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Review

# Life cycle assessment of additive manufacturing processes: A review

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A R T I C L E I N F O

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Social Life Cycle Assessment (S-LCA)
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A B S T R A C T

Growing consciousness regarding the environmental impacts of additive manufacturing (AM) processes has led to research focusing on quantifying their environmental impacts using Life Cycle Assessment (LCA) methodology. The main objective of this paper is to review the state of the art of the existing LCA studies of AM processes. In this paper, a systematic literature review is carried out where a total of 77 papers focusing on LCA, including social-Life Cycle Assessment (S-LCA), are analyzed. Accordingly, the application of LCA methodology to different AM technologies was studied and different research themes such as the goal and scope of LCA studies, life cycle inventory data for different AM technologies, AM part quality and mechanical properties, the environmental, economic, and social performances of various AM technologies, and factors affecting AḾs sustainability potential were analyzed. Based on the critical analysis of the existing research, five major shortcomings of the existing research are realized: (i) some AM technologies are under studied; (ii) more focus only on the environmental sustainability dimension of AM, neglecting its economic and social dimensions; (iii) exclusion of AM pat quality and its mechanical performance from the sustainability assessment; (iv) not enough focus on the life cycle stages after product manufacture by AM; (v) effect of different product variables on AḾs sustainability not studied extensively. Lastly, based on these shortcomings realized, the following research directions for future works are suggested: (i) inclusion of new AM materials and technologies; (ii) transition to a triple-bottom-line sustainability assessment considering environmental, economic, and social dimensions of AM; (iii) extending the scope of LCA studies to post-manufacture stages of AM products; (iv) development of predictive environmental impact and cost models; (v) integration of quality and mechanical characterization with sustainability assessment of AM technologies.

## 1. Introduction

In Additive Manufacturing (AM) technology, a product is fabricated from its 3D model by depositing the material layer-by-layer, in contrast to conventional moulding, subtractive, and formative manufacturing processes. Benefits of AM include lower material wastage, the ability to fabricate complex geometries [1], mass personalization [2], reduction in lead time and inventory by decentralizing manufacturing [3], and the ability to repair damaged parts [4], among many others. Owing to these advantages AM has found applications in several sectors including aerospace, automotive, construction, and health care, to name a few [5]. Although the general AM technique remains the same, various AM processes have been developed over the years that differ from each other in terms of raw materials, type of feedstock material required and energy

*Abbreviations:* 3DCP, 3-Dimensional Concrete Printing; ADP, Abiotic Depletion Potential; AM, Additive Manufacturing; AP, Acidification Potential; BJ, Binder Jetting; CED, Cumulative Energy Demand; CLAD, Construction Laser Additive Directe; CM, Conventional Manufacturing; DALM, Direct Additive Laser Manufacturing; DED, Directed Energy Deposition; DMLS, Direct Metal Laser Sintering; EP, Eutrophication Potential; FDM, Fused Deposition Modelling; GHG, Green House Gases; GWP, Global Warming Potential; IJP, Ink Jet Printing; LBM, Laser Beam Melting; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LENS, Laser Engineered Net Shaping; LOM, Laminated Object Manufacturing; ME, Material Extrusion; MJ, Material Jetting; MJP, Multi Jet Printing; ODP, Ozone Depletion Potential; PBF, Powder Bed Fusion; PCOP, Photochemical Oxidation Potential; SCR, Solid-to-Cavity Ratio; SEC, Specific Energy Consumption; SLA, Stereo-lithography; S-LCA, Social Life Cycle Assessment; SLM, Selective Laser Melting; SLS, Selective Laser Sintering; WAAM, Wire Arc Additive Manufacturing.

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sources required [6]. Hence, it is necessary to classify the different AM processes to understand their similarities and differences from each other and to select the most appropriate AM process for a given application. The classification of AM processes is open-ended, and they can be classified based on different criteria. For instance, Kruth [7] classified AM processes based on the raw material state (powder, liquid, and solid) and shape-building technique (direct 3D technique and 2D layer technique). Tony et al. [8] classified AM processes based on 3 different criteria namely 1) the principle to create one layer (melt solidification, thermal diffusion, photo-resistivity, extrusion, etc.), 2) the principle to glue two layers (diffusion, photo-resistivity, microwave irradiation, ultraviolet curing, etc. 3) starting state of the material (polymer, resin, powder, sheet, or liquid). The ISO/ASTM52900 "Standard Terminology for Additive Manufacturing-General Principles-Terminology" categorizes AM processes are categorized into 7 different categories: Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination, and VAT Polymerization [9]. These 7 AM categories are briefly summarized in Table 1. The AM classification by ISO/ASTM52900 is appears to be more based on the method of material deposition on the substrate and considers the differences in starting raw materials and energy sources for each AM category. It can be more effective in choosing an AM process from an AM practitioner's perspective. Hence, this classification will be used throughout in this paper.

Nowadays, with higher awareness regarding climate change and its effects, stricter environmental regulations are being framed. To comply with these regulations, industries need to develop and implement manufacturing solutions that cause lesser harmful emissions on the environment, compared to the existing manufacturing processes [11]. AM technology, given that requires lower material compounded by the ability to fabricate complex shapes, does have the potential to make the fabrication of parts environmentally cleaner and more sustainable. However, it must be noted that the advantages of AM such as reduced material waste, do not automatically make it a "greener" process. For instance, Kellens et al. [12] reviewed the resource consumption of different AM processes and pointed out that while AM processes have better material utilization, their specific energy consumption was seen to be 10–100 times higher than that of conventional moulding and machining processes. In the same study, raw material production for AM requires additional processing steps such as powder atomization or wire drawing depending upon the type of AM process and feedstock material used. Furthermore, the impact of AM part quality cannot be overlooked. Owing to their poor surface quality and the presence of residual stresses in some AM parts, they need post-processing operations such as finish machining to achieve the desired surface finish and dimensional accuracy, and heat treatment procedures to relieve the residual stresses. Lack of quality products can cause consumer dissatisfaction, loss of company reputation, economic losses, and environmental impact due to wasted resources [13]. Hence, to assure quality parts, the post-processing of AM products cannot be neglected. Moreover, to improve product quality, philosophies like lean manufacturing, six sigma, lean six sigma, total quality management, and zero defect manufacturing, among others need to be implemented [14]. These post-processing and quality control/assurance steps have additional environmental impacts and/or costs associated with them. Therefore, advantages of AM like material savings can be misleading sometimes from a sustainability perspective and are not appropriate indicators for assessing the sustainability of AM processes. For a comprehensive understanding of environmental sustainability of AM processes, all the required inputs and outputs need to be considered across the different life cycle stages of an additively manufactured product. Therefore, it is necessary to understand first the different life cycle stages of an additively manufactured part. The life cycle of an additively manufactured part is illustrated in Fig. 1.

From Fig. 1, the Life cycle of an additively manufactured product can be broadly divided into the following stages:

- **Primary material production**: It involves activities like the extraction of primary raw materials like metals from the ore and their processing into ingots. The primary material acts as an input for

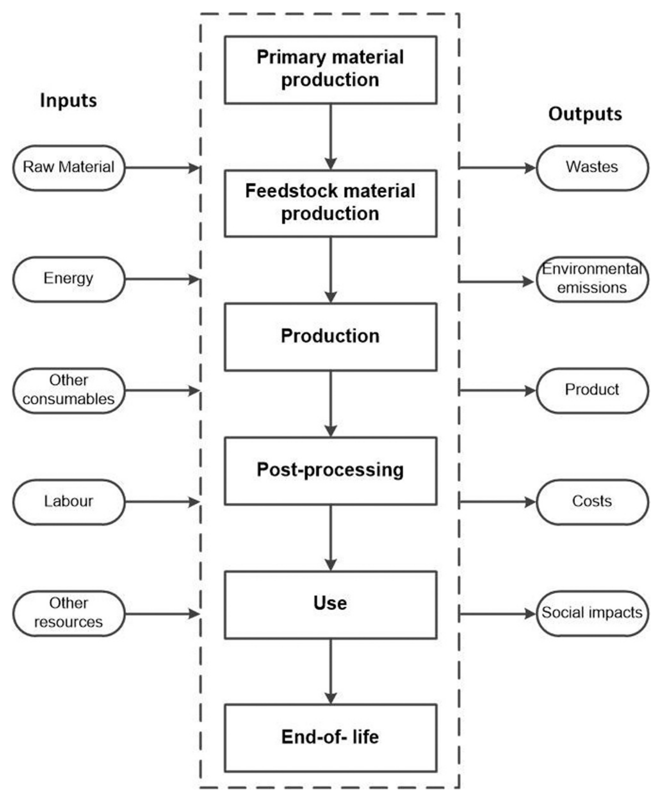


**Fig. 1.** Life Cycle of an additively manufactured part.

**Table 1**
7 AM Categories according to ISO/ASTM52900 standard (Adapted from [9,10]).

| AM category | Technologies | Description | Energy source | Materials |
|---|---|---|---|---|
| Binder Jetting | BJ | A liquid bonding agent is used selectively deposited to join powder materials. | Thermal energy | Metal powders |
| Directed Energy Deposition | LENS, WAAM | Material is melted by focused thermal energy followed by their fusion and deposition | Laser beam/electric arc | Metal powders/wires |
| Material Extrusion | FDM | Material is selectively deposited through a nozzle/orifice | Thermal energy | Polymer filaments |
| Material Jetting | IJP, MJP | Droplets of materials are selectively deposited | Thermal energy/ photocuring | Polymers, wax |
| Powder bed Fusion | SLS, SLM, DMLS, EBM | Powder bed is selectively fused using thermal energy | Laser/electron beam | Polymer, metal, and ceramic powders |
| Sheet Lamination | LOM | Sheets of material are bonded to create a part | Laser beam | Plastic/Metal sheets |
| Vat Polymerization | SLA | Liquid photopolymer in a vat is selectively cured by light-activated polymerization | Ultraviolet light | Photopolymers |

the production of AM feedstock material such as powders, wires, or filaments.

- **Feedstock material production**: In this stage, the primary material is transformed into the AM feedstock material. It involves processes like gas/water atomization for the transformation of metal ingots into powders, wire drawing for the production of metal wires, or extrusion for producing plastic filaments.
- **Production**: Here, a 3D model of the product is generated using computer-aided design (CAD) software. This design is divided into different layers and a G code for AM printer is generated using a slicing software. Based on this G-code, the feedstock material is deposited layer-by-layer to achieve the desired product geometry.
- **Post-processing:** This stage includes activities like the removal of AM support structures, heat treatment to relieve residual stresses, and finishing of parts and their inspection**.** AM parts have lower surface quality due to the "staircase effect" resulting from layer-wise material deposition. To achieve better surface smoothness, AM parts are often subjected to finishing processes. Some metal AM parts may also require heat treatment procedures to lessen the residual stresses and refine the microstructure to achieve better mechanical properties.
- **Use:** This stage involves the distribution, purchase, and installation of the additively manufactured product by consumers, their regular utilization, maintenance, and repair.
- **End-of-life:** This is the final stage in a product's life cycle after its useful lifespan where it is either disposed of, reused, recycled, refurbished, or remanufactured.

In every life cycle stage of an additively fabricated product resources (also known as life cyle inventory) like raw materials, energy, and consumables like compressed air, and inert gas, among others are consumed which results in the generation of wastes and environmental emissions. Therefore, these environmental emissions need to be quantified to determine the environmental friendliness of AM processes. This is done using the Life Cycle Assessment (LCA) methodology defined by ISO 14044:2006 "Environmental management — Life cycle assessment — Requirements and guidelines" standard [15], where all the inventory data such as input resources and output wastes, emissions involved in different stages across a product/process life cycle are quantified. Based on these inventory data, the environmental impact is calculated and expressed in different environmental impact categories like "Greenhouse gas emission [expressed in kg $CO_2$ eq.]", "Acidification Potential [expressed in kg SO2 eq.]", "Cumulative Energy Demand [expressed in MJ]", among many others. Additionally, these resources incur their cost of consumption throughout a product's life cycle and may have a social impact on the different stakeholders involved such as the manufacturer, consumer, workers, local communities, and the broader society. As the application of AM technologies is gaining momentum, the authors believe that it is essential to conduct a thorough state-of-the-art review of their Life Cycle Assessment. This paper presents a critical review of the Life Cycle Assessment of different AM technologies based on the scientific literature published between 2011 and 2022 with the following objectives:

- To present state-of-the-art research in the Life Cycle Assessment of AM technologies.
- To review the requirements of different resources such as raw material, energy, process consumables, and waste generation, among others across the different stages of AM products' life cycles.
- To compare the environmental impacts of AM technologies and conventional manufacturing (CM) technologies along with their economic and social impacts (whenever applicable) and determine the factors affecting their sustainability.
- To determine the shortcomings of the existing research and provide the guidelines for future research.

This paper is structured as follows: Section 2 presents the review of the existing literature related to LCA of AM and analyses their limitations. Section 3 describes the review methodology implemented in this paper. Section 4 provides a brief overview of environmental and social LCA along with Life Cycle Costing (LCC) methodologies. In Section 5, the reviewed literature is classified based on the year, country, and sources of publication and then the different research themes such as goal and scope of LCA studies, life cycle inventory data across the different lifecycle stages of AM parts, AM part quality and mechanical properties, environmental, economic and social performance of AM technologies are discussed. In Section 6, the results are discussed, shortcomings of the existing literature are identified and directions for future research are suggested. Finally, the conclusions of this study are presented in Section 7.

## 2. Related literature

This section analyses the previously published review studies related to the sustainability of AM processes in general and indicates the issues that will be addressed in this study. Previous studies overviewing the environmental performance of AM processes have extensively focussed on their energy consumption, ignoring other resource consumption and factors affecting the sustainability of an AM process. Liu et al. [16] comprehensively reviewed the energy consumption in metal AM processes at different process levels (machine level and process level), different process modes (idle, standby, operation modes), the embodied energy of AM raw materials, and strategies to reduce AM energy consumption. Garcia et al. [17] reviewed the environmental performance of AM processes and pointed out that energy consumption was the most studied aspect, covered in 87% of the articles considered in the study. Only 25% of the articles used LCA of some level to characterize the environmental performance of AM categories. A similar trend was seen by Agrawal et al. [18] in the review focusing on the state-of-the-art of sustainable AM. The studies analyzed in this paper emphasized mainly energy consumption. Therefore, a need to consider other resource consumption and process emissions along with energy consumption to understand the sustainability of AM processes was outlined in this paper. Kellens et al. [19] studied the environmental dimensions of AM processes and realized that despite the growing emphasis on sustainability, fewer full LCA studies are available that analyze and compare the environmental impact of an AM process with other AM processes and conventional manufacturing (CM) processes. Saade et al. [20] reviewed the existing LCA studies of AM processes and focussed on comparing global warming potential (GWP) and embodied energy of AM and CM processes. It was seen that energy consumption is the main contributor to GWP of AM processes while the raw material was the main source of GWP in CM processes. This review highlighted the need for higher energy efficiency of AM processes to be more competitive environmentally.

Based on the above studies, it is clear that energy consumption of AM processes has received higher attention compared to other inventories such as raw material, inert gas, material wastes, material required for building support structures, and material removed in post-processing operations of AM products. Therefore, a comprehensive compilation of different life cycle inventory (LCI) data in AM processes at different process conditions needs to be comprehensively explored and performed. Additionally, there is a need to compare the environmental impact of AM and CM processes to determine the most sustainable process(es) that enable the sustainable manufacturing of a given product. To address this gap, this paper reviews the existing LCA studies of different AM processes and compiles different inventory data such as AM feedstock material production, energy and inert gas consumption during AM process, and the AM wastes generated. Moreover, the comparative LCA studies of AM and CM are presented to find out which process is more sustainable and what factors affect the environmental sustainability of a process. Some studies also analyzed the economic and social impacts of AM processes along with their environmental impacts. Therefore, the environmental and social impacts of AM processes are also discussed in this paper in addition to its associated environmental impacts. The compiled LCI data and different factors affecting sustainability can help manufacturers conduct a preliminary LCA of their products in the early stages of the design phase which in turn can help in the selection of the most sustainable material/process/scenario for manufacturing their products as well as in planning necessary mitigation steps right from the design stage of their products.

