Sustainability Implications of Using Additive Manufacturing for Production Tool Design

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Abstract: As the application of Additive manufacturing (AM) is moving from prototyping to final product manufacturing, exploring its sustainability implications is crucial. This paper explores the sustainability impacts of AM on production tool manufacturing and the role of digitalisation in enabling sustainable tool production. It emphasizes the necessity of a design tool that helps designers adopt a holistic sustainability approach (including environmental, social and economic aspects), while also being comprehensive and user-friendly to ensure practical applications.

Keywords: Additive Manufacturing, Sustainability, Sustainable Design, Digital Manufacturing

1 Introduction

AM as an emerging technology offers numerous advantages over the subtractive and formative manufacturing techniques commonly referred to as "conventional methods". Design for AM enables design flexibility, weight reduction, and the possibility of tailored design (Gibson et al., 2015). Unlike traditional methods that remove material from a bulk, AM uses material only as needed, which minimizes material consumption and waste, aligning with sustainability goals. This helps reduction of material consumption and reducing waste, which can be in line with sustainability. Research indicates that for low-volume production and the manufacturing of complex products, AM can significantly reduce production costs (Majeed et al., 2021). As companies become increasingly aware of these benefits, the use of AM is extending beyond prototyping to include the manufacturing of final products.

AM fundamentally differs from conventional techniques. For instance, it eliminates some conventional manufacturing constraints yet introduces new challenges that must be identified and considered during the design phase (Borgue et al., 2019). This fundamental change requires product designers to shift their mindset from traditional design thinking and figure out new ways of exploiting AM capabilities (Kumke et al., 2016). In parallel, sustainability awareness is increasing, and companies are deemed to take action for more sustainable practices. Despite its potential, the sustainability impacts of AM are still not fully understood and there remains much more to discover (Hegab et al., 2023). Adding to the complexity, there is currently no AM standard process model let alone being integrated with sustainability considerations, due to several factors: 1) AM is not a single technology but rather a family of technologies each with specific characteristics, and still undergoing significant development in terms of equipment, materials and processes. This rapid evolution hinders the establishment of a standardized process model. 2) standards such as those by ISO and ASTM are still under development 3) Many established companies are only beginning to integrate AM into their manufacturing ecosystems. Given these factors, it is essential to explore how sustainability can be systematically integrated into AM processes, especially in the absence of a standardized process model (Kumke et al., 2016). This study focuses particularly on the context where companies are in the initial stages of adopting AM, lacking a standardized process model. It is thus crucial to identify and integrate sustainability implications before a common AM process model becomes established (Sauerwein et al., 2019).

Simultaneously, Industry 4.0 encourages companies to leverage digital technologies to enhance their operations and stay competitive in the market. AM is digital in nature and is one of the key elements of this industrial transition. However, the intersection between sustainability and digitalisation is underexplored (Despeisse et al., 2022). Therefore, it is critical to explore how digitalisation can leverage sustainable AM production.

To do this, our research investigates how AM sustainability benefits can be recognized and considered in the product design phase. Further, we discuss how digitalisation can enhance the sustainable manufacturing of products. We purposefully limit the scope to the early design phase, as the decisions made at this phase have a high impact on the products' whole lifecycle. To investigate this, a collaborative study is conducted with one of the largest Swedish Original Equipment Manufacturers (OEMs). Three production tools implemented in the production line are remanufactured with AM, sustainability benefits of AM based on literature study are explored and potential ways on how digitalisation can leverage sustainable design and manufacture of such tools are discussed. This study aims to enhance understanding of the sustainability implications of using AM for final products that are traditionally manufactured using conventional methods. It investigates the often-overlooked advantages offered by AM for such products, including improved ergonomic design and reduced material consumption. Additionally, we explore the critical role of digitalisation in supporting sustainable design and manufacturing processes with AM, a topic that remains largely underexplored. The research questions guiding this study are:

RQ1: What are the sustainability implications of AM application for production tool design?

RQ2: How can digitalisation enable sustainable design and manufacture of production tools?

