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A framework to assess the sustainability of additive manufacturing for spare parts

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Abstract: Additive manufacturing (AM) is a promising technology for the optimization of the spare parts supply chain. A complete evaluation of whether it is advantageous to switch to this technology for spare parts management should include a comprehensive assessment of its sustainability in addition to its techno-economic viability. General analyses of the economic, environmental, and social impacts of AM have been conducted, but assessments of the sustainability effects of AM in the spare parts field is limited to specific industries. Thus, based on the literature, we designed a framework that can support a life cycle evaluation of the emerging application of AM technology. It represents a methodological approach that covers all the stages of the spare parts life cycle and the three dimensions of sustainability. It has been designed to support both researchers and practitioners who are considering AM for the manufacturing of spare parts.

Keywords: Additive manufacturing, spare parts, sustainability, life cycle assessment, methodological framework.

1. INTRODUCTION

In the industrial environment, additive manufacturing (AM) has many advantages over conventional manufacturing (CM) technologies, including its efficient use of raw materials, ability to manage complex geometry and produce small batches, and its simplification of the product supply chain (Dircksen and Feldmann, 2020; Huang et al., 2013; Pilz et al., 2020). AM has been perceived to be a sustainable technology due to these characteristics, leading to broader discussions about its economic, environmental, and social sustainability (Colorado et al., 2020) and its contributions to the circular economy (Ponis et al., 2021). The degree of sustainability of AM is thus considered a key issue when evaluating the advantages of switching to this technology (Paris et al., 2016). This approach captures the complexity of AM and evaluates its economic, environmental, and social impacts by applying the methodologies of life cycle cost (LCC), environmental (LCA), and social (S-LCA) assessments.

Although general sustainability frameworks (Ribeiro et al., 2020) have been established to evaluate AM, the sustainability of AM technology is generally recognized as dependent on the specific application and product (Taddese et al., 2020) and on the used approach (Saade et al., 2020). Comparative LCA studies have demonstrated that metal AM products can be more sustainable when complex geometrical components are necessary (Hapuwatte et al., 2016). The increased efficiency in terms of time is also essential for both environmental and economic sustainability (Lunetto et al., 2021). LCC studies have identified economic advantages associated with AM usage, in terms of the ability to manufacture complex components and a small quantity of products, and limitations in terms of the limited palette of materials, the slow processing speed and the post-processing requirements (Baumers et al., 2016). Soares et al. (Soares et al., 2016) applied the S-LCA methodology to investigate the impact of adopting AM in the medical devices industry considering two applications. They identified both positive and negative social effects on various stakeholders from the shift to AM technology.

AM has been applied to the spare parts supply chain, and has significant potential in this field (Huang et al., 2013), as it can bring benefits in terms of the economic feasibility of small production batches, the ability to rapidly change the part design, to produce complex geometries, and to potentially simplify supply chains and reduce lead times and inventories (H. Khajavi et al., 2018), providing also a good supply chain robustness (C.F. Durach et al., 2013). The technical viability and the potential economic advantages of applying AM to spare parts have been investigated within the aircraft (Holmström et al., 2010; Liu et al., 2014), automotive (Isasi-Sanchez et al., 2020), maritime (Kostidi et al., 2021), mechanical engineering (Wits et al., 2016), and defense sectors (Westerweel et al., 2021). However, to the best of our knowledge, no sustainability analysis of AM application in the spare parts supply chain that considers the economic, environmental, and social dimensions has been conducted. Thus, we address this research gap with an analysis of the sustainability issues specific to AM within the spare parts supply chain, with the aim of developing a framework that can support a life cycle evaluation of this emerging use of AM technology.

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2. AM USE IN THE SPARE PARTS MANAGEMENT – RESEARCH BACKGROUND

AM technology offers various repair and restoration opportunities, and thus supports the effective recovery of end-of-life products in the circular economy (Rahito et al., 2019). It is also cost-effective for low-volume production (Chekurov et al., 2020) and enables on-demand manufacturing, thus reducing the need for warehousing and transportation and simplifying supply chain configurations (Huang et al., 2013). These characteristics mean that AM can be applied to spare parts supply chains. Unlike consumer products, spare parts are characterized by intermittent demand, long procurement lead times and high downtime costs (Knofius et al., 2019).