## 3. Methodology

The main aim of this literature review is to provide a comprehensive review of existing studies carrying out the LCA of AM processes. This literature review was performed in multiple steps as detailed in Fig. 2.

The first step involved searching for relevant literature in academic databases such as Scopus, Web of Science, Science Direct, and IEEExplorer due to their wider coverage of research items. The following keyword strings were introduced in the "Title, abstract, keywords" field: {"Life Cycle Assessment" AND "additive manufacturing" OR "3D printing"}. This initial search yielded 184,158,89 and 60 research items on Scopus, Web of Science, Science Direct, and IEEExplorer databases, respectively. Then the duplicate results were removed which led to a sample of 281 items. The next step involved screening these research items. The first filtering criteria applied was the language of publication. The items not published in English were excluded from this study. To ensure the comprehensiveness of this review, research items from all sources i.e., journals, conference proceedings, and book chapters were included. Further, the articles were filtered based on their title, abstract, and context of the full article. Only the articles that carryout LCA of an AM process were included at this step. This resulted in a total of 71 articles involving LCA from an environmental sustainability perspective. Out of these 71 articles, 12 studies involved the calculation of economic costs associated with additive manufacturing in addition to its environmental impact. It was seen that 6 additional studies emphasized social-Life Cycle Assessment (S-LCA), assessing the social impacts of AM processes. Therefore, a total of 77 articles were shortlisted for this study. The next step involved the analysis of the filtered articles. Here, firstly the articles were categorized based on criteria such as year of publication, number of publications, and country of origin among others. Then, the content of the filtered articles was analyzed thoroughly to identify and study the different trends and patterns in the application of LCA for AM processes.

## 4. Life cycle assessment and life cycle costing methodologies

In the literature analyzed in the previous section, it is realized that while the majority of the studies applied LCA from an environmental perspective, 6 studies applied "Social-Life Cycle Assessment" to study the social impacts of AM processes. Additionally, 12 studies involved economic assessment of AM technologies using Life Cycle Costing (LCC) in addition to their environmental LCA. Therefore, this section reviews the steps involved in the implementation of environmental LCA, social-LCA, and economic LCC methodologies.

### *4.1. Environmental life cycle assessment*

The environmental Life Cycle Assessment or simply Life Cycle Assessment (LCA) is a well-known and internationally standardized methodology used to calculate the environmental emissions of a product or a process across its different life cycle phases. The framework for conducting LCA methodology is defined by ISO 14044:2006 standard [15] and is performed in the following steps (see Fig. 3).

- **Goal and Scope Definition**: This step includes defining the goal of the study, system boundaries i.e., the life cycle stage(s) analyzed, functional unit i.e., reference unit to which inputs and outputs are

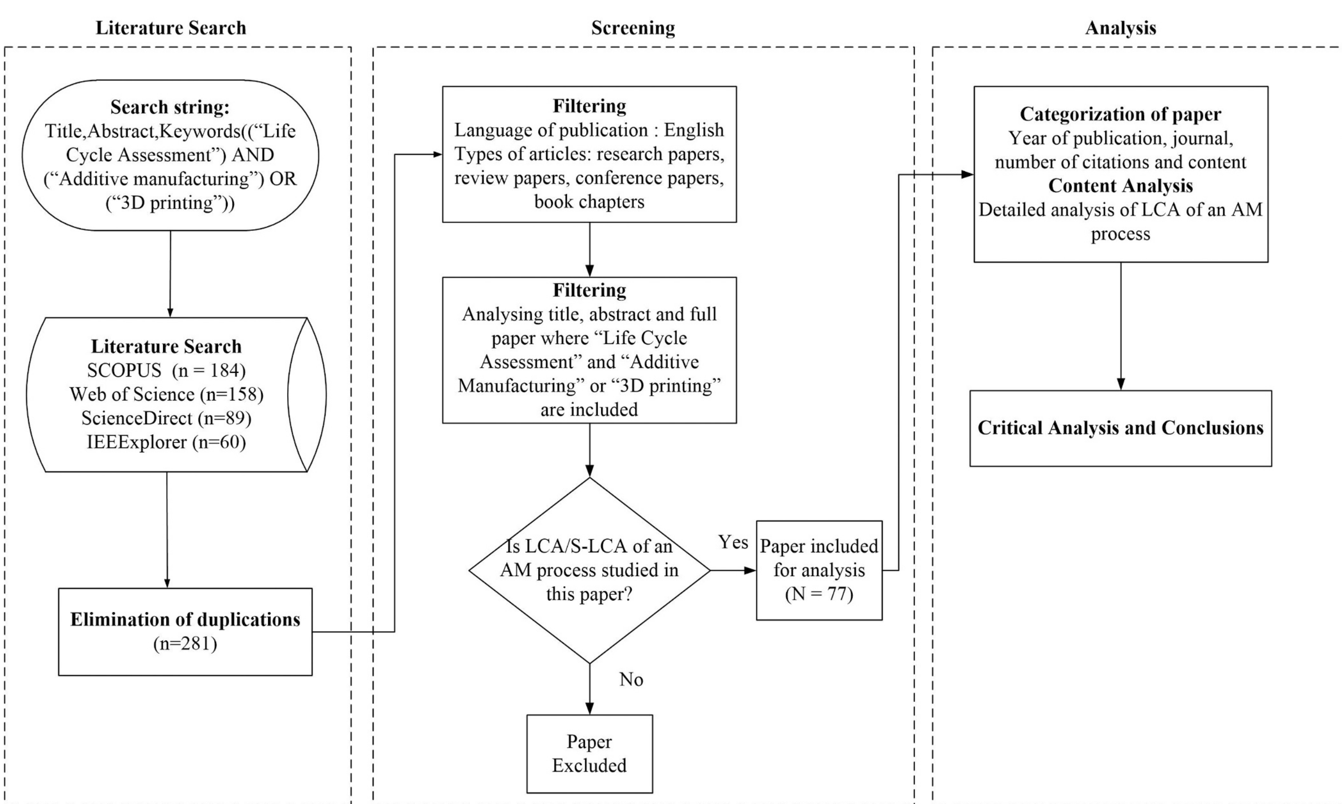


**Fig. 2.** Review methodology (includes articles published up to the end of August 2022).

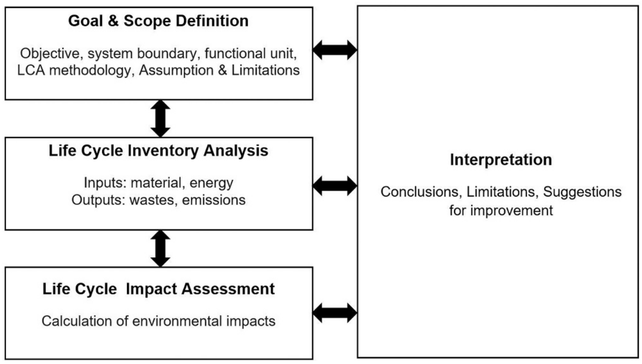


**Fig. 3.** Steps involved in carrying out an environmental LCA based on ISO 14044:2006 standard.

mapped, impact assessment method used, assumptions, and limitations of the LCA study.

- **Life Cycle Inventory Analysis**: Here the inventory inputs and outputs associated with each unit process within the scope of the study are quantified. The inputs refer to the raw materials, energy, and other resources consumed in each step while outputs refer to the wastes and emissions from each step. The inventory data is collected based on experiments, existing life cycle inventory databases, and related scientific literature, among others.
- **Life Cycle Impact Assessment**: Based on the inventory data collected in the previous step, the environmental impact in different categories like Global warming (kg CO2 eq.), Acidification (kg SO2 eq.), Ozone Depletion (kg CFC-11 eq.), etc., are calculated in this step.
- **Interpretation**: In this step, the results of the impact assessment are analyzed, the contribution of different inventories and life cycle stages are determined, environmental hotspots are identified, limitations and opportunities for improvements are derived, and suggestions to minimize the environmental impact are made based on the results of impact assessment.

### 4.2. *Social-life cycle assessment*

The social-Life Cycle Assessment (S-LCA) is a methodology used to assess the potential positive as well as negative social impacts of different products on different stakeholders such as workers, consumers, local community, society, and value chain actors across their different life cycle phases. The guidelines for carrying out an S-LCA of products are defined by the United Nations Environment Programme/ Society of Environmental Toxicology and Chemistry (UNEP/SETAC) [21]. S-LCA is complementary to environmental LCA and can be carried out alone or simultaneously with environmental LCA to aid decision-making based on the social aspects of a product. S-LCA is carried out in a similar way as the environmental LCA framework defined by ISO 14044:2006 standard and UNEP/SETAC guidelines in the following steps:

- **Goal and Scope Definition**: In this step, the goal of S-LCA, the system boundaries under consideration, the functional unit, or a reference flow is defined similarly to an environmental LCA.
- **Life Cycle Inventory Analysis**: This step involves collecting the necessary data related to the social aspects of the functional unit. The inventory data could be quantitative and qualitative and can be collected by literature review, internet search, auditing, structured and semi-structured interviews, questionnaires, and surveys.
- **Life Cycle Impact Assessment**: Here the collected inventory data is related to the relevant social impact indicators, subcategories, and categories and assigning them an indicator score as illustrated in Fig. 4.

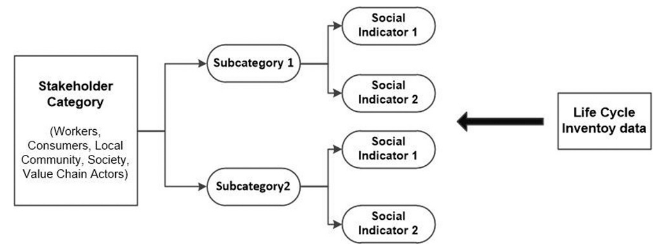


**Fig. 4.** Correlation between life cycle inventory data, stakeholder categories, subcategories, and social indicators based on [21].

- **Interpretation**: Here, the results of the social impact assessment are analyzed, significant issues and social hotspots are identified, conclusions are drawn, and recommendations are made.

### 4.3. *Life cycle costing*

The life cycle cost of a product is simply the sum of all costs incurred over its lifespan. Life cycle costing (LCC) is an effective methodology to assess the life cycle costs of a product or a system. The definition of LCC as quoted from "IEC 60300–3–3:2017 Dependability management - Part 3–3: Application guide - Life cycle costing" standard is as follows [22]:

> *" Life cycle costing is the process of performing an economic analysis to assess the cost of an item over a portion, or all, of its life cycle in order to make decisions that will minimize the total cost of ownership while still meeting stakeholder requirement ".*

Thus, LCC can help manufacturers in making cost-effective decisions in different stages of a product's life cycle. When applied in the early stages of a product's design and development, LCC can help in saving 70–85% of the total product cost [23]. Over the years, many LCC techniques and models have been formulated but no specific model has been accepted as a standard model due to differences in inclination of users, nature of the problem, cost data collection systems, equipment, devices, and systems [24]. While there are different standards like IEC 60300–3–3 [22], and ISO 15686–5 [25] describing the framework of an LCC, Green and Shaw [26] have outlined generic, simple, and effective steps in conducting an LCC analysis as illustrated in Fig. 5. An LCC analysis starts with determining its objective such as a comparative cost analysis between two systems, LCC estimation for budget preparation, and cost-benefit analysis, among others. The scope of the analysis is defined by reviewing the performance, technical and scheduling parameters and selecting the required systems and subsystems. Then, the analyst chooses the most suitable cost estimation method and LCC model depending on the objective of the LCC task. The relevant data is gathered from different sources and LCC inputs are formulated based on the data collected. Next, the input and output data are checked for their consistency, accuracy, validity, and completeness. Sensitivity and risk assessments can also be carried out to express the cost ranges with variations in input parameters. Then, the results of the LCC assessment are analyzed, cost drivers are identified, and the best alternatives are selected and justified. The next steps are systematic documentation of the results and their presentation to the target audience. Additionally, the LCC analysis must be regularly updated due to changes in funding, performance,technical, and schedule parameters, among others.

## 5. Results & analysis

In this section, the major research patterns in the research publications shortlisted are analyzed. Firstly, the publications are categorized according to their year, country, and source of publication, AM processes studied, system boundaries considered, data sources considered for data collection, and environmental impact categories assessed. These categorizations are carried out using Biblioshiny, a web interface of the

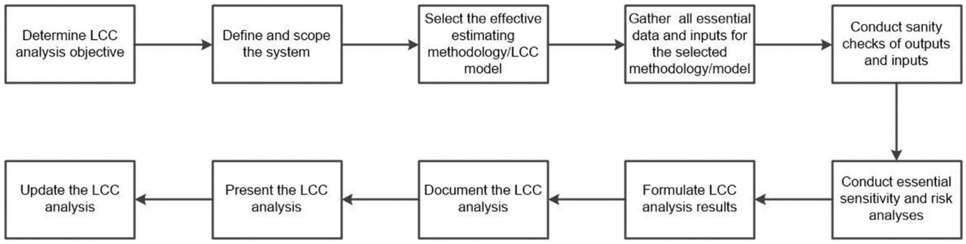


**Fig. 5.** Steps for conducting a life cycle costing analysis based on Green and Shaw [26].

bibliometric R package used for comprehensive bibliometric and co-citation analysis [27]. Then different research trends such as all stages in LCA analysis i.e., goal and scope of the studies, life cycle inventory data for different life cycle stages of different AM processes, AM part quality and mechanical performance, AM environmental, economic, and social performance are reviewed in this section.

### 5.1. Distribution based on year, country, and source of publication

The selected articles were categorized based on their year of publication as illustrated in Fig. 6. The earliest articles on the LCA of AM process were reported in 2011. In the early 2010 s, LCA of AM processes gained little attention. However, from 2017 on, this interest seems to be rising among the scholarly community. The highest number of publications were reported in the year 2020 (23 articles) followed by years 2021 (15 articles) and 2017 (10 articles).

The articles considered in this study were also categorized based on the country of origin of their authors as depicted in Fig. 7. The highest number of articles were written by authors from the United States (30) followed by Italy (24), China (18), and France (12).

Then the sources of these articles were analyzed and the articles were distributed based on their source journal. The Journal of Cleaner Production (13 articles), Journal of Industrial Ecology (8 articles), and International Journal of Advanced Manufacturing Technology (7 articles) were identified as the top 3 sources of articles focusing on LCA of AM processes, considered in this study. A detailed list of journals is displayed in Table 2.