This paper is organized in the following manner: Section 2 provides a comprehensive background on the correlation of AM, sustainability, and digitalisation. It highlights the sustainability benefits of AM as identified in literature setting the stage for our empirical investigation. Section 3 outlines the methodology employed to explore these benefits and the associated sustainability challenges in the use cases, directly addressing our first research question regarding the sustainability implications of AM for production tool design. The findings from the case study are presented in Section 4. Subsequently, Section 5 delves into a discussion that, while rooted in these findings, further addresses the second research question on how digitalisation can enable sustainable design and manufacture of production tools. The paper concludes in Section 6, summarizing our contributions and suggesting directions for future research. This study stands out due to the limited number of studies focused on the sustainability assessment of additive manufacturing of production tools found in literature and further distinguished itself by exploring the potential role of digitalisation in this context.

2 Background

The impact of AM on sustainability is difficult to assess. On one hand, several studies indicate that the AM process is more energy-intensive compared to the conventional manufacturing process (Sauerwein et al., 2019). On the other hand, some point out that solely focusing on one production phase is not enough and a comprehensive lifecycle approach is needed to assess the sustainability impacts of AM (Majeed et al., 2021). For instance, the results of Gebler et al. (2014) study revealed that AM has the potential to cut costs, energy use, and CO2 emissions if considering the whole life cycle of the product. In another study, Faludi et al. (2015) performed a Lifecycle Assessment (LCA) to compare the environmental impacts of AM with traditional CNC machining. The results indicate that one of the AM techniques outperformed other technologies. However, they claimed results vary based on usage profile, suggesting that it is not straightforward to label one process universally more environmentally friendly than the other. It is important to note that the current lifecycle assessments for conventional manufacturing do not seamlessly translate to AM, prompting suggestions for an updated framework (Tang et al., 2016).

Adding to the complexity of sustainability assessment of AM, it is critical to note that sustainability goes beyond environmental aspects further including social and economic dimensions. These dimensions, i.e. ecological, social and economic, have nested interdependencies and continuously affect one another, meaning that changes in one dimension impact other dimensions (Geissdoerfer *et al.*, 2017; Mebratu, 1998). Yet, the social sustainability implications of AM remain less explored compared to its economic and environmental aspects (Naghshineh et al., 2021).

Given the multifaceted nature of sustainability assessments, it is even more challenging to compare AM with conventional manufacturing and assess the real sustainability implications of AM, particularly from a quantitative perspective (Sauerwein et al., 2019). Nevertheless, qualitative assessment remains valuable offering insights into AM characteristics aligned with sustainability objectives. The subsequent section will look into the general sustainability benefits of AM in sub-section 2.1, review of social sustainability aspects of AM in sub-section 2.2, and how digitalisation enhances more sustainable AM practice in sub-section 2.3.

2.1 General sustainability benefits of AM

To benefit from the advantages of AM, parts need to be designed for AM, incorporating strategies such as topology optimisation and other design for AM guidelines. Based on the literature review, five main themes are identified as possible AM sustainability advantages, described below:

- **Personalisation/customisation**

AM enables the distinct advantage of creating customised and complex products without necessitating additional tools or extra effort (Tang et al., 2016). Such a feature can improve the performance, and functionality of the product, and reduce the need for overdesign. Further, it can add psychological value to the product. If a product is personalised, consumers tend to feel a stronger connection to it often leading to better maintenance and higher longevity (Diegel et al., 2010; Sauerwein et al., 2019).

- **Resource efficiency**

AM offers the potential to minimize waste, as in this process material is added only where needed, unlike in conventional manufacturing where material is subtracted from a larger mass (Diegel et al., 2010). Furthermore, AM enables the manufacturing of complex products, offering the possibility for functional integration which means fewer parts are required for each product. This promotes product consolidation and reduction of material use and assembly steps leading to a more efficient process. Additionally, topology optimization is one of the features enabling the manufacturing of lightweight components that also contribute to less material consumption (Sauerwein et al., 2019).

- **Repairability and function enhancement**

Some of the AM technologies allow damaged parts to be repaired rather than replaced entirely. Moreover, AM offers design flexibility that enables design modifications in case of requirement change. For instance, Al Handawi et al. (2022) investigated an aero-engine component known as the turbine rear structure. They proposed a method to remanufacture with AM and allocate the design margins to adapt the design according to the changed requirements. Further, modular design is also feasible with AM (Borgue et al., 2019) allowing individual module replacements in case one segment fails rather than discarding the entire part.

- **Distributed manufacturing**

AM facilitates local manufacturing streamlining the supply chain and minimizing transportation dependencies. Bonham et al. (2020) explored this capacity by establishing a system connecting kayak manufacturers and service providers through a digital thread system. While the kayak data originated in one country, the tangible product was manufactured in another.