AM can improve inventory management as spare parts can be printed on demand, thus reducing the inventory costs (Pfähler et al., 2019). Reducing the spare parts inventory can also simplify the maintenance policies of businesses (Westerweel et al., 2019). The maintenance, repair, and overhaul (MRO) strategies of end-users can be improved through installing AM equipment, by creating new process flows in which the original equipment manufacturer (OEM) provides only the file to be printed to the end-user. A further optimization step involves the end-user editing the 3D model to adapt or improve it before printing (Wits et al., 2016).

The application of AM to spare parts management has been extensively examined in the aircraft, maritime, and automotive industries. AM can be integrated into the aircraft spare parts supply chain using centralized and distributed approaches (Holmström et al., 2010; Liu et al., 2014). A centralized distribution center can allocate AM machines to produce slow-moving spare parts on demand; a distributed approach considers the deployment of AM equipment at each service location if the demand is sufficiently high to justify the capacity investment. These configurations can reduce the inventory level and transportation distance. The introduction of AM into after-sales automotive spare parts supply chains is dependent on technical feasibility, while the distribution chain can be organized by creating AM hubs, which are platforms through which orders are collected and redirected to distributed AM manufacturers (Isasi-Sanchez et al., 2020). In the maritime industry, equipment must function under severe and corrosive operating conditions, and thus such an environment is recognized as very promising for its application. The required spare parts can also be printed on vessels (Kostidi et al., 2021).

The reluctance in the machine-building industry to use AM for spare parts production is due to various barriers, as identified by managers and practitioners in the survey conducted by Chekurov et al. (Chekurov et al., 2020). The product quality level and the lack of expertise in AM are the main issues. Recent studies of industrial machinery have analyzed the conditions that make the shift from CM to AM for spare parts supply economically profitable under a corrective maintenance strategy, considering post-process treatments and specific inventory management systems (Sgarbossa et al., 2021). Lolli et al. (Lolli et al., 2021) proposed age-based preventive maintenance policies that use AM, and also investigated the conditions under which the shift from CM to AM is profitable.

3. AM USE IN THE SPARE PARTS MANAGEMENT – SUSTAINABILITY ISSUES

The spare parts supply chain involves many business functions and activities, including production processes, service and after-sales, maintenance and inventory management, and the distribution network (Pfähler et al., 2019). These, must all be considered when analyzing the sustainability of applying AM to spare parts. Table 1 summarizes these aspects in terms of the significant life cycle stages (production, use, and end-of-life) and sustainability dimensions (economic, environmental, and social).

The selection of technology and associated raw materials is important in assessments of 3D-printed spare part sustainability. These can include metals, composites, ceramics, cement and concrete, polymers, food, clays, metamaterials, and organ tissue (Colorado et al., 2020). The literature suggests that issues such as materials preparation, technological difficulties, build failure and quality, and expensive post-processing requirements make AM less cost effective than CM (Baumers et al., 2016; Peng et al., 2018). In addition, in some industries (e.g. aerospace), the use of recycled materials is limited since components demand high quality performance (Villamil *et al.*, 2018). However, AM requires fewer types and lower volumes of raw materials, which leads to environmental benefits in terms of extraction and related emissions (Agrawal and Vinodh, 2019; Peng et al., 2018). AM also generates less waste in the overall process (Mami et al., 2017; Rejeski et al., 2018).

The manufacturing strategy can also affect the 3D-printed spare parts production stage (Ott et al., 2019). On-demand production decreases the equipment downtime costs (Alt parmak et al., 2021). The simplification of the supply chain and the ability to produce customized products are considered the main social benefits of AM (Arrizubieta et al., 2020). The potential reduction of storage and transport requirements, along with transport distances (Li et al., 2017), can also contribute to sustainability in terms of the consumption of resources and generated emissions.

Table 1. Economic (ECO), environmental (ENV) and social (SOC) issues in the application of the AM technique to spare parts.

