A Review of the Sustainability Assessment Techniques for Both Metal Conventional and Additive Manufacturing

Danial Pazoki[1*], Denis Dowling[1], and Pezhman Ghadimi[1]

[1] I-Form Advanced Manufacturing Research Centre, School of Mechanical & Materials Engineering, University College Dublin, Belfield, Dublin, Ireland
danial.pazoki@ucdconnect.ie

Abstract. There is increasing interest in enhancing the sustainability of manufacturing processes. This paper presents a systematic literature review on sustainability approaches used in the fabrication of parts using both metal additive manufacturing (AM) and conventional manufacturing (CM). A search using the Scopus database initially identified 440 papers focused on AM and CM of metallic materials in the period from 2019 to mid-2024; from these, 21 papers were selected for in-depth investigation due to their importance for processing sustainability. Reviewing these papers, the most frequently used AM or CM processing technologies were identified and correlated with the assessment approaches used to investigate processing sustainability. It was found that 90% of these papers utilised Life Cycle Assessment (LCA) while 24% utilised Life Cycle Costing (LCC) analysis alongside LCA. Sustainability encompasses three pillars: environmental, economic, and social, and it is necessary to consider each and address them together. In this context, this investigation has indicated that while the environmental pillar has received significant attention, the social pillar has been largely overlooked. Finally, the paper is concluded with some remarks and future directions.

Keywords: Sustainability assessment, Additive manufacturing, Conventional manufacturing, Comparative studies.

1 Introduction

Additive manufacturing (AM), or 3D printing, creates objects by adding materials sequentially, layer upon layer [1]. As a manufacturing processing technology, it is unique in its ability to fabricate geometrically complex objects. A further advantage of AM is that it eliminates the use of excess material during part fabrication and, therefore, reduces unnecessary waste. Therefore, AM has significant advantages over conventional manufacturing (CM) approaches, including CNC machining, milling, and casting. In addition to part performance, an important consideration in the selection of a manufacturing process for the fabrication of a component is processing sustainability. This consideration is crucial for developing more sustainable manufacturing techniques [2].

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Sustainability is based on three key pillars: environmental, economic, and social. It is necessary to pay attention to all three pillars and employ them together [3] . Numerous papers investigate the sustainability of various manufacturing technologies in terms of these three pillars, comparing the sustainability of AM with CM, as well as AM with other AM technologies.

However, to the best of the authors' knowledge, no review paper compares a broad range of AM and CM technologies. Existing review papers in the field of sustainability in manufacturing often focus narrowly on specific groups of technologies. For instance, [4] reviews only laser powder bed fusion (LPBF) for aluminium alloys and conventional aluminium alloy processes, while [5,6] focuses solely on AM technologies or in [7], only 3D concrete printing technologies are considered for the construction industry. This gap motivates us to explore more comprehensively in this field and provide a broader scope in comparing manufacturing methods with regard to their sustainability comparisons. Therefore, this paper reviews recent comparative studies in the context of sustainability over the past approximately five years, from 2019 to mid-2024.

To this end, the following three questions are raised:

RQ1: What manufacturing technologies (both metal AM and CM) are most frequently involved?

RQ2: Which sustainability assessment techniques are utilised in the considered papers?

RQ3: What are the research gaps and future works in the context of manufacturing sustainability?

The remainder of this paper is organised as follows: Section 2 presents the research methodology. Then, content analysis results are provided in Section 3. Finally, the research gap and future work are discussed in Section 4, followed by concluding points in Sectoin 5.

2 Research methodology

Scopus database search was utilised to gather the relevant papers using the following keywords: "additive manufacturing" OR "3D printing", AND "compar*" OR "versus" OR "vs", AND "sustain*" OR "environment*" OR "energy" OR "material" OR "life cycle". This search initially yielded 440 papers, from which 21 papers were identified as being particularly relevant to the aims of this study. These 21 papers were selected based on whether they compare AM vs. AM, AM vs. CM, AM-CM vs. AM-CM, or AM-CM vs. CM, and all of them focus on metal manufacturing methods in the context of sustainability and its key pillars. The research methodology adopted in this paper is graphically represented in Fig. 1.