- **Print on demand**

A significant advantage of AM is the possibility of print on demand which is useful, especially in the case of spare parts manufacturing. Leveraging AM allows for digital storage of such parts that can be printed only upon demand. Often, there is an inventory of physical parts that may remain unused (Diegel et al., 2010). Transitioning to digital inventory leads to less material consumption and more storage room (Ford and Despeisse, 2016).

2.2 Social sustainability

Naghshineh et al. (2021) identified 42 social impacts that AM has on various stakeholders such as workers, value chain actors, local communities, consumers, and society at large. One significant social benefit of AM is its facilitation of local manufacturing, which can lead to local empowerment. This shift not only fosters education and training opportunities for community members but also enhances local economic development.

However, the introduction of AM leads to a high degree of automation, which impacts labor demand. While automation reduces the time workers spend directly involved in the manufacturing process (Mehrpouya *et al.*, 2021), it can also lead to health concerns, such as issues related to material toxicity and nanoparticle emissions (Arifin *et al.*, 2022). Additionally, this automation may lead to worker isolation, potentially causing psychological problems.

On a positive note, AM significantly improves design capabilities, facilitating a more open collaboration among stakeholders through co-creation (Rayna *et al.*, 2015). This capability allows organizations to engage more directly with customers and incorporate their feedback into product designs. Beltagui et al. (2020) explored this benefit in the context of a mobile phone producer that enabled customers to personalize their mobile cases, enhancing supply chain innovation and consumer satisfaction.

Despite these insights, the social sustainability impacts of AM remain overlooked, highlighting the need for further research in this area (Graziosi *et al.*, 2024; Matos and Jacinto, 2019; Naghshineh *et al.*, 2021)

2.3 Digitalisation

Hallstedt et al. (2020) emphasize the necessity for industries to prioritize digitalisation, such as data collection and analysis, to be strong players in the future. In the context of AM, this digitalisation is integral as the process starts with creating a 3D model, which is then digitally transferred to a printer. The following printing process largely operates autonomously, minimising human interactions. This digital approach holds significant potential for data acquisition, storage, and utilization, enhancing not only the quality of both the product and the process but also offering opportunities for more sustainable production. Further, the application of lifecycle data management systems such as Product Lifecycle Management (PLM) systems facilitates in-depth lifecycle knowledge of a product, which in turn can promote sustainable production (Duque Ciceri et al., 2014). For instance, Bonham et al. (2020) integrated a digital thread system tailored for the additive manufacturing of kayaks. Their platform incorporated the CO2 model and LCA to offer feedback to consumers and assess the ecological impact of the product. Further, incorporating technologies such as Machine Learning (ML), Artificial Intelligence and the Internet of Things can make AM smarter. Leveraging these data-driven technologies paves the way for achieving environmental, economic, and social sustainability. Majeed et al. (2021) introduced a framework that integrates AM, big data analytics, and sustainable smart manufacturing. They demonstrated how the implemented digital tools can draw a connection between AM parameters and sustainability performance. In this case, AM parameters can be tuned for greener production by enhancing part quality and reducing energy consumption and CO2 emissions. Moreover, numerous researchers highlight the potential of ML algorithms in improving product and process quality. For instance, Özen et al. (2021) employed ML to assess the microstructure of the printed parts and measure the porosity. Using computational homogenisation, they obtained effective properties of the printed parts.

3 Method

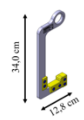
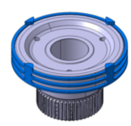
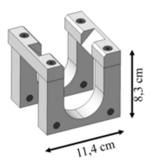
As highlighted in the Introduction (Section 1), many companies are in the early stages of adopting Additive Manufacturing (AM) and lack a standardized process model. Therefore, it is crucial to explore how sustainability considerations can be identified and integrated early in the AM adoption phase (Kumke *et al.*, 2016; Sauerwein *et al.*, 2019). This study was conducted in collaboration with a leading Swedish OEM that is in the early stages of adopting AM, aiming to assess its applicability as an alternative to traditional manufacturing methods such as welding and machining for manufacturing tools used in the production line. While the broader research initiative explored various dimensions of AM application, this paper focuses specifically on the practical sustainability implications of using AM to redesign production tools. These tools are used internally on the shop floor by the manufacturing operators and are produced in low volume for specific applications, making them suitable candidates for exploring the potential benefits of AM.