### 5.2. Author analysis

The articles are also categorized based on their number of citations to find the most influential paper in terms of the number of citations received and their corresponding authors as indicated in Fig. 8. The most cited paper by Huang et al. [28] estimated the potential savings in greenhouse gas (GHG) emissions and cumulative energy demand that can be achieved by 2050 by the adoption of AM processes for manufacturing five different aircraft components that are currently

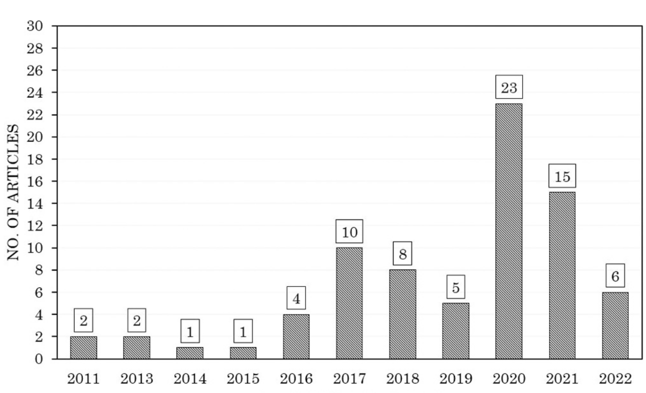


**Fig. 6.** Number of publications per year considered in this study.

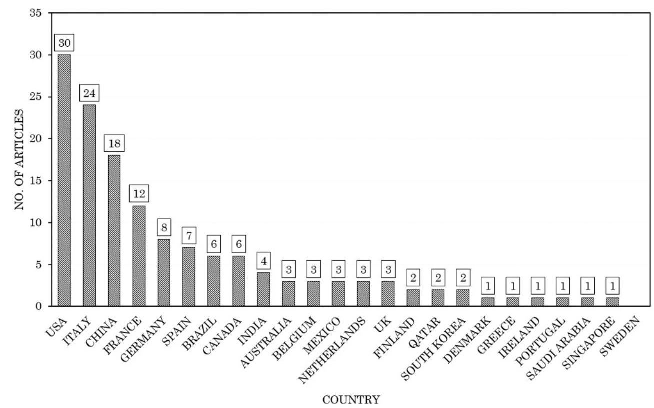


**Fig. 7.** Country-wise categorization of articles studied in this paper.

**Table 2**
Journal-wise articles considered in this study.

| Sources | Articles |
|---|---|
| Journal Of Cleaner Production | 13 |
| Journal Of Industrial Ecology | 8 |
| International Journal of Advanced Manufacturing Technology | 7 |
| Procedia CIRP | 5 |
| Sustainability (Switzerland) | 4 |
| CIRP Journal of Manufacturing Science and Technology | 3 |
| Procedia Manufacturing | 3 |
| Sustainable Production and Consumption | 3 |
| Additive Manufacturing | 2 |
| Other journals with 1 paper each | 29 |

manufactured by conventional manufacturing processes, such as milling, cutting, turning and casting. The second most cited paper by Faludi et al. [29] carried out a comparative cradle-to-grave LCA study of Fused Deposition Modelling (FDM) and CNC machining. The study concluded that it cannot be firmly said that AM is more environmentally friendly than CNC machining. The environmental impacts of a process depend primarily on its usage profile and type of machines. The third most cited study by Bourhis et al. [30] developed a predictive model to estimate the amounts of different environmental flows (raw material, fluids, and electricity) and their environmental impact on the Directed Laser Additive Manufacturing (DLAM) process. A case study calculating the total environmental impact of manufacturing a wall with the DLAM process was also presented to show the utility of the proposed model.

To find the most productive author(s) in the LCA of AM research area, Lotka's inverse square law of scientific productivity was applied [31]. According to this law in bibliometrics, the number of authors with 'n' contributions is about $1/n^2$ of those with 1 contribution; and the proportion of all authors who make 1 contribution is about 60% in a given sample [32]. In other words, only fewer authors contribute to a higher number of articles. Hence, the number of authors and their contributions were plotted in Biblioshiny software to determine the most productive author (refer to Fig. 9). A total of 259 contributing

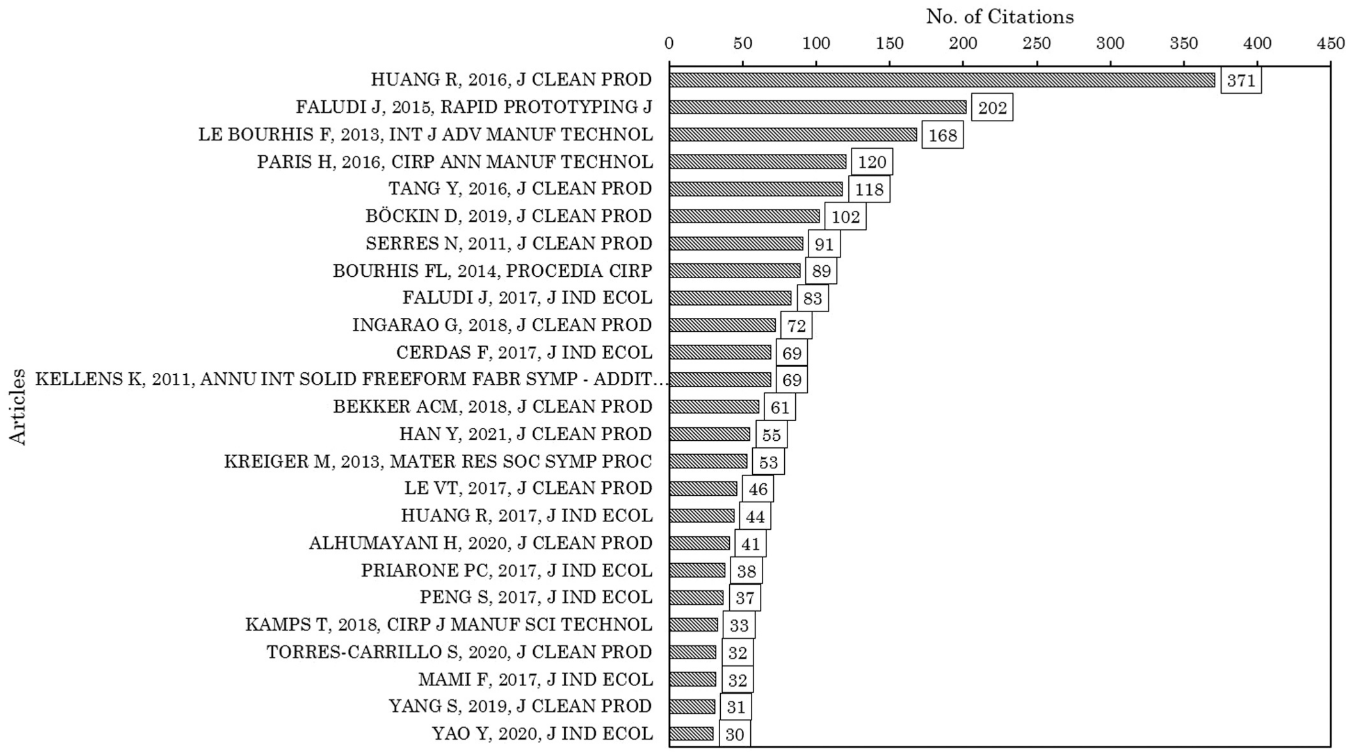


**Fig. 8.** Citation-wise categorization of articles studied in this paper.

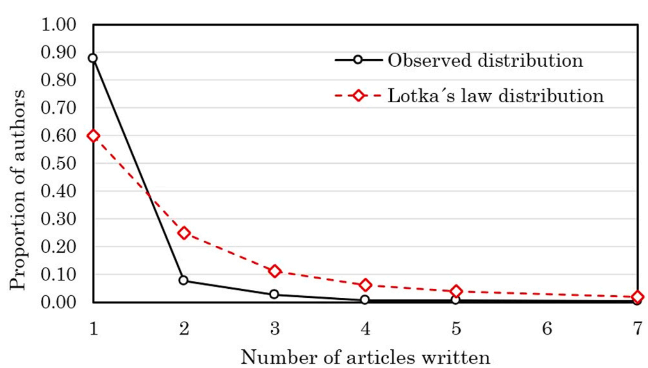


**Fig. 9.** The distribution of the number of articles and proportion of the authors.

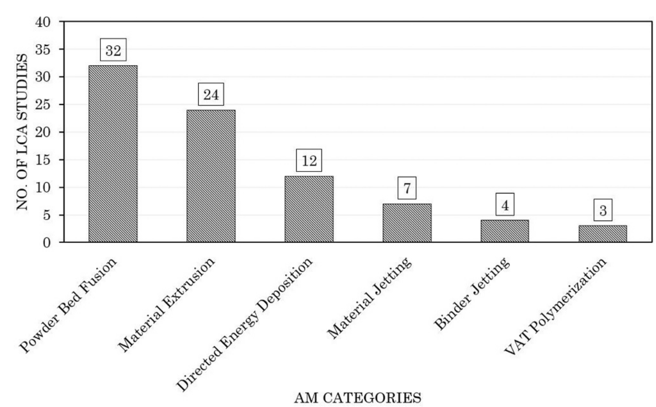


**Fig. 10.** Frequency of LCA studies conducted for each AM category.

authors were found in the literature sample. It was seen that nearly 88% of the authors have written a single article as compared to 60% as per the Lotkás law. Priarone was found to be the most productive author with 7 publications [4,33–38] followed by Campana and Mele with 5 publications each [39–43]. Hence, it is seen that just 3 authors (or 1.1%) contributed 12 articles or 16% of the total articles in the sample.

### 5.3. Review of goal and scope of studies

In this subsection, the different elements defined in the first step of LCA i.e., the Goal and Scope Definition are reviewed. The papers in the literature sample are classified based on the AM process studies, type of assessment (environmental, economic, and social), system boundaries considered, life cycle inventory databases used for data collection, and impact assessment methodologies used.

#### 5.3.1. Distribution based on AM processes studied

The articles were classified based on the 7 categories of the AM process considered in the LCA study as illustrated in Fig. 10. Powder Bed Fusion (PBF) processes were most extensively studied (32 articles) followed by Material Extrusion (ME) processes (24 papers). Out of the 32 articles performing the LCA of PBF technologies, 5 articles analyzed the ecological impacts of Selective Laser Sintering (SLS), 18 articles studied Selective Laser Melting while 12 articles considered Electron Beam Melting (EBM) process. In articles analyzing ME technologies, 18 articles focussed on Fused Deposition Modelling (FDM) while 6 articles focussed on 3D Concrete Printing (3DCP). Other AM categories received comparatively less attention for their LCA. The greater emphasis of LCA of PBF and ME technologies could be attributed to their better technological maturity. Lezama-Nicolas et al. [44] assessed the technological maturity of different AM processes and found that Powder Bed fusion, Material Extrusion and Material Jetting were the most mature AM technologies followed by Directed Energy Deposition while Binder Jetting and Sheet Lamination had the lowest technological maturity. Hence, higher technological maturity would have led to better commercialization of PBF and ME technologies, which in turn might have attracted the application of LCA methodology to these technologies and their products.

*5.3.2. Distribution based on environmental, economic, and social types of assessment*

The goal of the publications selected was analyzed and it was observed that not all studies were limited to LCA of AM processes estimating their environmental footprints (see Fig. 11). As such, 59 studies carried out LCA only, just focussing on the environmental performance of AM processes, and 12 articles focused on both LCA and LCC of AM processes. Only 5 articles evaluated the social sustainability of AM processes assessed using the S-LCA methodology. Only one article assessed the environmental, economic, and social impacts of AM using LCA, LCC, and S-LCA methodologies respectively [45].

*5.3.3. Distribution based on system boundaries considered*

The scope of an LCA study refers to the system boundaries i.e., life cycle stage(s) considered in the investigation. Based on the scope of assessments, they can be classified into cradle-to-gate assessments or cradle-to-gate assessments. In cradle-to-grave assessments, all the life cycle stages starting from the production of raw materials (cradle) to end-of-life (grave) are analyzed. On the other hand, in cradle-to-gate assessments, only a portion of the life cycle from the production of raw materials (cradle) to production in the factory (gate) is analyzed as shown in Fig. 12.

Out of the 72 LCA articles, 42 articles carried out cradle-to-gate LCA studies. Only 16 articles contained cradle-to-grave studies while 14 articles performed cradle-to-gate + end-of-life phase, excluding the use phase. One article included the cradle-to-gate + use phase in its LCA study.

*5.3.4. Distribution based on LCI data sources used*

The Ecoinvent database was the most popular data source for life cycle inventory (LCI) in the articles considered as seen in Fig. 13. Nearly one-third (24 articles) of the total articles considered relied solely on the Ecoinvent database for LCI data and a sixth (12 articles) have Ecoinvent as one of the sources of LCI data and 18 articles relied on a combination of different LCI data sources. However, 10 articles did not explicitly mention the source of LCI data used. Other notable databases were CES, and Gabi reported to be used (solely or in combination with other sources) in 9 and 6 articles respectively, as the only or one of the LCI data sources.,

*5.3.5. Distribution based on impact assessment methodology used*

ReCiPe was the most common impact assessment method used in the articles considered in this study (see Fig. 14). As such, 12 articles used ReCiPe Endpoint (E), 5 articles used ReCiPe Midpoint (M), and 3 articles used both ReCiPe Midpoint and Endpoint impact assessment methods. Energy consumption and $CO_2$ emissions calculation was the second most common method, reported by 10 studies. Additionally, 6 studies quantified only energy consumption while 3 studies considered $CO_2$ emissions alone. Other significant methods reported were Eco indicator (6 articles) and CML (5 articles). Three studies did not specify the impact assessment method used.

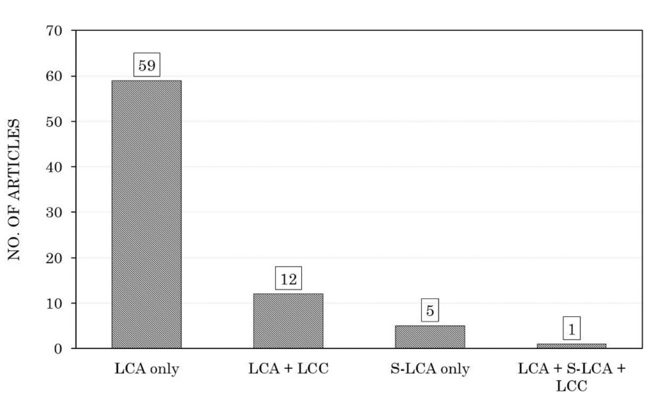


**Fig. 11.** Type of assessments performed in the articles analyzed in this study.

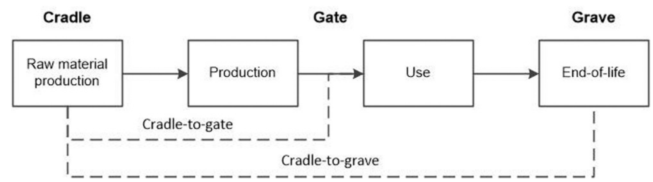


**Fig. 12.** Cradle-to-gate and cradle-to-grave system boundaries of LCA.

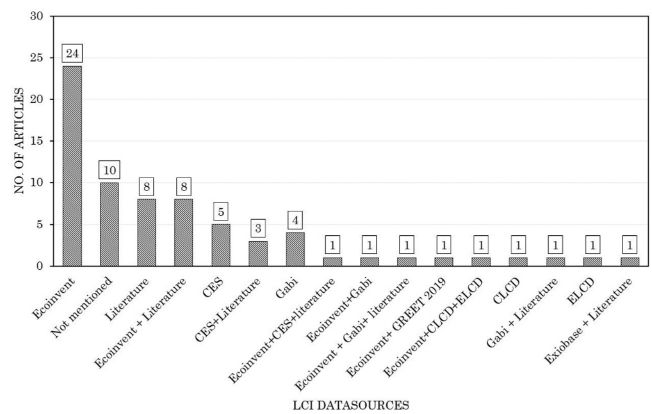


**Fig. 13.** Different LCI data sources used and their frequency.

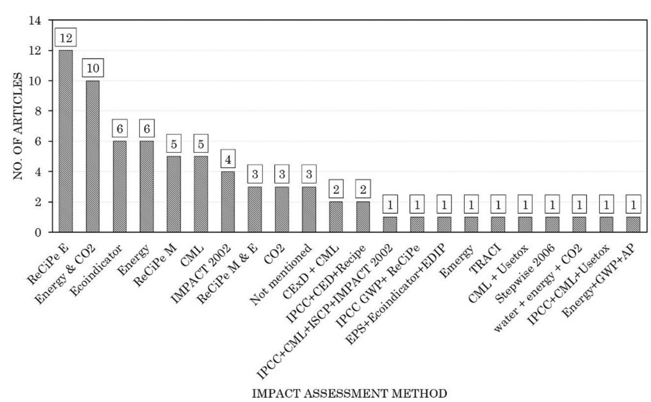


**Fig. 14.** Frequency of different impact assessment methods used by considered studies.

## 5.4. Review of life cycle inventory for AM products

Life Cycle Inventory (LCI) refers to the inputs from nature such as raw material, energy, and other consumables, and outputs to nature such as wastes and emissions. The LCI assessment involves the mapping of these inputs and outputs associated with each step in the life cycle of a product. This is a very important step in environmental LCA because the environmental impact assessment and interpretation of LCA results are based on the LCI data collected. Hence, the LCI should be comprehensive for a good LCA. In this section, the LCI data associated with different life cycle stages of an AM product is compiled based on data mining from the existing literature. Using these compiled LCI data, AM practitioners can carry out preliminary LCAs right in the product design stages to make decisions regarding the selection of sustainable manufacturing processes, and materials or identify the major drivers of environmental impacts of their products.