3 Content analysis

Building on the research methodology detailed in the previous section, this section now presents an analysis of the most frequently used metal AM and CM technologies, as well as the sustainability assessment techniques.

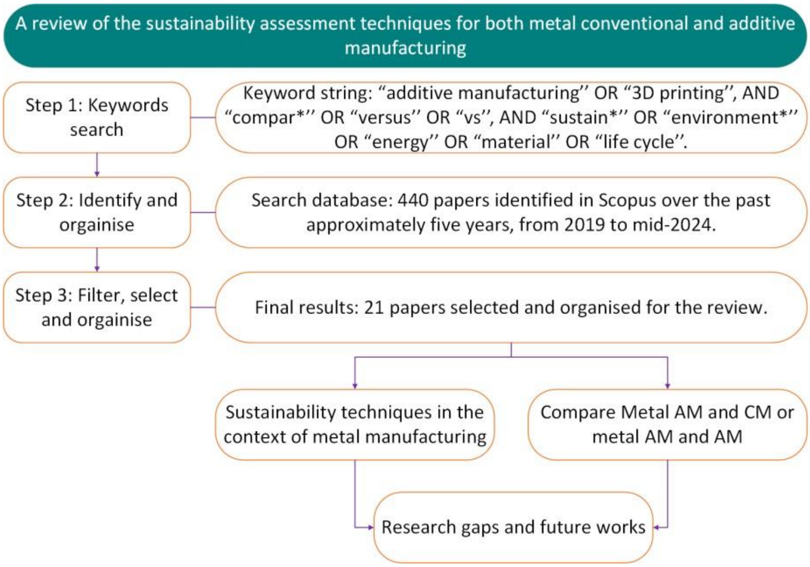

Fig. 1. Graphical representation of the research methodology.

3.1 Most frequently metal manufacturing technologies

This section provides a detailed evaluation of the 21 papers selected from the literature review. Of these papers 2 are categorised as metal AM vs. metal AM, and 17 are classified as metal AM vs. metal CM. Table 1 presents the references that compare metal AM technologies with metal CM methods, except for [16], which compares powder bed fusion (PBF) with a metal CM method without specifying which one. However, this paper is still considered in this category. Additionally, there are two other papers: [24], which falls under the category of metal AM-CM vs. metal AM-CM and compares hybrid wire arc additive manufacturing (WAAM) and drilling with hybrid WAAM and turning, and [25], which falls under the category of metal AM-CM vs. metal CM and compares hybrid deposition and micro rolling with casting and forging.

In the category of AM vs. AM, which includes both metal AM methods, only two papers were found in our search: [8], which compares direct metal laser sintering (DMLS) from the PBF family with additive friction stir deposition (AFSD) from the solid-state AM (SSAM) family, and [9], which compares WAAM from the directed energy deposition (DED) family with metal laser PBF. In the category of metal AM vs. metal CM, PBF is the most employed technology, as shown in Table 1. In some of the references mentioned for the PBF family in Table 1, specific methods are used, such as selective laser melting (SLM), DMLS, direct metal laser melting (DMLM), and electron-beam melting (EBM), with SLM being the most frequently used in comparison with CM methods. After PBF, DED ranks second. One of the most well-known methods of DED is WAAM, which is the most used in these comparative studies. The third-

Table 1. Comparative Assessment: metal AM vs. metal CM

AM	CM	Ref.	Sustainability Pillar
PBF	Machining, Forging piercing, Casting, and Welding	[4], [10], [11], [13], [14], [15], [17], [19], [21], [22], [23]	Environmental and economic: [4], [10], [13]- Environmental: [11], [14], [15], [17], [19], [21], [22]- Environmental, economic and social: [23]
DED	Machining, Casting, and Forging	[2], [10], [12], [18]	Environmental and economic: [2], [10]- Environmental: [12], [18]
Material extrusion	Machining	[20]	Environmental, and economic
SSAM	Machining	[1]	Environmental

ranked AM technologies are metal material extrusion and SSAM with the method of cold spray AM, each used once in [20] and [1], respectively. For CM, various manufacturing methods are utilised in the field of sustainability, with machining being the most common, followed by casting and forging.

