MAM as a more resource efficient alternative to conventional machining: A systematic review

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The consciousness of stakeholders about sustainability grew rapidly in recent years. This is supported by the existing initiatives and policies, such as the sustainable and development goals (SDGs) (United Nations, 2022), Climate and Energy Framework (European Commission, 2022a), and the European Green Deal (European Commission, 2022b). To face the current climate emergency, ambitious targets, and cross-sectorial engagement are required towards reducing overall carbon emissions, promoting resource efficiency, circular economy, and industrial ecology principles. Thus, studies assessing the sustainability of products and services have been rising. Metals are valuable commodities required in multiple sectors such as transports (automotive, railway, aeronautics), industrial machinery, and building construction. Usually, this material has associated high-energy requirements for extraction, refining, and production stages (*e.g.*, casting). In addition, conventional machining (CM) of metal parts requires considerable amounts of raw materials (that end up being milled away), as well as high-energy demand for secondary processes (*e.g.*, machining to the surface finishing). Given the current need to reduce, emissions, the use of resources (*e.g.*, metals), and, consequently the number of wastes generated along the manufacturing process, metal additive manufacturing (MAM) may be seen as an opportunity to improve the sustainability performance of the metal manufacturing industry. For example, the aeronautic sector, and its metals use, are responsible for considerable emissions of CO_2 around the world (Monteiro et al., 2022). Because of their multi-material and processes route options, MAM can produce the same part that is shaped by CM, with less material, leading to the reduction of metal manufacturing, and, consequently, a reduction of the aeronautic sector's potential environmental impacts. Therefore, MAM is seen as an opportunity to reduce the waste and costs of conventional subtractive metal parts production (Kanyilmaz et al., 2022). Research reviewing the potential benefits of MAM from a sustainability point of view can be found in the literature. However, to the author's best knowledge, there is no work that systematically assesses the quantitative implications of this area on the environment, economy, and human health.

In this context, to understand the state-of-art of MAM sustainability, a systematic literature review was undertaken. To do so, a hybrid approach was considered. Firstly, research of the articles available in the literature that assess (1) environmental, (2) economic, and (3) social aspects of MAM was performed (Figure 1). Then, to investigate how *data mining* can be used to find patterns and which are the principal areas associated with this application field, a clustering algorithm was used to perform a bibliometric analysis. Afterwards, the papers were studied, and the main conclusions and results were analysed and discussed.

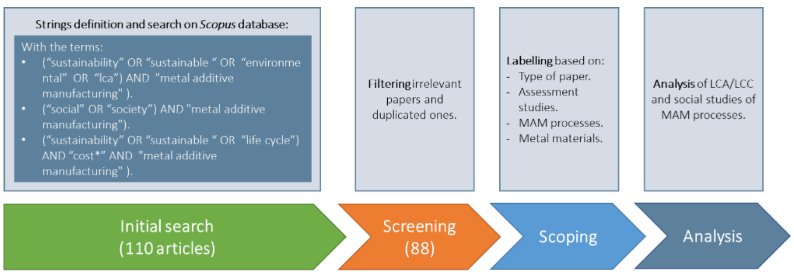

Figure 1. Methodological approach adopted for the search of papers available in the literature.

Overall, most of the studies evaluate the environmental impacts jointly with the economic implications of the several AM processes. Some of them also compared the sustainability of AM production of a part with its conventional manufacturing route (Jayawardane et al., 2022; Raoufi et al., 2022, 2020; Van Sice and Faludi, 2021). Considering the raw materials used, stainless steel in powder shape is the most studied material used for printing parts by additive manufacturing (AM). Thus, techniques based on Powder Bed Fusion (PBF) such as Laser Powder Bed Fusion (LPBF), Electron Beam Melting (EBM), and Bound Metal Deposition (BMD) were the procedures that were operated in the majority of the case studies. In the sample analysed, areas such automotive (Böckin and Tillman, 2019), and aeronautic (Galey et al., 2022) were evaluated to understand the environmental and the social implications of the AM technology, respectively.

The results corroborated the current connection between AM (more particular MAM), and its environmental and economic impacts to assess the sustainability of the area. Furthermore, from a social point of view, AM may have some benefits, namely the possibility of producing customised products (*e.g.*, healthcare goods), and supply chain's simplification (Raoufi et al., 2022). Overall, the scientific community seems to agree that AM methods are economically efficient for small manufacturing scales (Raoufi et al., 2022). Nevertheless, the sustainability of MAM is not fully understood. Thus, further work is still needed. Currently, there is no standardised approach that assesses the economic, environmental, or the social impacts of MAM. Therefore, the obtained results were very variable and depend on the assumptions made by the different authors. The same conclusion was taken by van Sice & Faludi, (2021) that considered that standard methodologies must be performed to make better comparisons. Furthermore, there are studies that lacks experimental data. Thus, most of the assessments rely on assumptions, which increase the uncertainty of the studies. Other gaps and suggestions for further research were also pointed out. In general, the need for more comprehensive sustainability studies (*i.e.*, evaluation of economic, environmental, and social impacts) (Raoufi et al., 2022) by, for example, understanding AM implications along the supply chain (Peng et al., 2020; Raoufi et al., 2020), and evaluating other applications, and potential advantages of MAM besides the existing ones (Böckin and Tillman, 2019) were highlighted in the available literature. Moreover, the use of recycled raw materials, and other operations (*e.g.*, finishing operations for the surface improvement) should also be assessed (Jayawardane et al., 2022) to prevent waste generation.

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