*5.4.1. Primary material production*

The feedstock material for AM processes is generally in the form of powders, filaments, or wires. These specific feedstock materials are produced from primary raw materials that generally exist in the form of ingots. The production of primary material involves the extraction of primary raw material from the earth and its processing into ingots. Generally, the existing LCA studies considered the embodied energy as LCI in the primary material production stage. The embodied energy is the total energy consumed in the production of primary material. The embodied energies for the production of 1 kg of different primary materials reported in the literature are listed in Table 3.

*5.4.2. AM feedstock material production*

Metal powders are the most common feedstock material form used in different AM processes like powder bed fusion (PBF), binder jetting (BJ), and directed energy deposition (DED) processes. These powders are often produced using powder atomization processes. In an atomization process, a material ingot is melted, and the melted material is disintegrated into fine droplets using a high-pressure stream of gas or water. Table 4 enlists the specific energy, water or argon gas requirements and the material efficiency of the atomization process for producing 1 kg powder of different raw materials.

*5.4.3. Production of AM parts*

This subsection provides a detailed summary of the LCI data such as feedstock material, specific energy consumption (SEC), inert gas, and other resources consumed along with material wastage for different AM processes analyzed in the articles considered in this study.

*5.4.3.1. Selective laser sintering.* Table 5 contains the compiled LCI data for the production of components by the SLS process. Polyamide (PA) powders were used as the raw material in this process. According to a study by Kellens [54], the specific energy of this process lied between 96.48 and 131.4 MJ/kg while the material wastage lied between 43.9% and 46.4% of the input material weight. Kwon [53] reported relatively lower specific energy (12.13–29.23 MJ/kg) but higher material waste (97–98%) as only 1 small test artifact of 101 $cm^3$ was printed. However, this wasted powder after the sintering process can be recycled by refreshing it with new powder.

*5.4.3.2. Selective laser melting.* The LCI data for part fabrication by the SLM process is summarized in Table 6. The specific energy for SLM varies between 55 and 569 MJ/kg. The material wastes in this process include waste powder during SLM, powder required for building supporting structures, and material removed during post-processing processes. The material wastage varied depending upon the geometry and orientation of the final product. Priarone et al. [37] showed that the additional material required for building support structure varied between 30%– 45% of the final part weight in 3 different scenarios involving different orientations of the same part fabricated by SLM. Nagarajan et al. [59] reported a powder waste of 6.15 kg for manufacturing a 1 kg iron final product but this powder was assumed to be recycled. Additionally, the deposition rates and inert gas (Argon in most cases) consumption rates reported in the literature are also documented in Table 6.

**Table 3**
Embodied energy for the production of different primary materials.

| Material | Embodied Energy (MJ/kg) | Reference |
|---|---|---|
| AlSi10Mg | 189 | [37] |
| AlSi10Mg | 224 | [46] |
| H13 tool steel | 65 | [4] |
| Stainless steel | 84.5 | [47] |
| Steel | 19.3 | [48] |
| Stainless steel | 25.7 | [35] |
| Inconel 718 | 279.5 | [49] |
| Ti6Al4V | 685 | [38] |
| Ti6Al4V | 475.54 | [50] |
| Ti6Al4V | 556.2 | [5] |
| Aluminium | 127.1 | [51] |
| Steel | 18.5 | [51] |
| Titanium | 556.2 | [51] |
| PLA granule | 50.4–61.2 | [52] |
| PA12 powder | 129.1 | [53] |
| ABS resin | 93.04 | [53] |

**Table 4**
Life Cycle Inventory for powder atomization of different materials.

| Material | Specific Energy (MJ/kg) | Water (l/kg) | Argon gas (/kg) | Material Efficiency (%) | Reference |
|---|---|---|---|---|---|
| H13 tool steel | 17.62–32.81 | - | - | - | [54] |
| AlSi10Mg | 8.10 | - | - | - | [46] |
| AlSi10Mg | 82.90 | - | - | - | [37] |
| Stainless steel 316 L | 2.48 | 4.54 | - | 90 | [55] |
| Stainless steel | 1.00 | - | - | - | [47] |
| Stainless steel | 7.20 | 280 | 3.5 $m^3$ | 85 | [56] |
| Stainless steel | 2.90 | - | - | 95 | [35] |
| Steel | 15.90 | 155 | 1.25 kg | - | [48] |
| Stainless steel | 2.94 | - | - | - | [57] |
| AISI 4140 steel | 1.65 | - | - | 92.5 | [58] |
| Aluminium | 1.59 | - | - | - | [57] |
| Nickel | 2.94 | - | - | - | [57] |
| Iron | 28.80 | 1.33 | - | - | [59] |
| Inconel 718 | 55.58 | - | - | - | [49] |
| Ti6Al4V | 23.76 | 155 | 5.5 $m^3$ | 97 | [60] |
| Ti6Al4V | 23.80 | - | - | - | [47] |
| Ti6Al4V | 7.02 | 155 | 0.3 kg | 93 | [61] |
| Ti6Al4V | 70.00 | - | - | - | [33,34] |
| Ti6Al4V | 93.24 | - | - | - | [50] |
| Ti alloy | 0.91–2.34 | - | 0.18 $m^3$ | 92.5 | [62] |
| Glass | 14.40 | 155 | 7 $m^3$ | 46 | [63] |

*5.4.3.3. Electron beam melting.* The LCI data for the production of parts by EBM are compiled in Table 7. The specific energy consumption for EBM of Ti alloys was reported in the interval of 85–508 MJ/kg for deposition rates of this process varying between 0.02 and 0.12 kg/h, by Lunetto et al. [33] and an empirical model to estimate the SEC of EBM during printing phase as a function of average deposition rate ($DR_a$) was proposed as follows:

$$SEC_{EBM} = \frac{C}{DR_a}, \tag{1.1}$$

where C is a constant expressed in MJ/h. For example, C= 2.82 for an ARCAM A2X machine).

The supporting structures build during the printing phase lied in the range of 10–127% of the final part weight, depending upon the build height [61], complexity, and orientation of the part [34]. In addition to the supporting structures, the machining allowance to achieve the final dimensions of the part was 1 mm depth of material removed across the surface area of the product in different studies [34,50].

*5.4.3.4. Fused Deposition Modelling.* Table 8 summarizes the LCI data compiled for the fabrication of components using the FDM process obtained from the literature. The raw materials commonly used were

**Table 5**
Life Cycle Inventory of the SLS process.

| Machine tool | Raw material | SEC (MJ/kg) | Build rate (kg/h) | Material waste (% wt.) | Consumables | Reference |
|---|---|---|---|---|---|---|
| EOSINT P760 | PA2200 0.12 mm | 131.4 | 0.17 | 44.9 | Compressed air: 20 $m^3$/h | [54] |
| | PA2200 0.15 mm | 143.28 | 0.15 | 43.9 | | [54] |
| | PA3200GF 0.15 mm | 96.48 | 0.24 | 46.4 | | [54] |
| P770 | PA12 | 12.13–29.23 | - | 97–98 | | [53] |

**Table 6**
Life Cycle Inventory of the SLM process.

| Machine tool | Raw material | SEC (MJ/kg) | Deposition rate (kg/h) | Material waste (% wt. of final part) | Inert gas | Reference |
|---|---|---|---|---|---|---|
| Concept Laser M3 | Stainless steel | 80.32 | 0.168 | 20.5 | Nitrogen: pre-flushing: 6.5 $m^3$/h Production: 3.5 $m^3$/h | [54] |
| Renishaw AM250 | AlSi10Mg | 568.5 | 0.012 | 20.68 | Ar: 208 l/build | [46] |
| SLM 250 | stainless steel | 244.1 | - | - | - | [47] |
| - | AlSi10Mg | 566 | - | supporting structures:30–45%; finish machining allowance: 10% | - | [37] |
| Renishaw AM250 | steel | 365.01 | - | SLM losses: 3%; finish machining allowance: 50% | Ar: 0.37 kg/job | [48] |
| EOS M290 | Iron | 178.56 | 9 $cm^3$/h | 615% | Ar: 19.98 $m^3$/h | [59] |
| SLM 280 | Stainless steel | 383.13 | 9.9 $cm^3$/h | 34% | Ar: 3.08 kg/build | [55] |
| - | Stainless steel | 244.1 | - | Supporting structures: 8.4%; finish machining allowance: 1.7% | - | [35] |
| - | stainless steel | 55.71–67.88 | - | support structures: 4.3–5.5% | Ar: 10 l /build; | [56] |
| - | Inconel 718 | 427.47 | - | - | Ar: 2 l/min | [49] |

**Table 7**
Life Cycle Inventory of the EBM process.

| Machine tool | Raw material | SEC (MJ/kg) | Deposition rate (kg/h) | Material waste (% wt. of final part) | Reference |
|---|---|---|---|---|---|
| ARCAM | Ti6Al4V | 400.25 | 0.022 | - | [60] |
| ARCAM A1 | Ti6Al4V | 45.12–140.32 | - | - | [61,64] |
| - | Ti6Al4V | 59.96 | - | - | [38] |
| ARCAM A1 | Ti64Al4V | 61 | - | - | [47] |
| - | Ti6Al4V | 178.28–399.49 | - | Supporting structure: 11–127%; machining 17% | [61] |
| - | Ti powder | 178.28 | - | - | [65] |
| - | Ti6Al4V | 176.8 | - | Supporting structures:20%, machining allowance 1 mm depth | [34] |
| ARCAM A1 | Ti6Al4V | 176.35 | - | 55% assuming 1 mm depth machining allowance | [50] |
| ARCAM A2X | Ti6Al4V | 84.6–507.6 | 0.02–0.12 | support structure: 10% of final product, machining allowance assumed: 10% | [33] |

**Table 8**
Life Cycle Inventory of the 3D printing process.

| Machine tool | Raw Material | SEC (MJ/kg) | Deposition rate | Material waste (% final part weight) | Reference |
|---|---|---|---|---|---|
| Replicator 5th Generation FDM 3D printer | PLA | 32.23–63.79 | 3.6–8 g/h | supporting structure:30.6 | [52] |
| Stratasys Fortus 400mc | ASA | 457.2 | 25 $cm^3$/h | 51.5 | [59] |
| - | ABS | 122.9 | - | 3 | [53] |
| - | Nylon PA6 | 44.77–51.62 | 33–38 g/h | 0.9–6.6 | [69] |
| PrintRite CoLiDo 2.0 | PLA | 9.53–46.79 | 5–27 g/h | - | [70] |
| GTMAX 3D CoreAB 400 | ABS | 45.5–49.46 | - | 10.9–13.9 | [71] |
| Stratasys Dimension SST | Plastic | 533.36–611.78 | 4.7–5.4 g/h | - | [72] |
| Stratasys Dimension SST | PLA + PU composite | 0.36–3.96 | 6–18 g/h | - | [73] |
| Kuka robot | C-60 concrete | 3 | 4 kg/h | - | [66] |
| ABB IRB6700 + Putzmeister MP25 machine | Concrete | 108.48 MJ/m3 | 0.36 $m^3$/h | - | [67] |
| KUKA KR60 HA robotic arm | Concrete | 87.75 MJ/m3 | - | - | [68] |

filaments of Acrylonitrile styrene acrylate (ASA), Acrylonitrile butadiene styrene (ABS), and polylactic acid (PLA). The specific energy of FDM processes lied in the range of 0.36–612 MJ/kg. The material wastes lied between 0.9% and 51.5% of the final part weight. Additionally, the LCI data for the 3D printing of concrete [66–68] are also included in Table 8.

*5.4.3.5. Directed Energy Deposition processes.* The LCI consumed during the part manufacture by DED processes like Direct Additive Laser Manufacturing (DALM), Laser Engineered Net Shaping (LENS), Wire Arc Additive Manufacturing (WAAM), and Laser Cladding Forming (LCF) are summarized in Table 9. The SEC values for DALM of steel lie in the range of 77.32–87.16 MJ/kg. The material wastes for DALM are reported in the range of 20%– 65% of the final part weight. For the LENS

**Table 9**
Life Cycle Inventory of DED processes.

| AM Process | Raw material | SEC (MJ/kg) | Deposition rate (kg/h) | Material waste (% final part weight) | Inert gas | Reference |
|---|---|---|---|---|---|---|
| DALM | steel powder | 77.32–87.16 | 0.192–0.278 | - | Ar:1.54–1.56 $m^3$/kg part | [30] |
| DALM | Metallic glass powder | 19.21–102.61 | 0.174–0.184 | 20% – 65% | Argon: 0.22–2.484 $m^3$/kg part | [63] |
| LENS | AISI 4140 steel powder | 34.08 | 0.226 | 614% | Ar: 11.36 l/g part | [58,74] |
| WAAM | Stainless steel wire | 9.79 | 1 | - | Ar 98%+ $CO_2$ 2%: 12 l/min | [76] |
| WAAM | Aluminium, steel, Titanium wire | Al:6.3 Steel: 23.7 Ti: 33.4 | 0.66–2.40 | Finish machining allowance:143%–370% | - | [51] |
| WAAM | H13 tool steel wire | 6.7 | 2.28 | 281% | Ar: 1.51 l/g part | [4] |
| DED | H13 tool steel powder | 133.88 | 0.513 | 165% | Ar: 8.27 l/g part | [75] |
| LCF | Ti alloy powder | 318.26 | 0.478 | 25–43% | Ar: 10 l /min | [62] |

process involving AISI 4140 steel powder as the raw material, a specific energy consumption of 34.08 MJ/kg and high powder waste (over six times the final part weight) were reported by Liu et al. [58] and Jiang et al. [74], as large quantities of powders were seen to be lost during the deposition.

The SEC values for the WAAM process varied between 6.3 and 33.4 MJ/kg depending upon the wire feedstock material. The WAAM process exhibited relatively higher deposition rates varying between 0.66 and 2.4 kg/hr. The finish machining allowance for WAAMed structural elements was reported between 143% and 370% of the final part weights ranging between 7.8.8 kg and 188 kg, as reported by [51]. Gouveia [75] reported specific energy of 133.88 MJ/kg at a deposition rate of 0.513 kg/h for a powder-based DED process using H13 tool steel powder as the raw material with material wastage of 165% of the material required to be deposited (14.5 g) to repair the steel mold considered. For the LCF process using Ti alloy powder, the specific energy of 318.26 MJ/kg with powder wastage between 25% and 43% of the product weight (depending upon the powder utilization) was reported by Peng et al. [62]. Additionally, the argon gas consumed during each process is also reviewed in Table 9.

*5.4.3.6. Other AM processes.* AM processes like material jetting (MJ), multiple jet fusion (MJF), Ink jet fusion (IJF), binder jetting (BJ), and Stereolithography (SLA) are not been extensively studied in LCA studies of AM processes. Kwon et al. [53] reported specific energy for MJ of ABS resin as 115.8 MJ/ with a utilization rate of 61%. London et al. [77] reported the SEC of 98.7 MJ/kg for the MJF process involving PA12 powder with a scrap rate of 5% [77]. The SEC for BJ of stainless steel lay in the range of 32.5–99.66 MJ/kg, according to the studies by Tang et al. [78] and DeBoer et al. [79]. Shi and Faludi [80] computed an SEC of 258.92 MJ/kg for ink jet fusion of PA 12 powder along with material wastage of 6.3% of the final part weight Mele et al. [41] calculated the SEC of 86.54 MJ/kg for desktop stereolithography process where the supporting structure accounted for 40% of the final product weight. Table 10 summarizes the LCI data for the above-mentioned AM processes.