3.2 Considered sustainability assessment techniques

Regarding the sustainability assessment approaches, life cycle assessment (LCA) is the most popular method for assessing sustainability, as it facilitates a quantitative assessment of the environmental impacts associated with a product lifecycle [4]. 19 out of 21 reviewed papers employed LCA to assess sustainability throughout the life cycle. Many impact categories are considered, such as global warming (kg CO_2 eq), ozone formation, human health (kg NOx eq), stratospheric ozone depletion (kg CFC11 eq), marine ecotoxicity (kg 1,4-DCB), human carcinogenic toxicity (kg 1,4-DCB) [4,10,11,13]. Following LCA, life cycle costing (LCC), a tool used to quantify the economic impacts by assessing the total costs of a product throughout its life cycle [4], ranks second, being utilised in 5 references [2,4,10,13,20], all of which also employed LCA. There are some common cost types for both metal AM and CM, such as material cost, energy cost, tooling cost, labour cost, and setup cost. However, in AM, there are additional costs associated with processing and post-processing, while in CM, machining costs may also be involved [4,8,10,13]. There are two papers that do not adopt LCA or LCC: [25] utilises an industrial metabolic model for assessing energy and material consumption, and [23] focuses solely on energy consumption. Regarding the sustainability pillars, the environmental aspect is investigated in all 21 reviewed papers, but the economic and social aspects are not explored in every paper. The economic pillar is examined in [2,4,8,10,13,20,23], and only in [8,23] are all three sustainability pillars investigated. The social pillar discussed in [8] is related to job satisfaction and in [23] to job opportunities, job losses and customization. Since the social aspect is not examined in most papers, it is often mentioned as an area that needs to be addressed in future work.

4 Research gaps and future works

Despite the extensive research in the literature on addressing sustainability issues in metal processing by AM and CM technologies, there is still considerable scope for further research. For instance, exploring the role of the use of digital technologies, such as computational materials modeling and/or artificial intelligence techniques, could provide greater insights based on the analysis of in-process tool monitoring data. These approaches used either individually or in hybrid could provide real-time operator feedback, for example, on process energy or material usage. Thus, they potentially yield both enhanced processing efficiencies as well as sustainability. Moreover, the number of comparative studies in the category of metal AM vs. metal AM is not high, and many AM methods have not been studied with a sustainability evaluation focus. Furthermore, some works utilise optimisation in manufacturing, aiming for a more sustainable environment, or employ prediction, automation, control, and data-driven methods. Therefore, investigating these topics in the field of sustainability can be a direction for future research, as they have the potential to lead to more sustainable manufacturing processes. Additionally, as this paper only reviews studies from 2019 to mid-2024, extending the timeline and delving deeper into more details of sustainability and its contributing factors, as well as giving more attention to the economic and social pillars of sustainability, could be another future direction.

5 Conclusion

This study reviewed 21 papers which were selected based on an initial review of over 440 papers. The selection was based on the relevance of the papers in their approach to addressing sustainability issues during the processing of metallic materials either by Additive Manufacturing or Conventional manufacturing. This assessment included a comparison of the sustainability assessment methods used in the studies reported in these papers. The results showed that in the category of AM vs. CM for sustainability, PBF and machining are the most frequently compared technologies. Furthermore, in terms of assessment, 90% of these papers utilise LCA and 24% utilise LCC alongside LCA. Notably, all the papers that utilise LCC also employ LCA to assess sustainability.

Regarding the sustainability pillars, the environmental pillar is the most examined, while the social pillar is the least addressed in the reviewed papers and needs more investigation. Finally, the research gaps and future works were discussed. Extending the timeline for reviewing these studies in greater detail or reviewing the papers that integrate optimisation, control, automation, prediction, and data-driven methods for sustainable manufacturing, would benefit future research.

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