts in developed countries with aging workforce[45]. • AM has potentially a positive impact relative to health and safety, gender equality, fair salary, social responsibility and security, local suppliers, consumers ́ privacy[97,98]. • Shifting from the supply chain to internal production enables easier intervention and mitigation of social risks[98]. • In some cases, MAM allows to substitute materials that are not socially sustainable, e.g., cobalt-based alloy, employed in conventional manufacturing[98].	• Employees might not be hired locally and have to work extra hours. The main cause of this is the novelty of AM technology, which requires specific qualifications for the workers[97]. • AM could lead to reduction in job demand which might be particularly critical in developing countries [45].
Sustainable Development Goals	• MAM enables some of prosperity-related SDGs as it is an innovative technology which can enhance sustainable management of resources (SDG 12), economic productivity (SDG 8), and resource-use efficiency (SGD 9). • Many studies investigated planet-related SDGs that accordingly to the application have positive impact on climate (SDG 13), water resources (SDG 14), and land (SDG 15). • Some studies emphasized the positive impact of adopting AM on the inclusion of women in leadership positions (SDG 5)[97] as well as its effects on health and safety (SDG 3).	• Potential job demand decrease due to automation with AM could be crucial in developing countries [45]. This is against SDG 10, which relates to equal opportunities in developing countries. • Some analysis showed an adverse impact on climate (SDG 13)[66,118], or human health (SDG 3)[65,75] in comparison to CM.
Trade-offs among sustainability aspects		
• High quality materials for AM are typically more costly than those required for traditional manufacturing. However, implementing lightweight and near-net shape designs may result in savings in both metals and fuel or energy usage, depending on the application. This, in turn, can lead to a reduction in environmental, economic, and social impacts, aligning with SDGs related to the planet, prosperity, and people (e.g., SDGs 3, 9, 12, 13). • Binder Jetting shows promise in enhancing safety, but it has also exhibited adverse effects on human toxicity and relevant SDGs (e.g., SDG 3). • Multi-material additive manufacturing demonstrates potential in reducing the utilization of critical and potentially costly raw materials. Nevertheless, it may introduce complexities in recycling processes at the end of a product's life cycle, and thus adverse environmental impacts and SDGs (e.g., SDGs 8, 9, 12, 13).		

function. Thus, as mentioned in Sections 3.2 and 4, considering several impact categories is crucial, rather than focusing solely on CO_2 or GHG emissions in conjunction with cumulative energy demand or embodied energy. The analysis of the existing literature showed that conventional manufacturing in general currently has a better sustainability performance than MAM for simple parts that need serial production. However, many authors mentioned that this is partially due to the infancy of the MAM technology for industrial application. Moreover, when assessing the overall sustainability, it is relevant to include environment, economic and social aspects. For instance, utilizing indicators aligned with SDGs can contribute to a more holistic approach. Particularly, the number of papers investigating social aspects is rather limited, but they generally find potential positive impacts. Nonetheless, a few papers have pointed out adverse effects associated with the necessity to recruit highly specialized personnel who may not be readily available locally and the reduction of job opportunities resulting from process automation can be particularly critical in emerging countries. Finally, in order to guarantee the comparability across different studies on similar products, reach more robust conclusions, and have more transparent assessment; it is recommended to assess the sustainability impact of MAM with a more similar approach, develop a sensitivity and uncertainty analysis, and disclose to the public characterized results.

Declaration of Generative (AI) and AI-assisted technologies in the Writing Process

During the preparation of this work the authors used ChatGPT3.5 in order to improve orthography and enhance the overall effectiveness of their writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Valentina Pusateri: Data curation, Methodology, Visualization, Writing- Reviewing and Editing. **Michael Zwicky Hauschild:** Conceptualization, Visualization, Writing- Reviewing and Editing. **Sami Kara:** Conceptualization, Visualization, Writing- Reviewing and Editing. **Constantinos Goulas:** Conceptualization, Writing- Reviewing and Editing. **Stig Irving Olsen**: Conceptualization, Visualization, Writing-Reviewing and Editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Associated Content

Supplementary material associated with this article includes details regarding the considered reviewed publications, papers data systematization (including criteria), scores considered for environmental sustainability performance.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.cirpj.2023.12.005.

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