**Table 10**
Life cycle inventory of MJ, MJF, IJF, BJ, and SL processes.

| AM Process | Machine Tool | Raw material | SEC (MJ/kg) | Material wastage (% wt.) | Reference |
|---|---|---|---|---|---|
| MJ | J750 PJ | ABS resin | 115.8 | 39% of input material wt. | [53] |
| MJF | HP MJF 4210 | PA12 powder | 98.7 | 5% scrap rate (assumed) | [77] |
| IJF | - | PA 12 powder | 258.92 | 6.3% of final part wt. | [80] |
| BJ | - | Stainless steel powder | 32.5 | - | [79] |
| BJ | - | Stainless steel powder | 67.1–99.66 | - | [78] |
| SLA | Form2 | Clear 4 resin | 86.54 | Supporting structures: 40% final part wt. | [41] |

### 5.4.4. *Post-processing of AM parts*

Rough surface quality and the presence of residual stresses are major issues in AM fabricated parts. To achieve the desired surface smoothness, AM parts are often subjected to different finish machining operations. To relieve the residual stresses, as-built AM parts are often subjected to heat treatment processes. Additionally, there is a need for the removal of the excess material, support structures build during material deposition, and part removal from the substrate. All these activities are covered in the post-production phase of AM parts. These post-processing activities consume additional electricity and generate material wastes, limiting the resource and cost efficiency of AM processes. Some studies have considered the effect of these post-processing activities on the environmental performance of processes like SLM [35,37,48], EBM [34,50,61], WAAM [4,51], and LCF [62]. Apart from finish machining, some studies also considered heat treatment procedures to relieve residual stresses. Davis et al. [35] and Priarone et al.[4] considered annealing for relieving the residual stresses in steel parts fabricated by SLM and WAAM, respectively. Ingarao and Priarone [34] considered the wire EDM process for the removal of support structures from EBM built part, hot isostatic pressing (HIP) for residual stress relief, and finish machining of functional surfaces. The remainder studies just considered finish machining to achieve better surface accuracy, as illustrated in Table 11. The different post-processing operations, their

**Table 11**
Life Cycle inventory for post-processing operations of different AM processes.

| AM process | Raw material | Post-processing operation | SEC (MJ/kg) | Reference |
|---|---|---|---|---|
| SLM | Stainless steel | Annealing | 1.5 | [35] |
| | | Finish machining | 245.5 | [35] |
| SLM | AlSi10Mg | Finish machining | 6.6 | [37] |
| SLM | Steel | Finish machining | 44.84 | [48] |
| EBM | Ti6Al4V | Rough machining | 14.77 | [61] |
| | | Finish machining | 86.58 | [61] |
| EBM | Ti6Al4V | Wire EDM | 37 | [34] |
| | | HIP | 122 | [34] |
| | | Finish machining | 5.4 | [34] |
| EBM | Ti6Al4V | Milling | 80.44 | [50] |
| | | Grinding | 23.6 | [50] |
| WAAM | Aluminium | Finish machining | 9.9 | [51] |
| | Steel | Finish machining | 3.6 | [51] |
| | Titanium | Finish machining | 22.1 | [51] |
| WAAM | H13 steel | Annealing | 1.19 | [4] |
| | | Finish machining | 41.76 | [4] |
| LCF | Ti alloy | Finish machining | 600 | [62] |

energy requirements for different AM processes, and raw materials are compiled in Table 11.

#### 5.4.5. Use phase of AM parts

The material savings achieved by the application of AM processes in the production of parts can result in energy savings in the subsequent use phases, depending upon the application of the product. As discussed previously, a majority of the LCA studies considered in this paper limited their scope either ranging from raw materials to production phase (cradle-to-gate) or raw materials to production and end-of-life phases, excluding the use phase (cradle-to-gate + EoL). Out of the LCA studies that analyzed cradle-to-grave system boundaries, it was observed that most of the studies assumed similar use phases for additive and conventionally manufactured products. Only a handful of papers comprehensively studied the energy saved during the utilization of products enabled by material savings achieved by AM processes [4,28, 81]. Hetteshiemer et al. [81] studied the energy savings that can be achieved by the implementation of SLS in manufacturing a small turbine wheel made up of AlSi10Mg for automotive applications and Ti6AL4V for aerospace applications. The AM fabricated turbine wheel weighs 57 g using AlSi10Mg and 90 g using Ti6Al4V, as opposed to 162 g using conventional manufacturing of steel. By using this lightweight product in different products like passenger cars, tractors, and short and long-haul aircraft manufactured in Germany, huge energy savings in the utilization phases of these products can be achieved as calculated in Table 12.

Huang et al. [28] studied the material and energy savings obtained by the adoption of AM processes like SLM, DMLS, and EBM in the manufacturing of 5 aircraft components namely Bracket, bionic bracket, engine cover door hinge made up of titanium alloys, seat buckle and fork fitting composed of aluminum alloys. AM enables a mass reduction ranging between 35%– 65%, saving thousands of tonnes of aluminum, titanium, and nickel by 2050. Additionally, energy savings in millions of gigajoules (GJ) per year were projected by the adoption of AM depending upon slow (28 years), medium (15 years), or fast (5 years) pace of 80% AM adoption by component producers in the fleet of aircraft by 2050, as displayed in Fig. 15. The majority of these energy savings (95%–98%) were seen due to reduced fuel consumption enabled by AM fabricated light weight components, while the cradle-to-gate energy savings accounted 2%– 5% of the overall energy savings.

Using AM processes there is a technological feasibility of repairing a worn-out part using AM as opposed to part replacement, where a new part is manufactured, which replaces the worn put pat. Priarone et al. [4] studied the opportunity of wire arc additive manufacturing (WAAM) in extending the service life of a mold insert part to multiple life cycles by conducting repairs at the end of each life cycle using WAAM as opposed to replacement where a new mold insert is produced by conventional subtractive manufacturing. The WAAM-enabled repair-based approach resulted in obvious material and energy savings at the end of the first life cycle. Furthermore, it was seen that the material energy reductions using a repair-based approach amplified as the number of extended life cycles due to repair increased due to the accumulation of material and energy savings achieved at the end of each life cycle.

**Table 12**
Annual energy savings achieved by utilization of a light weight AM part based on Hettesheimer et al. [81].

| Unit | Annual energy savings (MJ/year) | Lifetime (years) | Lifetime Energy savings/unit (MJ) | No. of units produced in Germany in 2015 | Annual energy savings (GJ/year) |
|---|---|---|---|---|---|
| Passenger car | 1.65 | 9 | 14.82 | 5700000 | 9405 |
| Tractor unit | 2.27 | 4.2 | 9.52 | 188000 | 426.76 |
| Short-haul aircraft | 360 | 26 | 9360 | 260 | 93.6 |
| Long-haul aircraft | 480 | 26 | 12490 | 125 | 60 |

#### 5.4.6. End-of-life of AM part

A majority of the LCA studies analyzed in this paper limited their scope of investigation up to the production phase of AM products. Among the studies that considered the end-of-life of AM products, the majority of them considered product disposal as the end-of-life strategy. Fewer studies considered the recycling approach of material wastes. In these studies, the life cycle inventories considered for recycling different waste materials were documented in the form of energy required and carbon dioxide emissions per unit kilogram of the waste material processed. These life cycle inventories for recycling different waste materials are documented in Table 13.

### 5.5. Review of AM part quality and mechanical properties

One of the major limitations of AM technology is poor surface quality and dimensional accuracy, especially in the cases of directed energy deposition, material jetting, and sheet lamination technologies [5]. Furthermore, AM parts can have anisotropic and heterogenous mechanical properties due to directional heat extraction, rapid solidification, repeated melting, or the presence of defects such as pores or lack of fusion [82]. Therefore, it is also important to assess the mechanical properties of AM parts and test if AM parts can guarantee a similar level of mechanical performance as that of conventionally manufactured parts. The part quality or mechanical characterizations of different AM processes in the shortlisted publications are also studied. It was seen that only 5 studies included mechanical characterization of AM parts along with their sustainability characterizations [51,55,62,71,83]. The mechanical properties of AM parts and their comparison with conventionally produced parts are summarized in Table 14. Some studies [29, 52,62] explicitly mentioned the assumption of identical part quality and mechanical performance achieved by AM and CM processes, while others implicitly assumed the same.

Peng et al. [56] fabricated a weight-optimized stainless steel hydraulic valve body using SLM. For its good functioning, this valve body needed a yield strength greater than 549 MPa and hardness greater than 195 HV. SLM fabricated valve body demonstrated a yield strength of 624.6 MPa and hardness of 212.9 HV. On the other hand, the conventionally fabricated valve body showed a yield strength of 300 MPa and hardness of 195 HV. Thus, it was seen that the SLM approach resulted in superior mechanical properties along with weight reduction compared to conventional manufacturing. Similarly, Guarino et al. [55]reported better tensile strength of 590 MPa and harness of 230 HV for SLM fabricated stainless steel flat washers, compared to 515 MPa and 155 HV obtained for laser cut flat washers. However, SLM made part had a rougher surface (8.99 μm) compared to the laser cut part (0.8 μm). Priarone et al. [51] evaluated the ultimate tensile strength (UTS) and elongation at break for WAAM fabricated aluminium, steel, and titanium samples. The values were not disclosed due to confidentiality reasons but it was reported that WAAM fabricated samples showed slightly lower UTS values by 3–8% but higher elongations at break compared to the parental materials.

Prakash et al. [83] compared surface roughness, surface hardness, and dimensional deviations in an Al-6063 cast obtained by conventional investment casting (IC) and FDM-assisted IC. By the FDM-assisted IC approach, slightly higher surface roughness, surface hardness, and dimensional deviation of 54.2 HRB, 6.02 μm, and 0.84 mm compared to 53.3 HRB, 5.53 μm, and 0.25 mm obtained by conventional IC. As these differences were marginal, it was concluded that the adoption of FDM-assisted IC does not affect its ability to produce precise and tight dimensional tolerances.

Garcia et al. [71] studied the variation in tensile strength and elongation at the break of 3D-printed ABS samples as a function of infill

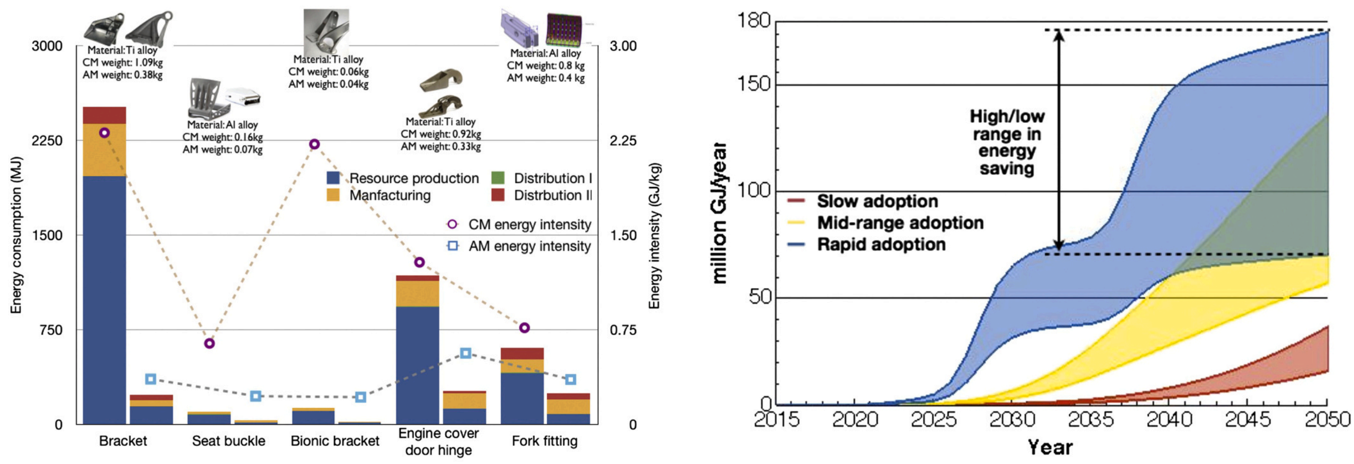


**Fig. 15.** a) Cradle-to-gate energy savings by AM adoption b) Cumulative energy savings by AM adoption at different rates [28] . Images repirnted from Huang et al. [28] with permission from Elsevier.

**Table 13**
Life cycle inventory for recycling of different waste materials.

| Waste material | Energy (MJ/kg) | $CO_2$ emissions (kg/kg) | Reference |
|---|---|---|---|
| Titanium | 14.68 | - | [60] |
| Ti6Al4V | 87 | 5.2 | [38,50] |
| Aluminium | 6.85 | - | [36] |
| Steel | 7.5 | - | [35] |
| Steel | 12 | 0.7 | [47] |
| Steel | 5.45 | - | [48] |
| Stainless steel | 23 | 1.45 | [79] |
| Cast iron | 10.4 | 0.31 | [79] |

**Table 14**
A comparison between mechanical properties achieved by AM and CM processes.

| Study | Material | Mechanical properties studied | AM | CM |
|---|---|---|---|---|
| Peng et al. [56] | Stainless steel 316 L | | SLM | CNC machining |
| | | Hardness (HV) | 212.9 | 195 |
| | | Yield strength (MPa) | 624.6 | 300 |
| | | | SLM | Laser Cutting |
| Guarino et al. [55] | Stainless steel 316 L | Vickers Hardness (HV) | 230 | 155 |
| | | Surface roughness (μm) | 8.99 | 0.8 |
| | | Tensile strength (MPa) | 590 | 515 |
| | | | FDM assisted IC | Conventional IC |
| Prakash et al. [83] | Aluminium (Al-6063) | Rockwell Hardness (HRB) | 54.2 | 53.3 |
| | | Surface roughness (μm) | 6.02 | 5.53 |
| | | Dimensional deviation (mm) | 0.84 | 0.25 |
| | | | FDM | Injection Molding |
| Garcia et al. [71] | ABS | Tensile strength (MPa) | | |
| | | 25% infill | 24.67 | 39.2 |
| | | 50% infill | 24.67 | |
| | | 75% infill | 30.7 | |
| | | 100% infill | 33.03 | |
| | | Elongation at break (%) | | |
| | | 25% infill | 5.6 | 30.1 |
| | | 50% infill | 6.98 | |
| | | 75% infill | 8.09 | |
| | | 100% infill | 8.28 | |

percentage (%). It was observed that as the infill % increased from 25% to 100%, the tensile strength increased from 24.67 MPa to 33.03 MPa and the elongation at break also increased from 5.6% to 8.28%. The increase in infill percentages resulted in increased mass and reduced empty spaces in each sample, improving their ability to withstand greater traction. However, a tensile strength of 19% higher and an elongation approximately 3 times higher than that of FDM parts was found in conational injection molded parts. This was attributed to the stretching of molecular chains in the direction of injection that gives better strength to the injection molded part as opposed to FDM where layers are deposited on top of each other.

### 5.6. Review of the environmental performance of AM processes

This section discusses the findings of the articles which compared the environmental performances of AM and CM processes. 41 out of 71 articles considered in this study did a comparative LCA of AM and CM processes (mostly casting and CNC machining). These studies are categorized into 3 types: 1) studies where AM is seen as more sustainable than CM; 2) Studies where CM is seen as more sustainable than AM; 3) Studies where the sustainability of AM or CM is dependent upon certain factors affecting their environmental performance.