LC stage		ECO	ENV	SOC
Production	Raw materials	High cost for material preparation (Peng *et al.*, 2018) Elimination of delay costs (Atzeni and Salmi, 2012) Reduction in the cost of sold goods (Raoufi *et al.*, 2022)	Lower volume of raw materials (Agrawal and Vinodh, 2019; Peng *et al.*, 2018; Rejeski *et al.*, 2018)	Local manufacturing improvement (Petrick and Simpson, 2013) Customized products (Arrizubieta *et al.*, 2020) Worker's health and safety improvement (Arrizubieta *et al.*, 2020)
	Energy		Higher energy consumption (Kellens, K., 2017) (Peng *et al.*, 2018)	
	Emissions		Potential generation of VOC (Wojtyła *et al.*, 2017)	Potential to reduce hazards (Rejeski *et al.*, 2018) Potential eye irritation and skin reactions (Kellens *et al.*, 2017)
	Storage	Stock levels decreasing and stock-out risk reduction (Knofius *et al.*, 2019)	Reduction of stored parts (Ott *et al.*, 2019) Elimination of obsolete stock (Arrizubieta *et al.*, 2020)	
	Transport	Reduction of logistic costs (Liu *et al.*, 2014)	Reduction of distance and weight of products (Li *et al.*, 2017)	Ability to simplify the supply chain (Arrizubieta *et al.*, 2020)
	Waste		Lower waste generation (Mami *et al.*, 2017; Rejeski *et al.*, 2018)	
Use	Maintenance	Time dependent cost increasing (Baumers *et al*., 2016) Expensive post-processing (Baumers *et al*., 2016) Failure and quality related increased costs (Baumers *et al*., 2016)	Greater number of replacements (Baumers et al., 2016) Increased resources associated with build failure and quality (Baumers *et al*., 2016)	Response to disasters and improvements in development operations (Tatham *et al.*, 2015)
EoL	Secondary materials	High material recycling costs (Peng *et al.*, 2018)	Potentially high level of recycled and reused material (Peng *et al.*, 2018)	
	Waste	Economically valuable streams of service creation (Baumers *et al*., 2016)	Increasing support structure waste (Peng *et al.*, 2018)	Extension of product lifetime (Villamil *et al.*, 2018)

However, volatile organic compounds such as styrene, cyclohexanone, butanol, and ethylbenzene can be generated by some polymeric materials used in AM, such as ABS, PLA, and nylon (Wojtyła *et al.*, 2017). In terms of other resources, most researchers agree that the energy consumed through AM processes may be two orders of magnitude higher than through subtractive processes (Kellens et al., 2017) due to the relatively low level of productivity, and particularly for AM methods that involve lengthy processing at elevated temperatures (Peng et al., 2018). The components and products manufactured with AM technologies have both economic and environmental limitations. These are mainly associated with slow process speeds, which increase the time-dependent cost, and with expensive post-processing requirements, which may require additional resources. In addition, as AM is an emerging technology, the quality of the components is typically below those produced with conventional technologies. Thus, the increased costs and resources associated with build failure and quality must be considered (Baumers et al., 2016). Although these aspects can compromise the sustainability of spare parts produced through AM technologies, the potential social benefits include improving the responses to disasters and development operations (Tatham et al., 2015).

In terms of the end-of-life (EoL) stage, although the treatment techniques of products and components remain very expensive and energy consuming, the materials used in AM and the produced components have the potential to be recycled and reused, which can influence the entire supply chain and bring environmental benefits by enabling circular economy strategies (Peng et al., 2018).

4. RESULTS: FRAMEWORK

Based on a conventional LCA framework (SETAC, 1991), our framework focus on spare parts and considers the sustainability aspects discussed in the literature aiming at assessing AM sustainability in the spare parts market. The proposed framework is shown in Figure 1 and considers all the product life cycle stages and the economic, environmental, and social aspects of sustainability. The central block of the framework describes the three main steps of the life cycle of a SP (production, use and EoL). To each step, economic (ECO), environmental (ENV) and social (SOC) input and output data are linked. The main input/output data are listed in the framework in an aggregate manner. Obviously, data need to be adapted accordingly the technology and the used raw materials, as well as the specific case study, as done for example by Raoufi et al. (Raoufi et al., 2002) who characterize the economic and environmental performance of metal additive manufacturing and powder metallurgy processes for producing a stainless-steel microscale chemical reactor.