To explore the practical sustainability implications of AM, three production tools were redesigned and manufactured using AM, with the goals of enhancing performance, efficiency, and cost. Details of these tools are provided in Table 1. We evaluated the sustainability benefits of AM in this scenario by identifying key sustainability drivers from the literature (outlined in Section 2) and comparing these theoretical benefits with the practical outcomes observed.

Comprehensive information about the current tools was collected through eight semi-structured interviews and workshops with design engineers, manufacturing engineers, and end-users. The tools were redesigned in collaboration with a design engineer who had experience with conventional manufacturing methods. We adhered to design for AM guidelines, including topology optimization, for redesigning the parts. For validation, the redesigned tools were tested on the assembly line, and feedback was collected from end-users to assess sustainability benefits such as customization and functional enhancements. Resource efficiency was also evaluated by comparing the weight and part counts of each tool when manufactured with traditional subtractive methods versus AM.

Figure 1 summarizes the methodology of the study. As shown in Table 1, the tools are traditionally made either of polymer or metal. In this study, Fused Deposition Modeling (FDM) with polymer printing was employed to explore whether polymer can replace metals in the current context and to assess the potential sustainability implications.

Table 1. Production tool specifications, all traditionally made by subtractive manufacturing

Tool name	Main function	Main requirements	Current material	CAD	CAD, part in action
Lifting tool	Lift articles oriented vertically with crane up	Maximum lift of 30 kg	Structural steel and polyamide		
Gear protector	Protect gears during washing	Withstand temperature of 65°C, and washing chemicals	Stainless steel		
Washing machine basket interior	To place and fit some specific articles into the washing machine baskets during washing	Top level, 4.5 kg, lower level 11 kg. Withstand temperature of 65°C , and washing chemicals	Polyamid 6		

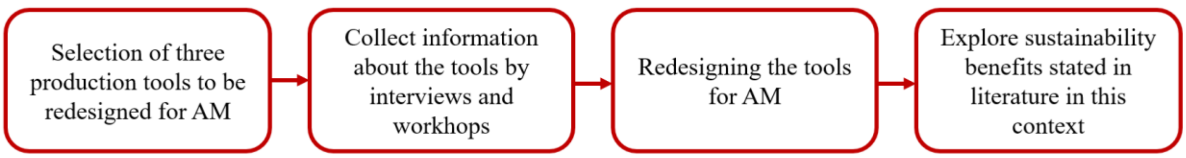


Figure 1. Methodology of the current study

4 Results

4.1 AM general sustainability benefits and challenges in the production tool context

Table 2 demonstrates the tools manufactured conventionally and with AM. In the following section, results from sustainability benefits offered by AM reported in the literature are investigated within the context of production tools, along with an exploration of the associated challenges.

- **Personalization/customization**

AM offered design flexibility for all three tools. For instance, based on the discussion with the operators, a better grip for the lifting tool was required and designed which the operators found useful. Also, the grooves were added (Shown in Table 2) that can be potentially used to estimate the lifetime of the tool. These new features were added to the tool without any need for special equipment. Also, it was investigated if the tools are better to be personalized, i.e., having a personal grip that follows the shape of the fingers for the individual operator. This idea was not applicable in this case since on the shop floor one tool needs to fit all.

- **Resource efficiency**

For all three redesigned products, less material was utilized (Table 2). Further, in the lifting tool redesign, additional parts (indicated in yellow plastics in Table 2) were integrated into the main body, streamlining part consolidation (as illustrated in Table 2, the number of parts drastically decreased). Highlighting resource efficiency, the original lifting tool was in metal, whereas the new version is made in polymers with air pockets, referred to as "infill percentage" in AM. This not only saves material but also results in a lighter and more ergonomic design. Also, topology optimisation was applied to the washing machine basket further reducing material consumption. It should be highlighted that, in every instance, the tools' delivery time and cost were significantly reduced when compared to those produced conventionally. Nonetheless, given that the previous orders consisted of larger quantities (ranging from 10 to 20), a direct comparison may not be entirely equitable, thus specific figures have not been included in Table 2. Despite this, remains a promising opportunity to reduce overall manufacturing time and cost.