#### 5.6.1. AM more sustainable than CM

AM was found to be more environmentally friendly in 19 articles. Out of these 19 papers, 9 papers were focused on the LCA of a PBF process [3,28,49,50,56,60,84–86]. Serres et al. [86] carried out a comparison of the environmental impacts of Construction Laser Additive Directe ( CLAD) and CNC milling processes in manufacturing a Ti6Al4V mechanical part. The CLAD process was found to be more ecological due to lower material wastage than CNC milling. Lower material wastage of the titanium alloy outbalanced its higher energy consumption than CNC milling. Huang et al. [28] showed that the reductions that can be achieved in terms of material, energy consumption, and GHG emissions by the adoption of AM processes (EBM, SLM, and DMLS) in manufacturing aircraft components are due to the part weight reductions enabled by AM. The major reductions were achieved due to savings in fuel consumption facilitated by part weight reductions. Similar conclusions were drawn by Mami et al. [84], where the impact reduction due to AM process was seen due to reduction in fuel consumption in use phase caused by AM facilitated weight reduction of Ti6Al4V aircraft doorstep.

Paris et al. [60] reported almost identical energy consumption for manufacturing a Ti6AlV turbine by EBM and CNC milling. Here, EBM showed lesser environmental impacts than CNC milling due to its better material utilization. Huang et al. [3] compared the environmental performance of DMLS and injection moulding in the production of a mould. Two scenarios for DMLS i.e., current, and future scenarios were considered. The current scenario considered the DMLS process with current performance, while the future scenario for AM considered an advanced performance of DLMS with a higher machine utilization rate, lower machine and material costs, higher machine throughput, and a higher degree of automation. DMLS with the current scenario showed a slight reduction in cradle-to-gate energy consumption and GHG emissions, while significant reductions in these two categories were observed in the future case scenario. Torres-Carrillo et al. [49] reported a slightly lesser (4%) carbon footprint for SLM than that for investment casting in the manufacturing of an Inconel 718 aircraft engine turbine blade due to slightly lower electricity consumption by the SLM process. Peng et al. [56] showed that the cradle-to-gate impact of a hydraulic valve body manufactured by SLM had a 37% lower impact than that of CM processes (casting + CNC milling) due to the better material efficiency of SLM. The environmental impact of SLM for manufacturing the valve body with an optimized design was about 48% lower than that of CM. Likewise, Lyons et al. [50] and Cappucci et al. [85] demonstrated lower environmental impact for Ti6Al4V knee implant and femoral stem respectively, manufactured by EBM and SLM processes, correspondingly compared to those manufactured by CM processes due to lower material wastage in these processes.

Out of these papers, 5 studies compared the environmental impacts of DED processes with CM processes [4,74–76,87]. Bekker and Verlinden [76] carried out a comparative LCA of WAAM, green sand casting, and CNC milling used in the production of a 1 kg stainless steel part. It was found that the environmental impact for WAAM was slightly lower than that for green sand casting but significantly lower than that for CNC milling. Priarone et al. [4] demonstrated the savings in primary energy and $CO_2$ emissions obtained by the repair of H13 mould steel inserts by WAAM instead of the production and substitution of new tool inserts produced by CM processes. A similar analysis depicting reductions in cumulative energy consumption and $CO_2$ emissions achieved by WAAM in comparison with CM processes in the production and repair of a steel driver disk was presented by Pagone et al. [87]. Gouveia et al. [75] showed that a hybrid powder-based DED + machining route for the repair of cast iron mold causes lesser environmental impacts than the production of cast iron mold by the CM route. Jiang et al. [74] carried out an energy-based LCA (Em-LCA) of laser-engineered net shaping (LENS) and CNC milling in the production of AISI 4140 spur gear. Here, CNC milling was found to have a higher environmental burden due to higher consumption of non-renewable resources.

Out of these papers, 4 studies compared the environmental impacts of material extrusion (ME) processes with CM processes [83,88–90]. Abdalla et al. [88] carried out a comparative LCA of 3D printing and conventional construction methods considering a functional unit of 1 $m^2$ single-story house surface area. 3D printing showed lower environmental impacts than the conventional method due to the absence of formworks, steel reinforcement, and the use of lesser materials than the conventional construction method. Prakash et al. [83] employed the FDM process to fabricate making the pattern and tree in investment casting (IC) as opposed to conventional IC, which uses Wire EDM, CNC milling, and injection moulding to fabricate the IC tree. It was observed that FDM-assisted IC led to a decrease of 70% in specific energy consumption and 71% in carbon emissions, compared to the conventional IC process. Ferreira et al. [89] compared the environmental impacts of 3D printing and conventional methods in manufacturing solid oxide fuel cell (SOFC) stack. 3D printing was found more sustainable in this case due to its lower material usage and use of low-impact material (ceramics) as opposed to chromium-based alloys used in conventional methods. Kafara et al. [90] reported a lower ecological impact for cores manufactured by fused layer modeling (FLM) than those manufactured by casting and drilling.

One study comparing the environmental impacts of the binder jetting (BJ) process with the CM process was also reported [78]. Tang et al. [78] reported lower $CO_2$ emissions and energy consumption for an engine bracket manufactured by the binder jetting (BJ) process than CNC milling. The material consumption in the BJ process can be further reduced by topological optimization, further lowering the emissions of the BJ process. The studies discussed above are enlisted in Table 15.

#### *5.6.2. AM less sustainable than CM*

AM was not found to be more environmentally sustainable than CM processes in 4 articles [55,58,69,91]. Liu et al. [58] compared the cradle-to-gate environmental impacts of a powder-based DED process LENS and CNC milling for manufacturing an AISI 4140 gear. DED processes showed higher environmental impact in 5 out of 6 impact categories studied due to their higher energy consumption and lower material efficiency, compared to CNC milling. Guarino et al. [55] carried out a comparative environmental assessment of SLM and laser cutting of 316 L stainless steel flat washers. SLM exhibited a higher environmental impact than laser cutting due to higher energy consumption. Similarly, Patricio-Sanchez et al. [69] found that injection moulding generated lesser $CO_2$ emissions than the FDM process in the manufacturing of two Nylon PA6 parts due to its lower energy consumption. Han et al. [91] compared cradle-to-gate impacts of 3D concrete printing and traditional cast-in-situ concrete construction. 3D printing showed higher impacts than the traditional method due to the high amount of cement required in concrete used for 3D printing, required for maintaining its dependable concrete performance. These studies are briefly summarized in Table 16.

#### *5.6.3. Sustainability of AM and CM is conditional*

In 18 studies it was found that the sustainability of an AM or CM process depends on different factors like part geometry, machine usage profile, raw material type, production volume, and batch size among others. Therefore, it was not able to state unconditionally that AM or CM is the most sustainable process. The following factors affecting the sustainability of an AM process are identified:

*5.6.3.1. Machine usage.* Faludi et al. [29] revealed that the environmental impact of a process depends mainly on its machine tool utilization and then on individual machine tools. This study showed that the environmental impacts of the FDM and inkjet printing processes with minimal machine utilization are higher than that of the CNC machining process with maxima utilization. On maximizing the machine tool usage, a reduction in the environmental impact of all processes was seen.

*5.6.3.2. Raw material.* Yao et al. [92] conducted the LCA of a 3D printed geo-polymer concrete and ordinary concrete panels. Although 3D printing geo-polymer concrete produced lesser waste, it reported higher cradle-to-gate impacts than ordinary concrete. This is attributed to the raw material production phase where fly ash and slag are used along with high energy requirements for silicate production. However, lower environmental impacts for 3D printed geo-polymer concrete were reported on assuming different scenarios like efficient energy consumption, reduction in transportation distance, replacement of slag and fly ash with industrial wastes, and reduction in the use of silicate.

Alhumayani et al. [68] compared the environmental impacts of 3D printing and conventional construction methods using two types of construction materials: concrete and cob. 3D printed concrete showed lower overall environmental impact than conventional concrete due to the absence of reinforcing steel bars which are used in conventional concrete. However, 3D printed cob showed a higher overall environmental impact than its conventional counterpart due to the higher amount of electricity consumed by the robotic arm used in its printing.

**Table 15**
Studies where AM is more environmentally friendly than CM.

| Study | AM | CM | Functional Unit | Indicator (s) | Findings |
|---|---|---|---|---|---|
| [86] | CLAD | CNC milling | Ti6AL4V part | Eco points | AM is more sustainable than CM due to lower material wastage |
| [28] | SLM, EBM, DMLS | Casting, milling, cutting, turning | Stainless steel, aluminium, and titanium aircraft components | Primary Energy, GHG emissions | Adoption of AM can lead to cumulative energy savings of 1.2–2.8 billion GJ, GHG emission reduction by 92.14–215 million metric tons, and material savings of thousands of tons by 2050 |
| [84] | SLM | CNC machining | Ti6AL4V aircraft doorstop | | AM without design optimization shows an impact reduction of 1% compared to CM; AM with design optimization shows a reduction of 20% in environmental impact due to the reduction in energy and material consumption |
| [3] | DMLS+DED | CNC milling + PTA welding | steel injection mould | Primary energy and GHG emissions | AM can reduce 3%– 5% of primary energy and 4%– 7% of GHG emissions compared to CM |
| [49] | SLM | Investment casting | Inconel 718 turbine blade | Carbon footprint | Am exhibited a 4% lower carbon footprint than CM |
| [56] | SLM | Casting + machining | Stainless steel Hydraulic valve | Eco points | AM exhibited a 37% lower impact than CM. AM with design optimization showed a 48% lower impact than CM |
| [60] | EBM | CNC milling | Ti6Al4V turbine | | AM was more sustainable than CM due to lower material consumption |
| [50] | EBM | CNC milling | Ti6Al4V femoral knee implant | Primary energy + $CO_2$ emissions | Am exhibited material efficiency of 65% as opposed to 15% of CM. CM showed energy/part 2.2x and $CO_2$/part 3.2x that of AM |
| [85] | EBM | Machining | Ti6Al4V femoral stem | Eco points | CM reported a 17% higher impact than AM due to material waste 6x that of AM |
| [76] | WAAM | Green sand casting, CNC machining | 1 kg Stainless steel product | Eco points | AM has a slightly lower (~3%) impact than green sand casting. CNC milling shoed 54% higher impact than AM |
| [4] | WAAM repair | CNC milling | H13 tool steel mould insert | Primary energy and $CO_2$ emissions | AM enabled repair savings of 46% primary energy and 57% $CO_2$ emissions compared to the production of new inserts by CM |
| [87] | WAAM | CNC milling | ER70 driver disk | CED and $CO_2$ emissions | AM outperforms CM in environmental sustainability due to lower raw material usage |
| [75] | DED repair | CNC milling | Cast iron steel mould | Carbon footprint | AM enabled repair reduces the carbon footprint by 76% compared to the production of new moulds by CM |
| [74] | LENS | CNC milling | AISI 4140 spur gear | Emergy-based sustainability indicator | CM causes an impact over 4x that of AM as the majority if the inputs for CM are non-renewable resources |
| [88] | 3DCP | Conventional construction | 1 $m^2$ of a single storey house surface area | Eco points | AM reduces the environmental impact by 70% due to the elimination of formworks, reinforcing steel, and better material efficiency than conventional construction. |
| [83] | FDM-assisted Investment Casting | Investment casting (IC) | Investment casting tree | Energy consumption, carbon emission | AM can lead to 72% $CO_2$ emission and 70% energy consumption savings due to the elimination of various energy-consuming steps in traditional investment casting |
| [89] | 3D printing | Conventional process | 5 kW SOFC stack | GWP, PED, ADP, AP, EP, ATP, HTP | AM reduces the environmental impact by 60–95% depending on the impact category analyzed, compared to traditional method |
| [90] | Fused Layer Modelling | Casting, Drilling | A mould core | Eco points | AM shows an impact reduction of more than 80% compared to CM due to its low-impact core material |
| [78] | Binder jetting | CNC machining | Steel engine bracket | $CO_2$ emission, Energy consumption | AM reduces energy consumption by 24% and $CO_2$ emission by 58%, compared to CM due to its better material and energy efficiency |

Nevertheless, both conventional and 3D printed cobs showed a lower environmental impact than conventional and 3D printed concretes.

*5.6.3.3. Recycling of raw material.* Peng et al. [62] conducted a comparative LCA of a Ti6Al4V impeller production using the pure AM process (Laser Cladding Forming), CM process (Plunge Milling), and Additive Remanufacturing. Additive Remanufacturing was the most sustainable process due to material recycling. However, Pure AM had a larger environmental burden than CM due to higher consumption of electricity and metal powder.

*5.6.3.4. Product geometry.* Priarone et al. [38] analyzed the primary energy demand and $CO_2$ emissions for 3 geometries made up of Ti6Al4V alloy using EBM and machining approaches. For the geometry with the highest solid-to-cavity (SCR) ratio, machining was more sustainable, as the EBM approach involved a higher amount of material deposition and subsequent energy consumption. However, as the solid-to-cavity ratio decreased, AM became more sustainable as machining involved higher amounts of material removal. A similar conclusion was drawn in a study by Lunetto et al. [33], which developed break-even surfaces for $CO_2$ emissions and cumulative energy demand of EBM and CM processes as a function of SCR and average deposition rate. The EBM process reported lesser $CO_2$ emissions and CED than the CM process only for geometries with lower SCRs along with higher average deposition rates. Likewise, Ingarao and Priarone [34] found that EBM is a more energy-efficient process in manufacturing a Ti6Al4V component than machining for SCR values less than 0.3, without considering weight reduction. With strategies like weight reduction and the use of full build configuration, it was observed that the CED for EBM part could be reduced further.

Doran et al. [93] found that the DED process is more environmentally friendly than CNC milling only for product geometries that require above 85% material removal of the feedstock material by CNC machining. Ahmad et al. [94] quantified the energy consumption in the production of 3 geometries by EBM, DMLS, and CM. similar to the above 2 studies, the complexity of geometry was characterized by the solid-to-envelope ratio. EBM consumed the least energy in all 3 geometries. In the geometry with the lowest solid-to-envelope ratio (0.13), DMLS consumed lower energy than CM while in other 2 geometries with higher solid-to-envelope ratios (0.23 & 0.30), CM was more energy efficient than DMLS. Krishna and Srikanth [72] compared the environmental impacts of a bevel gear and PCB support manufactured by the FDM and CNC machining process. FDM was an eco-friendly option for bevel gear but not for PCB support. Lower material and energy consumption for FDM was seen in the case of bevel gear. However, for PCB support, lower material consumption but higher energy consumption was reported for FDM. This higher energy consumption can be attributed to the higher building time of the FDM process.

*5.6.3.5. Production Volume.* Raoufi et al. [95,96] showed the variation in $CO_2$ emissions per product for binder jetting (BJ) and metal injection moulding (MIM) processes by varying the annual production volume. For lower annual production volume (<1000 products/annum) MIM

**Table 16**
Studies when CM is more environmentally-friendly than AM,.

| Study | AM | CM | Functional Unit | Indicator (s) | Findings |
|---|---|---|---|---|---|
| [58] | LENS | Form milling + finish grinding | AISI 4140 spur gear | GWP, AP, EP, ODP, ADP, PCOP | AM is less ecological in 5/6 impact categories compared to CM due to higher energy consumption and lower powder efficiency |
| [55] | SLM | Laser Cutting | Stainless steel flat washers | Eco points | AM causes 2.5 times more impact than CM, primarily due to higher energy consumption |
| [69] | FDM | Injection Moulding | Nylon PA6 parts | $CO_2$ emissions | AM showed a higher impact than CM due to longer build times resulting in higher energy consumption |
| [91] | 3DCP | Traditional construction | Concrete models | GWP, AP, EP, PCOP | AM performs poorly than traditional construction as the 3D printed concrete production causes more impact than traditional concrete |

process showed higher $CO_2$ emissions than the BJ process due to mould plates. However, as the annual production volume increased (>10,000 products/annum), the emissions for the MIM process reduced drastically, making it the most sustainable alternative.