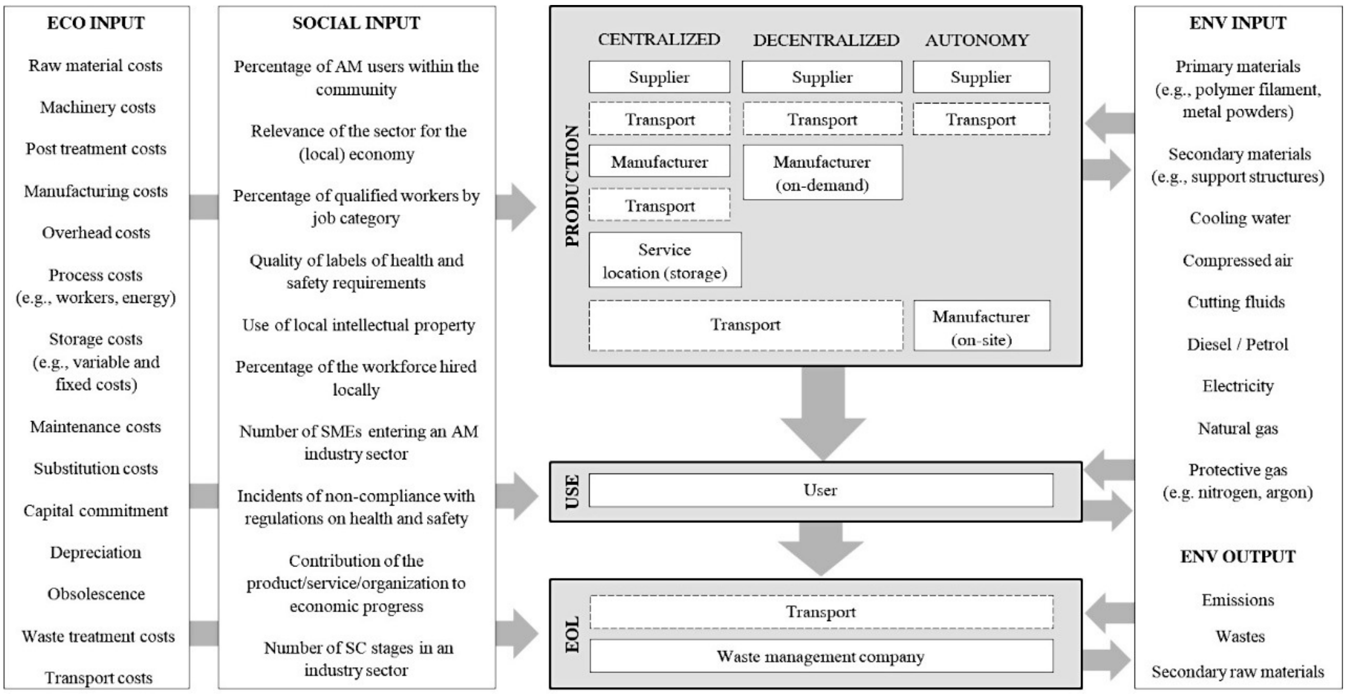

Figure 1. Framework to assess the sustainability of AM in the spare parts market.

The sustainability of AM technology is strongly influenced by the supply chain, and rather than the usual production processes the flow chart shown in the center of the graph highlights the various players in the supply chain (continuous line) for each step, with evidence of the transport (dashed line) that has significant weight. The input/output data cover the three sustainability dimensions (economic, environmental, and social), so we can evaluate the complexity of the AM. The most significant indicators for the spare parts sector are obtained from the literature, with the aim of highlighting the main features that can determine the sustainability of the production of components using AM technologies.

As mentioned, the production stage is significantly affected by the manufacturing strategy. We therefore identified three options: centralized, in which parts are produced in a sufficient quantity and stored by a service location company; decentralized, in which parts are produced by a specific manufacturer on-demand; and autonomous, in which parts are produced directly on-site by the user. As the flow chart shows, the strategies may have different economic and environmental implications related to the potential reduction of transport and distance and to raw materials and emissions. The flows of resources used in maintenance operations and in the replacement of poor-quality components and products, or those that can potentially fail, must be considered in the use stage.

The EoL considers the input/outputs related to the treatment of products and components at the final stage, by considering the potential environmental benefit derived from circular economy strategies. These are facilitated by the high levels of reused and recycled materials, but also by the emissions and high costs of waste treatment operations. In addition, social aspects, such as extending the lifetimes of products and including additional industries in the supply chain, can be included.

5. CONCLUSIONS

AM is a technology that can potentially help to optimize the spare parts business. The techno-economic viability of the transition to this technology has been extensively examined, and the conditions under which AM can improve the cost-effectiveness of the spare parts supply chain have been assessed. An evaluation of the sustainability impacts of AM in the field of spare parts management can provide an overview of the advantages of the technology, thus enabling a more informed choice.

The framework developed in this study represents a methodological approach for evaluating the sustainability of AM in terms of spare parts from a life cycle perspective. All the stages of the spare parts life cycle are considered, along with the three dimensions of sustainability. It can support researchers investigating the sustainability issues of AM, managers who intend to integrate AM technology into their spare parts supply chains, skilled practitioners designing improved MRO strategies, and LCA specialists considering this new technology. Our future research will focus on the application of the proposed framework to real case studies and will consider various maintenance and inventory management policies. We will therefore provide a complete sustainability evaluation of AM use in spare parts management by taking a life cycle approach.

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