- **Repairability and function enhancement**

AM showed a good potential for both repairability and functional enhancement. Repairability was more relevant in the case of the washing machine basket as the design was modular (Table 2). Apart from the fact that these modules can be redesigned in a way that eliminates the need for screws and decreases the assembly time, it helps the repair and reuse of the part. If one module breaks after a while, instead of scrapping the whole part, the broken module can be replaced by a printed new one. Regarding functional enhancement, in the case of the gear protector, the surface structure can be customized to allow better washability of the gears. As another example, the lifting tool can be more stable in the lifting process if a better grip is provided.

- **Distributed manufacturing**

One of the primary objectives of this production tool manufacturing study was to explore the feasibility of in-house tool production. Currently, certain tools or components of tools are sourced externally. The tools redesigned in this study were successfully manufactured in-house eliminating the need for external engagement and associated transportation. Utilizing AM in this case streamlined the supply chain, limited to design, manufacturing, and post-processing steps.

Table 2. Comparison between production tools manufactured with subtractive manufacturing and remanufactured with AM

	Subtractive Manufacturing		**Additive Manufacturing**	
Lifting tool		**Material:** Structural steel and PA6 **# of parts:** 13 **Weight:** 1500 g		**Material**: ASA **# of parts:** 1 **Weight:**530 g
Gear Protector		**Material**: Stainless steel **# of parts:** 1 **Weight:** 350 g		**Material:** ASA **# of parts:** 1 **Weight:** 136 g
Washing machine basket interior		**Material:** PA6 **# of parts**: 12 **Weight:** 490 g		**Material:** ABS **# of parts:** 12 **Weight:**200 g

- **Print on demand**

The studied tools were previously manufactured in case of need. Therefore, this benefit of AM was not directly applicable in this case.

Although AM shows significant sustainability benefits, some several challenges and ambiguities need to be addressed:

- In the following case study, with the application of AM both material and design of the parts are changed. Therefore, it is critical to explore if it is required to update the current quality assurance protocols or introduce new tests. For example, it needs to be confirmed if the polymer in the gear protector and washing machine basket interior can withstand temperatures over 60 ℃ (during the washing process) without emitting harmful fumes. As another example, the lifting tool is used by operators for heavy lifting so directly related to the safety of the operators, therefore quality measures need to be robust and changed if needed. Changing the quality assurance might potentially affect the design of the product.

- The redesigned tools have been tested by the operators but have not been used regularly. It is difficult to assess whether these new tools offer suitable longevity or overall quality compared to the previous tools. For example, the current use case showed that AM notably helped waste reduction, if the parts are prone to early failure and require frequent replacement, this complicates matters.

- AM enables part consolidation, yet it involves a trade-off when it comes to repairability. Reduction in part number reduces modularity, making repair complex. Therefore, the efficacy of part consolidation needs to be carefully evaluated on a case-by-case basis to assess its value and potential challenges.

- Although the parts' functionality has improved in the current case study, AM is still widely regarded as a technology primarily for prototyping. Therefore, if a tool produced through AM is subsequently discarded, its production serves no practical purpose.

5 Discussion

The case study explored the sustainability implications of using AM for production tools. Generally, AM demonstrated significant sustainability advantages, consistent with literature findings, yet important considerations must be addressed, as outlined in the subsequent section. Additionally, this section delves into the second research question, discussing how digitalisation can leverage sustainable design and manufacturing of such production tools.

AM sustainability challenges and uncertainty for production tool design

As the application of AM is extending beyond prototyping, companies need to understand its sustainability impacts. The results indicated several challenges and uncertainties of AM sustainability implications. For instance, additive manufactured polymer parts led to less material consumption, compared to conventional metallic components. However, the durability of the parts is in question. As another challenge, among polymers used for FDM techniques, designers prefer more durable but less sustainable materials such as nylon over options such as PLA, indicating the need for more study on more sustainable and durable materials for printing. Another example is the trade-off that arises when consolidating parts with AM. This feature can reduce material consumption but complicates repairability (Borgue et al., 2019). One of the main benefits offered by AM is local manufacturing that offers geographical proximity, shortens the value chain and potentially reduces environmental impacts. However, Faludi et al. (2015) showed in a study that the environmental impact of AM machines drastically decreases with maximized usage, implying that outsourcing to job shops is more environmentally friendly compared to in-house printing if the usage of the machine is not maximized. On the other hand, many studies have claimed that AM is more economical if used for low-volume production. This raises a substantial question that demands attention.