*5.6.3.6. Weight Reduction.* Yang et al. [48] carried out a comparative LCA of a throttle pedal manufactured by 2 design approaches: assembly design (AD) manufactured by CM processes and Part Consolidation (PC) manufactured by AM (SLM) and finish machining. It was found that the sustainability potential of the PC + AM combination was influenced by life span extension, weight reduction, and fuel reduction values. For instance, for weight reductions above 30%, the PC + AM route was more sustainable than the AD+ CM route. If the life span can be doubled by the PC approach, it is the most sustainable route irrespective of the weight reduction achieved. Similarly, AD + CM is the most eco-friendly route if it achieves more fuel reduction than its PC + AM counterpart and vice-versa.

DeBoer et al. [79] compared the $CO_2$ emissions, energy, and water consumption of casting, machining, and 3 AM processes: binder jetting (BJ), bound powder extrusion (BPM), and powder bed fusion (PBF) in manufacturing a cast iron H-yoke. Here, casting was seen as environmentally the best alternative and machining as the worst alternative. The emissions of AM processes lay in between those of casting and machining. Further, on topological optimization of the part geometry, emissions of all 3 AM processes were reduced. However, the PBF process was found to be the cleanest process environmentally, only when the design was topologically optimized, and renewable energy source was used.

Böckin and Tillman [57] studied the cradle-to-gate impacts of a light distribution truck engine made up of stainless steel manufactured by the CM and AM (PBF) process. A weight reduction of 25% was assumed to be achieved by the PBF process. However, PBF reported a marginally lower environmental impact than the CM route. Significant reductions in environmental impacts of PBF were achieved in a future case scenario where weight reduction enabled by design optimization, use of cleaner energy, and low-impact raw material (low alloy steel instead of stainless steel) were assumed to be used.

*5.6.3.7. Weight reduction and production volume.* Kamps et al. [97] compared the embedded energy required for the production of 3 gears: a reference gear A (1.1 kg) and two lightweight design gears B (0.8 kg) & C (0.6 kg) manufactured by hobbing, milling, and LBM processes. The embedded energy per part was calculated for production volume varying between 4 and 1000. For lightweight gear C LBM was always the most energy-efficient process. For gears A and B, milling was the most energy-efficient process for gears A and B for all production volumes. The hobbing process has a higher embedded energy requirement for lower production volumes due to extensive tooling. However, its embedded energy requirement decreases substantially with an increase in production volume. For gears A and B, LBM was the more energy-efficient process than hobbing for production volumes up to 29 and 55 respectively.

*5.6.3.8. Batch size and height.* Le and Paris [61,98] studied the influence of build height and batch size i.e. number of parts per build on the environmental impacts of the EBM process. It was found that EBM along with finish machining was more sustainable than CNC milling only for smaller build heights and batch size close to full build configuration. Additionally, a mapping of build height and batch size was developed, indicating different combinations of build height and batch size for which a process (AM or CM) is more sustainable environmentally.

*5.6.3.9. Functionality improvement enabled by AM.* Davis et al. [35] compared the cradle-to-grave energy demand for standard cooling mould manufactured by machining and conformal cooling mould manufactured by SLM and finish machining, used in injection moulding process. Standard cooling moulds have linear cooling channels that are machined while Conformal Cooling mould das helical-shaped cooling channels manufactured by SLM. It was seen that the overall energy demand for production of conformal cooling was much higher than that of standard cooling mould. However, conformal cooling mould lowers the cooling cycle time, which is an energy-intensive step in injection moulding. Therefore, after a pay-back period, significant energy savings are obtained using SLM made conformal cooling mould compared to CM made standard cooling moulds.

From the studies discussed above, AM and CM processes involved, their findings and factors that affect the environmental impacts of both processes investigated in these studies are summarized in Table 17.

### *5.7. Review of the economic performance of AM processes*

Mami et al. [84] computed the life cycle costs of a Ti6Al4V aircraft doorstep manufactured by conventional manufacturing, SLM and SLM with topological optimization of part design over the lifetime of an aircraft (35 years). As mentioned previously, 12 articles performed economic assessment along with LCA of AM processes. Out of these 12 articles, 4 computed the entire Life Cycle Cost (LC) while others calculated just the production cost (PC) of AM products.

It was observed that the LCC of SLM without design optimization was nearly 8% higher than conventional manufacturing due to higher machine costs. However, for SLM with design optimization, the LCC was about 12% lower than conventional manufacturing due to lower fuel consumption due to material savings enabled by topological optimization of part design. Huang et al. [3] compared the LCC of 1 million cycles of injection moulding produced by AM (fabricated by DMLS and repaired by DED) and CM (fabricated by CNC milling and repaired by PTA welding). AM route reduced by lead time by 12% due to on-shore

**Table 17**
Factors affecting the sustainability of AM and CM processes.

| Study | Factor (s) affecting sustainability | AM process | CM process | Key findings |
|---|---|---|---|---|
| Faludi et al.[29] | Machine Utilization | FDM & Inkjet Printing | CNC milling | The environmental impacts of AM with lower machine utilization were higher than that of CNC milling with a higher utilization rate. |
| Raoufi et al.[95,96] | Production Volume | Binder Jetting | Metal Injection Moulding (MIM) | • AM is more sustainable for lower annual production volume (<1000 p.a.).<br>• CM is more sustainable for higher production volumes (>10000 p.a.) |
| Yao et al.[92] | Raw Material type | 3D Concrete Printing | Traditional construction method | 3D printing reduces material waste but causes a higher environmental impact than ordinary concrete due to higher energy requirements in raw material production |
| Alhumayani et al.[68] | | 3D Printing | Traditional construction method | • 3D concrete printing caused a lower environmental impact than conventional concrete.<br>• 3D printing of Cob caused a higher environmental impact than conventional cob due to higher electricity consumption |
| Peng et al.[62] | Recycling | Laser Cladding Formind (LCF) | Plunge Milling | • Pure AM showed a higher environmental impact than the CM process.<br>• However, AM with recycling of waste material was seen to be more sustainable than the CM process |
| Doran et al.[93] | Product Geometry | Directed Energy Deposition (DED) | CNC milling | AM is more sustainable only for complex product geometries that require higher amounts of material removal by CM |
| Priarone et al.[38] | | EBM | CNC milling | |
| Ingarao & Priarone[34] | | EBM | CNC turning | |
| Ahmad et al.[43] | | EBM | CNC milling | |
| Krishna et al.[72] | | FDM | CNC milling | |
| Yang et al.[48] | Weight Reduction | SLM and Part Consolidation (PC) | CNC milling and Assembly Design (AD) | • AM + PC approach is more sustainable if more than 30% weight reduction is achieved in the baseline geometry.<br>• CM + AD approach is most sustainable if it achieves more fuel reduction than the AM+PC approach and vice-versa. |
| DeBoer et al.[79] | | Binder Jetting (BJ), Bound Powder Extrusion (BPE), Powder Bed Fusion (PBF) | Casting, CNC milling | • Casting was seen as the most ecological alternative.<br>• PBF was found to be the most sustainable approach only after the design was topologically optimized and renewable energy sources were used |
| Bockin and Tillman[57] | | Powder Bed Fusion (PBF) | CNC milling | PBF reported a slightly lower environmental impact than CM for a 25% weight reduction in the product geometry |
| Kamps et al.[97] | Weight Reduction & Production Volumes | Laser Beam Melting (LBM) | CNC milling and hobbing | • AM was more energy efficient than CM only for lightweight design and low production volumes.<br>• For designs with no weight reduction, CNC milling was an energy-efficient process |
| Le & Paris[61,98] | Batch Height and Batch Size | EBM | CNC milling | AM is more sustainable than CM only for lower build height and batch size close to full configuration |
| Davis et al.[35] | Improved Product Functionality | SLM | CNC milling | • AM showed higher energy consumption than CM in the production phase.<br>• However, due to improved product functionality enabled by AM, significant energy savings can be seen after a payback period as compared to CM. |

production, eliminating off-shore production and transportation phase. This resulted in a nearly 15% reduction in unit part cost as compared to the CM route. With further improvements in AM such as increased build rate, the lead time could be reduced by 60% facilitating about a 35% decrease in the unit part cost. Gouveia et al. [75] demonstrated that the hybrid DED + CNC machining repair process of a damaged mould for glass bottled is more economical than pure CM based production of a new mould due to the obvious material savings achieved by the repairing process. Abdalla et al. [88] carried out an LCC assessment of a 3D-printed house and found that it is 49% cheaper than a house constructed by traditional construction methods. This cost reduction was due to the elimination of steel bars, concrete, formworks, and manual labour by 3D printing as opposed to traditional construction methods.

Guarino et al. [55] computed the production cost of stainless-steel flat washers produced by SLM and Laser cutting processes. Here, unit part cost for SLM was over 70 times that of Laser Cutting. The major drawback of SLM was its limited production capacity, nearly 217 times lower than LC, resulting in a lower number of working cycles and components produced. A similar trend was seen by Raoufi et al. while comparing the production cost of stainless steel microreactor plates fabricated using binder jetting and metal injection moulding processes. Metal injection moulding had 17–22% lower unit production cost compared to binder jetting for annual production volumes ranging from 1000 to 100,000 respectively. This was attributed to lower machine tool costs and shorter cycle times of metal injection moulding resulting in better machine tool utilization than binder jetting.

Kamps et al. [97] carried out a cost assessment to determine the production cost of steel gear manufactured by laser beam melting (LBM), CNC milling, and hobbing. For gear without lightweight design, LBM was found to be the most economical only for batch sizes less than 6. With a part weight reduction of 27%, LBM was more economical than hobbing and CNC milling for batch sizes below 11 and 39, respectively. Therefore, it was observed that LBM was economical for small production volumes and was more cost-efficient for lightweight designs. Ingarao and Priarone [34] compared the production costs for a Ti6Al4V part fabricated using EBM and CNC milling process. CNC milling was the most economical process in this case. However, as the solid-to-cavity ratio (SCR) of the part design decreased (implying increased part complexity), the cost per part reduced drastically for the EBM process. Similarly, Doran et al. [93] found that DED is an economically better option only when more than 90% of the feedstock material needs to be removed while manufacturing the considered part using the CNC milling process. Likewise, Han et al.[91] observed that 3D concrete printing is more expensive than traditional cast-in-situ construction methods for constructing regular geometries. 3D printing required costlier raw materials while the traditional method required a larger amount of manpower. Therefore, 3D printing was economical only in the case of irregular geometries due to the elimination of formworks and reduction in manpower compared to the traditional method.

Priarone et al. [51] compared the production costs of WAAM and CNC milling for three products: aluminum frame, steel beam, and titanium bracket. WAAM was more economical for an aluminum frame and titanium bracket while CNC milling was cost-efficient for steel beam manufacture. This result can be attributed higher manufacturing time required for the WAAM approach in fabricating a steel beam. In the other two products, WAAM and CNC milling showed comparable manufacturing times. Mele and Campana [43] developed a production cost model for the liquid crystal display 3D printing process. This work compared the influence of an adaptive slicing strategy that uses non-uniform layer heights as opposed to conventional slicing where layer height is constant, on production cost. It was observed that the adaptive slicing strategy reduces the building time resulting in 6–30% cost savings compared to the traditional slicing method.

The above-discussed studies, their scope, AM process involved, cost elements considered, and their results are briefly summarized in Table 18.

### 5.8. Review of the social performance of AM processes

Only 6 studies based on the S-LCA of AM were reported. Ribeiro et al. [99] developed a generic model framework to assess the Triple Bottom Line (TBL) sustainability of AM processes considering their environmental, economic, and social impacts. A mapping tool was developed to help the users understand what life cycle phases and data inputs are required for LCA, LCC, and S-LCA of an AM process. For the S-LCA of AM process, data mining and interview with the stakeholders are recommended to collect the input data. Tadesse et al. [100] conducted an extensive review of the existing literature based on the sustainability of AM and identified 68 sustainability performance indicators: 29 environmental, 9 economic, and 30 social indicators.

Nagshineh et al. [101] did a similar literature review and identified 42 social impact categories stakeholder-wise and presented a framework to assess the social impacts of AM. An exploratory case study was also conducted by Nagshineh et al. [102] where the social impacts of SLM were assessed qualitatively by conducting structured interviews with employees of the company in England using the SLM process. Out of the 26 social indicators considered, SLM showed positive impacts in 16 and no impact in 8, and negative impacts in 2 social indicators. As AM is a relatively novel technology, most of the engineers in the selected company were continuously studying to keep themselves updated about recent advances in AM. Additionally, the engineers often took their excessive work home and worked more than 40 h a week. Due to this reason, SLM performed negatively in the social indicator “average weekly working hours by a full-time employee”. SLM also reported a negative impact in the social indicator “% of local employees hired” as most of the highly qualified employees came from different parts of England and Europe.

Soares et al. [103] conducted a comparative S-LCA of FDM and conventional processes in manufacturing two medical devices: a prosthesis and an orthosis. This study evaluated the social impacts on 5 stakeholders: “Workers/Employees”, “Local Communities”, “Society”, “Consumers”, and “Value chain actors”. Here, positive social impacts due to AM were found on the “Customers”, “Local community”, and “Society” stakeholders due to better AM performance in sub-categories like the presence of customer feedback mechanisms, lower customer health and safety risk, contribution to economic and technological development, and local employment. The negative AM social impacts were found on the stakeholders “Value chain actor” and

**Table 18**
Studies involving economic assessment of AM along with LCA.

| Study | AM | CM | Cost elements | Scope | Findings |
|---|---|---|---|---|---|
| [84] | SLM | CNC milling | R&D cost, material cost, indirect cost, transportation cost, labour cost, fuel cost, maintenance cost, crew cost, spare parts cost, EoL treatment cost | LC | LCC of AM is 8% higher than CM due to higher machine costs. LCC reduces by 12% for AM with optimization when compared to CM |
| [3] | DMLS + DED repair | Injection Moulding | Material cost, machine cost, labour cost, energy cost, design, process planning, assembling, inspection, diagnosis, and disassembly costs | LC | Cost per part is 13% lower for AM with current performance and 35% lower for matured future case performance, compared to CM |
| [55] | SLM | Laser Cutting (LC) | Machine cost, maintenance cost, material cost, inert gas cost, labour cost, energy cost, post-processing cost | PC | LC is more economical than SLM due to its high production capacity and lower processing time |
| [97] | LBM | Hobbing, CNC milling | machine cost, substrate cost, material cost, maintenance cost, production area cost, electricity cost, inert gas cost, post-processing cost | PC | AM is a cost-efficient alternative for small batch sizes. The economic efficiency of AM is higher for lightweight designs |
| [34] | EBM | CNC milling | Material cost, machine cost, energy cost, labour cost, post-processing cost, AM indirect costs | PC | CM process is more economical than AM for the given part. Costs of AM decrease as SCR decreases (or product complexity increases) |
| [51] | WAAM | CNC milling | machine cost, material cost, set-up cost, substrate preparation cost, facility cost, delivery cost, overhead cost, electricity cost, inert gas cost, post-processing cost | PC | Out of the 3 geometries considered, WAAM is economical for 2 geometries but costlier for 1 geometry due to higher manufacturing time |
| [93] | DED | CNC milling | Machine cost, material cost, labour cost, electricity cost | PC | DED is economical only when milling requires more than 90% removal of feedstock material |
| [75] | DED repair | CNC milling | material cost, machine cost, | LC | DED-based repairing is |

(continued on next page)

**Table 18** (*continued*)

| Study | AM | CM | Cost elements | Scope | Findings |
|---|---|---|---|---|---|
| | | | energy cost, labour cost, maintenance cost, environmental cost | | more economical than conventional production due to the material savings obtained |
| [95, 96] | BJ | Metal Injection Moulding (MIM) | Machine cost, production facility cost, maintenance cost, labour cost, material cost, consumables cost and utilities cost | PC | MIM is more economical due to lower machine costs and shorter cycle time |
| [88] | 3DCP | Conventional Construction | machine cost, construction material cost, energy cost | LC | 3DCP is 49% cheaper than conventional construction due to the exclusion of concrete, formworks, and manual labour. |
| [91] | 3DCP | Conventional Construction | Building material cost, formwork cost, machine cost, labour cost, energy cost | PC | 3DCP is economical only for geometrically irregular buildings due to lower labour and formwork costs. |
| [43] | LCD 3DP | - | machine cost, material cost, labour cost, energy cost | PC | Adaptive slicing significantly reduced the product cost by 6–30% than traditional slicing due to a reduction in building time |

"Workers/Employees" due to the risk of potential violation of the company against intellectual property rights and loss of freedom of association and collective bargaining power of the employees, respectively.