AM and social sustainability

Adding AM as a manufacturing alternative to the company portfolio promotes education and training for the designers and manufacturers (Naghshineh et al., 2021). This, however, can be challenging to ensure that designers and manufacturers are not overwhelmed by the need to develop new skills. In the current case study, the order demand is usually high leaving little room to spend on learning new skills. Although AM has the potential to reduce workload in the long run due to automation of the manufacturing process, mastering design for AM, selecting machine settings, support structures, materials, etc is time-demanding.

Regarding safety and living conditions, although automation in manufacturing reduces direct machine interaction, engineers still need to handle tasks such as build chamber preparation and post-processing. Additionally, health concerns arise from melting polymers during printing. For instance, in the following case study, ABS was used for the washing machine basket interior. Melting of such material in the printing process has raised health concerns (Garcia Gonzalez and Teresa Lopez Pola, 2023; Gümperlein *et al.*, 2018) necessitating engineering controls such as efficient ventilation systems while printing.

It is soon to evaluate whether AM would cause any psychological issues such as feelings of isolation or concerns about reduced labour demand in this context, as AM has not been fully adopted yet. Further, AM cannot fully replace conventional manufacturing in this case due to technological limitations such as build size and material options. Overall, it is too early to determine how AM would impact the workforce and the working environment, but it is important to proactively acknowledge potential challenges.

Sustainability sweet spot

Sustainability goes beyond environmental aspects, further including economic and social perspectives (Elkington, 1997). This has also been highlighted by Mallalieu et al. (Mallalieu et al., 2023) in studying the application of AM for aerospace components. Further, not only the whole lifecycle of the part needs to be considered but also all the stakeholders from cradle to grave need to be included for a comprehensive assessment. As there are many levels to sustainability, the question is how to implement sustainability considerations in industrial practices in a way that ensures both comprehensive evaluation and ease of use. This balance is critical to assure practicality and prevent incorrect conclusions based on limited assessment.

Role of all stakeholders

The design phase plays a crucial role in the sustainability implications of the product, yet it is equally important for all stakeholders involved in the lifecycle of the product to have sustainability awareness and commitment (Hallstedt et al., 2023). Additionally, as noted by Khan et al. (2020) top managers who are usually associated with major risk-taking actions have a significant impact on pushing the company toward sustainability objectives. Large corporations often face the challenge of tight schedules, making it difficult to allocate time to increase sustainability awareness of the employees, nevertheless, this is beyond the scope of the following paper.

Importance of design in sustainability assessment

It is important to note the critical role of design for a sustainable AM as the sustainability benefits of AM rely substantially on design. For instance, the design of a part has a direct effect on the durability of the part. As another example, in the following case study, the modular design of the washing machine basket interior plays a critical role in the repairability of the part. De los Rios and Charnley (2017) explored the role of designers in sustainability and circular economy. They also believe the design of a product has a direct effect on its value chain. Further sustainability thinking affects the practice in design. They stated that for circular and sustainable design, “scientific designers” are needed. They propose that the designers need to be solution providers not only object creators.

Importance of digitalisation and digital education

Industry 4.0 and 5.0 are undeniably revolutionizing the entire industry landscape. AM is at the heart of this transformation and relies significantly on end-to-end integrated digital solutions (Duboeuf *et al.*, 2021). Digital thread, digital twin or on a smaller scale, software such as topology optimisation should be implemented to fully leverage the capabilities of this technology. The company in question not only recognises this imperative but also has heavily invested to capitalize on the growing trend of digitalisation. Moreover, it is critical to underscore the significance of employee education (Braun et al., 2022), as Industry 4.0 requires the adoption of Education 4.0. Despite the challenges, particularly in large corporations with heavy workloads, companies must prioritize upskilling to navigate this new digital landscape effectively.

Sustainability and lifecycle data management

The modern concept of sustainability is as young as Additive Manufacturing as both are less than 50 years old. Consequently, sustainability studies on AM are in their infancy, predominantly qualitative or solely focused on environmental impacts such as LCA studies. Nevertheless, there is a significant need for comprehensive sustainability assessments of AM that incorporate environmental, social, and economic factors, especially when making decisions in the early design phase.

Increased traceability of the products can increase awareness of sustainability implications (Hallstedt et al., 2023). Thus, it is critical to capture information regarding the whole lifecycle of the products in the design phase to make more informed design decisions. In a complementary study (Hajali *et al.*, 2023) analysed the order-to-delivery information flow of such production tools. They demonstrated that to benefit from AM potentials, more data needed to be captured and managed in the design phase.

However, there are complications to this, as limited information is available in the design phase. Therefore, machine learning techniques can be used to predict useful information based on the historical data of the manufactured products.

Yet, determining the specific data to be captured presents a significant challenge. Given the vast amount of data generated throughout the whole lifecycle of a product, capturing all information is either impossible or unnecessary. With AM promoted to be used for creating customized products, the resulting database includes numerous unique data points, complicating storage, and prediction. Therefore, an important question to investigate is: what type of data needs to be captured during the product's whole lifecycle, and how can this information be used to foster sustainable design and manufacturing of products?

Qualitative vs. quantitative

As mentioned in the previous discussion point, advancements in digitalisation, artificial intelligence, and connectivity can enhance data traceability, reducing some uncertainties inherent in these early stages. For instance, detailed material data can reveal issues such as child labour involvement, while historical data on similar products can enable preliminary quantitative sustainability assessments or facilitate comparisons between different design concepts. However, such quantitative data is often unavailable or must rely on assumptions or existing reference designs. Even when accessible, quantifying certain factors, such as child labour or biodiversity impacts, requires extensive research. The integration of quantified data with tacit and systemic factors is an area where research is needed. Practically, designers can benefit from using qualitative data by awareness and risk analysis, and identification of what can, and needs to, be further considered in the detailing of the design. For tool design, where efforts are limited, several sustainability factors will likely need to be addressed qualitatively to increase transparency of information and data in the assessment.

6 Conclusion

In this paper, the sustainability implications of AM for the manufacturing of production tools were explored. The company in question implemented AM mainly for prototyping, but now considers AM for final product manufacturing which can be considered as a major transition. Our case study revealed the benefits of AM, including design customisation and resource efficiency. Nevertheless, the application of such technology imposes some risks and uncertainties, e.g. whether qualification methods should be updated as both design and material for such a product are changed when using AM, and whether such adjustments can be economically viable. Moreover, although AM allows for the creation of complex parts, this increased complexity may negatively affect repairability, creating a significant trade-off.

The sustainability impacts assessment of AM should extend beyond environmental aspects further including social and economic dimensions. Maintaining this broader view is vital yet should not overcomplicate sustainability assessments, ensuring the applicability in industrial settings.

Moreover, this study underscores the critical role of digitalisation in achieving sustainable AM production. The intersection between sustainability and digitalisation is often overlooked and it is hoped that this paper will contribute to advancing knowledge in this area. Digital solutions such as AI and cloud computing could assist designers in making more informed decisions during the design phase. For instance, such tools can enable access to information that was not previously available or difficult to retrieve, but also suggest more sustainable design based on predictive models, creating opportunities that were previously unattainable. However, challenges remain, including determining which data to capture, its reliability, and the accuracy of predictions. Additionally, the effectiveness of these digital solutions depends heavily on the accuracy and completeness of the data used. Inaccurate or insufficient data can lead to flawed assessments, potentially resulting in decisions that may adversely harm sustainability efforts. Thus, it is essential to approach the integration of digital tools with caution, ensuring rigorous data verification processes to prevent such adverse outcomes.

Therefore, it is critical to implement AI and other digital tools to facilitate quantitative analysis of the sustainability implications of AM, but it is equally important to incorporate qualitative analysis. Thus, there is a need for tools that can integrate both types of data to aid designers in making sustainable design decisions. Such tools should be user-friendly and compatible with the current design processes. Further research is necessary to develop these capabilities.

The application of such a tool is essential, especially as learning new skills (in the current case sustainable design for AM) can be challenging and time-consuming. Such a tool can facilitate the adoption process, particularly in scenarios such as the current case study where the company has not yet fully established a standard AM process model. Therefore, sustainability considerations will be proactively considered in the design phase.

To conclude, in the current study, AM showed advantages such as enhanced ergonomic design and reduced material consumption. These benefits are often overshadowed by the dominant prototype-centric mindset. Without a shift in this mindset, the comprehensive understanding of sustainability benefits and challenges of AM may only be recognized gradually leading to neglecting AM benefits or suboptimization of the manufacturing process.

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