Cardeal et al. [45] assessed the environmental impact, cost, and social impacts of business models involving powder-based AM and conventional processes in aircraft maintenance. In general, AM was reported to be better than conventional methods in indicators "Fair salary", "Decentralization & Migration", "Local employment", "Public commitment to sustainable issues", "Contribution to economic development", "Technology development" and "Feedback mechanisms" but performed adversely in "Health and Safety" and "Respect to Intellectual Property Rights" social indicators.

The studies involving S-LCA of AM processes are briefly summarized in Table 19.

**Table 19**
Articles involving social sustainability assessment of AM processes.

| Study | Description | AM | CM | Findings |
|---|---|---|---|---|
| [101] | Review of AM social impacts | - | - | This study reviews the social impacts of AM and presents 42 potential AM social impacts, their indicators, and their association with different stakeholders. |
| [103] | Comparative S-LCA between AM & CM in the production of 2 orthopedic devices | FDM | Manual labour | • AM had positive impacts on localized specialized jobs and economic and technological developments.<br>• Negative impacts of AM were loss of collective bargaining power of workers and abuse of intellectual property rights |
| [45] | Compares Social impacts of AM and CM | SLM | Forging | Adoption of AM benefits most of the subcategories except worker health and safety and intellectual property rights. |
| [102] | An exploratory case study assessing the social performance of SLM process is also presented in this paper | SLM | - | • AM had a positive or no impact on most of the social indicators.<br>• AM had negative impacts like increased working hours and decreased % of the workforce hired locally. |
| [100] | Review of sustainability performance indicators for AM | - | - | This study reviews the existing product life cycle studies and presents 68 sustainability performance indicators: 29 for environmental. 9 for economic and 30 for social dimensions of sustainability |
| [99] | This study developed a generic model framework to assess the Triple Bottom Line (TBL) sustainability of AM processes considering their environmental, economic, and social impacts. | - | - | • A mapping tool was developed to help the users understand what life cycle phases and data inputs are required for the LCA, LCC, and S-LCA of an AM process.<br>• For the S-LCA of AM process, data mining and interview with the stakeholders are recommended to collect the input data |

## 6. Discussion, shortcomings, and future research

Based on the literature review focussed on LCA of AM technologies, the following themes were identified and reviewed in this paper: Goal & Scope of LCA studies, Life cycle inventory for different AM processes, Part quality and mechanical performance of AM parts, and the environmental, economic, and social performance of different AM processes. A total of 77 articles were shortlisted for this review study. Articles involving social LCA of AM processes were also included Out of these 77 articles, 59 focussed solely on environmental impacts, 12 studied both environmental impacts and economic costs while 5 involved only social LCA of AM analyzing the social impacts of AM on its stakeholders, while only 1 article involved economic assessment, LCA and S-LCA. A majority of these studies are cradle-to-gate analyses. AM processes from Powder Bed Fusion and Material Extrusion categories were studied widely compared to other AM categories. This could be attributed to better commercialization of these technologies due to their relatively higher technological maturity than other AM technologies.

The AM processes were found to be more sustainable than CM processes, primarily due to their better material efficiency and lower material requirement. However, AM was found to be more environmentally damaging than CM in cases of higher energy consumption or use of high-impact raw material by AM. In some studies, it was seen that sustainability is affected by multiple factors such as AM machine utilization rate [29], production volume [95], batch size and height [61,98], product complexity [38,72,93,94], type of raw materials involved [68, 92], the effect of AM enabled design optimization and weight reduction [48,57,79], the effect of recycling AM raw material [62]. It was observed that superior environmental performance of AM can be achieved by maximizing the AM machine utilization and batch size, minimizing the batch height, reducing part weight using topological optimization, using low-impact materials, recycling waste raw materials, using AM for sufficiently complex geometries, and for lower production volumes.

AM was more economical than CM in following cases of complex product geometries [34,91,93], lightweight designs enabled by topological optimization [84,97], small batch sizes [97], AM-based supply chains reducing the overall lead time[3] and AM requiring lower material usage [75,88]. Major drawbacks of AM from an economic perspective are higher machine costs [95], lower production capacity [55], lower build rates leading to higher build times [55,95], and consequently higher AM costs.

As far as the social impact of AM is concerned, AM, in general, showed a positive impact on stakeholders like the local community, society, and consumers. However, some negative impacts were reported on workers (such as loss of association and weakening of collective bargaining power [104], higher weekly hours of work [102], and worker health risks related to metal powder inhalation [45]), local community (lower % of the locally hired workforce [102]), and value chain actors (violation of intellectual property rights regulations [45, 104]). However, it is realized that the research on the social impacts of AM is still in its infancy and more studies are needed to completely understand the social impacts of different AM technologies.

Currently, fewer studies considered the effect of post-processing operations of AM parts due to their residual stresses, and poor lower dimensional and surface accuracy. Furthermore, a majority of these studies were performed under the assumption that AM guarantees similar part quality and mechanical properties. However, it is crucial to assess the quality and mechanical performance of AM parts as the presence of defects or poor mechanical properties can adversely affect the product service life and its performance. Out of the fewer studies considering the quality and mechanical characterizations of AM parts, it was seen that steel parts fabricated by SLM had superior tensile strength and hardness but inferior surface roughness compared to conventionally manufactured products [55,56]. Also, FDM parts were seen to have significantly lower tensile strength and elongations at break compared to parts manufactured by conventional injection molding [71]. Hence, more studies are needed that take into consideration the quality and mechanical characterization of AM parts along with their sustainability assessments for a comprehensive understanding of AM's sustainability potential. The issues and limitations realized in the existing studies and future research efforts required to address them are discussed in depth in the following subsections.

### *6.1. Shortcomings of existing literature*

Based on the analysis of the existing scientific literature on LCA of AM technologies, the following shortcomings of the existing literature have been identified:

#### *6.1.1. Some AM technologies are under studied*

Based on Fig. 10 depicting the AM category-wise distribution of the literature sample, it is clear that powder bed fusion technologies such as SLM and EBM and material extrusion technologies like FDM have received relatively higher attention than other AM categories like directed energy deposition, material jetting, binder jetting, and VAT polymerization. This could be attributed to better technological maturity and greater penetration of PBF and FDM technologies in the industry compared to other AM technologies. Therefore, more studies investigating the environmental, economic, and social impacts of the lesser-studied AM technologies need to be carried out. Additionally, as new AM materials, novel AM processes, and their applications will be developed in the future, their sustainability assessments also need to be carried out to ensure their sustainable development.

#### *6.1.2. Focus on only the environmental dimension of sustainability*

As seen in Fig. 11, approximately 75% of the studies in the analyzed literature sample just aimed to assess just the environmental dimension of AM's sustainability, neglecting its economic feasibility and social impact. Only 16% of the studies analyze the economic impact of AM along with its environmental impact while just 8% of the studies assess the social impacts of AM. It is necessary to assess the economic feasibility of AM process adoption is an important decision-making criterion from an industrial application perspective. Also, there is a need to evaluate the social impacts of AM on its stakeholders such as employees, customers, local communities, value chain actors, and society in order to realize the positive and negative impacts and take measures to mitigate the negative impacts.

#### *6.1.3. Exclusion of AM part quality and mechanical characterization*

One of the major shortcomings of the literature reviewed is the exclusion of AM part's quality assessment and characterization of its mechanical properties. Except for the 5 studies discussed in Section 5.5, the remainder studies have either implicitly or explicitly assumed that additively and conventionally manufactured parts have similar quality and mechanical properties. However, owing to the poor part surface and dimensional accuracy, AM parts may need additional post-processing operations, adding to their environmental impact and costs. Their mechanical properties can affect their service life, maintenance, and repair activities. Therefore, it must be first established experimentally if a given AM process can deliver parts of the required quality and mechanical properties before conducting their environmental/economic assessment.

#### *6.1.4. Not enough focus on post-AM production life cycle phases*

Among the studies focused on environmental LCA, only about 20% of the studies investigated the whole cradle-to-grave life cycle impacts of AM fabricated products. The majority of the studies limited their scope up to the production of parts by AM, excluding the post-processing, use, and end-of-life phases. Based on the studies [28,81], it is seen that under certain conditions such as material change and weight reduction, AM fabricated products can save huge amounts of material and energy in their use phase compared to conventionally manufactured parts. As shown by a study by Davis et al. [35], AM parts can cause higher environmental impact in their production phase but can compensate for higher production related impact by reduced energy consumption in their use phase due to their AM enabled functional improvement. Additionally, as shown by Priarone et al. [4], the AM-based repair approach can extend the service life of a component to multiple life cycles, and thus amplify the material and energy savings obtained in its production phase. Therefore, to comprehensively understand the environmental sustainability potential of AM, a complete cradle-to-grave life cycle perspective of their products should be considered.

#### *6.1.5. Effect of production variables not extensively studied*

While analyzing the literature considered in this study, it was realized that environmental impact or cost associated with the manufacture of a part either by an AM or CM process is affected by multiple production variables such as raw material, product complexity, processing parameters, production volume, batch size, part weight reduction, among others apart from the manufacturing process selected. Only 25% of the studies analyzed in this review considered the effect of variation in these factors on the environmental impact or cost of AM or conventionally manufactured parts. These studies are discussed in Section

5.6.3. The remainder studies analyzed the environmental impact or cost of adopting a particular AM process under static scenarios without studying the effect of variation of other variables on the environmental impact or cost. Hence, there is a need to study how variations in different production variables affect the sustainability performance of an AM process and find out under what conditions/combinations of process variables is a given AM process more sustainable.

### 6.2. Directions for future research

Based on the shortcomings realized in the previous sub-section, the following directions for future research are suggested:

#### 6.2.1. Inclusion of new AM materials and technologies

Efforts must be made to study the environmental, economic, and social impacts of AM technologies other than powder bed fusion and material extrusion, as mentioned previously. Furthermore, these assessments should also be extended to emerging advancements in different AM processes. AM is a continuously evolving technology. As AM technology matures in the future with advances in research and development in terms of novel materials, processes, and applications, the environmental, economic, and social impacts of these advancements should be studied to ensure their sustainable development.

#### 6.2.2. Transition to triple-bottom-line sustainability assessment

A comprehensive understanding of the sustainability potential of AM technologies can be achieved by performing its sustainability assessment using the triple-bottom-line (TBL) approach where an AM technology's performance is evaluated on environmental, economic, and social lines. Efforts need to be done for carrying out an integrated sustainability assessment of AM technologies, where their environmental, economic, and social impacts are determined simultaneously using environmental LCA, LCC, and S-LCA respectively. Such integrated studies can give a holistic view of the sustainability of AM adoption and help AM practitioners understand related merits, demerits, or trade-offs and thus, will aid in better decision-making on adopting a more sustainable production process.

#### 6.2.3. Extending the scope and system boundaries of investigation

As mentioned previously, a majority of the studies analyzed in this paper limited the system boundary of their assessment up to the production phase of AM products. As discussed previously, the additional environmental burdens of AM adoption in the production phase can be mitigated in the use phase due to AM enables material and energy savings in some automotive and aerospace applications. Hence, Future studies should extend their scope to include post-production, utilization, and end-of-life life cycle phases of AM products to get a complete picture of the environmental, economic, and social impacts of AM products. This will help in better understanding of impacts associated with AM adoption and prevent practitioners from getting misleading conclusions due to assessments covering the partial life cycle of AM products.

#### 6.2.4. Development of predictive environmental impact and cost models

In this review, it was realized that most of the studies were case-specific studies, analyzing a particular product geometry manufactured by a particular AM process under particular process parameters and conditions. Hence, their results cannot be extended to other product geometries or raw materials processed by the same AM process. Additionally, it must be noted that conducting LCA or LCC assessments is a data-intensive and laborious task, requiring an expert to conduct them. Kellens et al. [105] developed a parametric model that predicts the environmental impact of the SLS process based on build height and volume. Hence, to increase the applicability of an LCA/LCC study, predictive environmental or cost models that express the environmental impact or cost of implementing AM as a function of product or process parameters need to be developed in future works. These predictive models can estimate the amount of resources required, environmental impacts, and costs associated with an AM process. This will help the AM practitioners in production planning, choosing the most sustainable manufacturing process, and initiating environmental impact/cost mitigation measures right from the design stage of their product.

#### 6.2.5. Integration of quality, mechanical characterization, and sustainability assessment

In the current review study, it is realized that most of the studies neglected the quality and mechanical characterization assessments to check if the given AM process and its process parameters considered, deliver products that match the dimensional accuracy and mechanical properties to that of conventionally manufactured products. It must be noted that life cycle sustainability and quality perspectives can be complementary to each other. Quality strategies like "Zero Defect Manufacturing" aims to "do things right in the first time" to eliminate or mitigate failure in manufacturing to deliver quality products with zero defects [106]. This in turn will improve sustainability performance due to better product quality, reduced cost of rework/repair, and waste reduction. Therefore, future works should focus on integrating quality assessment with environmental, economic, and social assessments to ensure the production of quality and sustainable AM products. The effect of adopting different strategies like Zero Defects Manufacturing in AM on its sustainability also needs to be investigated.

## 7. Conclusions

A systematic literature review of studies analyzing the application of LCA methodology to different AM processes was carried out. It was seen that the majority of the studies carried out an environmental LCA of AM fabricated products while few conducted economical assessment using LCC and social LCA along with environmental LCA to determine the economic and social impacts of AM adoption, respectively. Different themes such as the goal and scope of LCA analysis, different life cycle inventories associated with different life cycle stages of AM products, part quality and mechanical properties of AM parts, and environmental, economic, and social performances of different AM technologies were reviewed and discussed. It was observed that powder bed fusion and material extrusion AM technologies were studied extensively compared to other AM technologies. A majority of the studies were limited to the production phase by AM processes, excluding the post-processing, use, and end-of-life phases of AM products. AM was found to be more environmentally friendly than CM in cases where AM showed better material utilization and lower material consumption than CM. However, in some cases, higher energy consumption and the use of less environmentally-friendly materials can make AM more environmentally damaging than CM. Additionally, different factors affecting AM's environmental performance were also reviewed. From an economic perspective, AM was found to be an economical option for the production of complex and lightweight geometries, production in small batch volumes, and in cases where AM can reduce the overall lead time. Factors such as costly AM printers, lower production capacity, and lower build rates limit the economic potential of AM technologies. From a societal dimension, the social impacts of AM technologies on their different stakeholders such as Workers/Employees, Local Communities, Society, Consumers, and Value chain actors were also reviewed. It was seen that research on assessing the social impacts of AM is still in its infancy. The existing research on LCA of AM processes has some shortcomings like lesser attention to AM technologies other than powder bed fusion and material extrusion, singular focus on the environmental dimension of sustainability, exclusion of AM part quality and mechanical properties, not enough focus on the entire life cycle of AM products and not considering the effect of variation in different variables on the LCA results. To address these shortcomings, future works must perform LCAs of emerging and under studied AM processes, assess economic and social sustainability dimensions along with environmental sustainability, extend the scope of LCA studies by including post-production phases, develop predictive models to estimate environmental impacts and costs of AM processes and integrate the AM part quality dimension along with environmental, economic and social dimensions for manufacturing quality and sustainable AM products.

## 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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