OVERVIEW OF THE IMPACTS OF ADDITIVE PRODUCTION TECHNIQUES ON THE ENVIRONMENT: PRODUCTION OF CONTINUOUS FIBERS, DIRECT LASER SINTERING OF METALS AND SELECTIVE LASER SINTERING TECHNIQUES

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Additive manufacturing (AM) has experienced significant growth in recent years, emerging as a transformative technology with broad applications across various industries. This review explores the advantages, disadvantages, and environmental impacts of AM, an important area of consideration as this technology continues to gain popularity. By analyzing existing literature, we assess the challenges associated with AM processes, particularly in comparison to traditional manufacturing methods. AM has the greatest potential to contribute to sustainable development by the production of lightweight components and complex industrial products with intricate designs. These products are made with minimal material usage. Consequently, also waste and emissions are reduced, which are significant environmental advantages. Overall, this review highlights the importance of AM as a tool for advancing sustainability in manufacturing and offers valuable insights for Continuous Fiber Fabrication, Direct Metal Laser Sintering, and Selective Laser Sintering techniques to enhance their competitive advantage while reducing their environmental impact.

Keywords:
additive manufacturing,
3D print,
continuous fiber fabrication,
direct,
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1 Introduction

Additive manufacturing (AM) has emerged as a promising alternative to traditional manufacturing methods, offering potential benefits in terms of sustainability and environmental impact (Zhou et al, 2024, Rasiya et al, 2021). This review focuses on three key AM techniques: Continuous Fiber Fabrication (CFF), Direct Metal Laser Sintering (DMLS), and Selective Laser Sintering (SLS). By examining these methods through the lens of environmental considerations and life cycle assessment (LCA), we aim to provide an overview of their respective impacts, supported by relevant statistics.

CFF technique uses continuous fibers made from fiberglass, carbon fiber or even Kevlar. Fibers are integrated into thermoplastic matrices (e.g. polyamide), which improves the mechanical properties of printed parts, and makes those parts stronger and more durable (Kuschmitz et al, 2021). CFF is a dual-extrusion process, where the first extruder lays down the base material (matrix) and forms the shape of the printed product. The second extruder embeds continuous fiber within the printed layers of the matrix focusing on hot spots where mechanical wear out is expected. Working temperature in the nozzle (up to ~300 °C) depends on the matrix material and not on the continuous fiber, because fiber should not melt to contribute its physical properties to the melted matrix material. While targeting for the maximum performance of the layer-by-layer printed product, the use of the fiber is minimized, and the creation of waste is reduced with complete control of the process with the software. After printing, the thermoplastic with a reinforced internal structure cools and solidifies. It becomes a composite material that combines the strength of the fiber with the flexibility of the polymer. Because the addition of fiber is a selectively targeted process, printed products with enhanced mechanical properties remain lightweight and can be used for prosthetic limbs, frames for bicycles, brackets and fixtures for cars, parts for drones and even satellites.

While CFF is cited as particularly advantageous for producing lightweight, strong components, DMLS, an AM process that uses a high-powered laser to melt metal powders (titanium, stainless steel, aluminum, cobalt-chrome etc.), is often used for complex geometries (Anand et al, 2021). Computer-aided design (CAD) of the to-be-printed metal part is sliced into thin layers to guide the laser (working at the power from 100 to 500 W) layer-by-layer in the machine's build chamber which is filled with a fine metal powder. Layer bed temperature is often heated to reduce thermal stress (temperatures are from 100 to 200 °C). The laser selectively scans the chamber in the predefined path and melts (and not sinters) the "beamed" metallic powder particles together. After finishing each layer, the build platform lowers, a new layer of metal powder is spread over the previous and the sintering process continues until the part is built. Because the process demands high temperatures, the solidified printed part is cooled down in the chamber along with the machine to avoid thermal stress and crack formation. While the non-fused powder is removed for reuse purpose, the printed part requires additional post-processing like surface finishing, polishing etc. Like CFF, also DMLS is used for aerospace, automotive, and medical device manufacturing.

Like DMLS, also SLS is a powder bed fusion (PBF) layer-by-layer technique that fuses powdered materials using a high-powered (CO_2) laser (working at the power from 30 to 200 W). The entire build chamber is usually heated just below the melting point of the powdered material to gain uniform melting and prevent warping (temperatures depend on the material used; usually from 170 to 190 °C). While DMLS is used for metals only, SLS is used for polymers (thermoplastics: polyamide, polypropylene, polyether ketone) and elastomers (flexible polymers: thermoplastic polyurethane, thermoplastic elastomer), where both can be mixed with metals (like aluminum powder), ceramics, carbon-fiber, and glass beads or glass fibers to enhance desired properties of the final (composite) product. SLS uses mostly polyamide, while composites and elastomers increase the variety of materials, making SLS suitable for prototyping, low-volume production, and production of parts that require high performance making it suitable for the aerospace, automotive, and healthcare industry.

The environmental impact of additive manufacturing techniques presents opportunities and challenges (Zhau et al, 2024). While these methods offer significant potential for reducing material waste and increasing design flexibility, they also face challenges related to high energy requirements (some printing technologies), emissions from material production, and challenges in recycling or disposing of materials. This review addresses the challenges and opportunities for AM techniques selected in the AddCircles project.

2 Environmental benefits and challenges

The answer to how much impact a certain technology has on the environment requires a comprehensive overview of its entire life cycle (Figure 1), i.e. LCA, and not just the technological capabilities of the technology itself. For the AddCircles project used AM technologies, SLS, DLMS and CFF, focus was on the most in-literature-exposed characteristics.

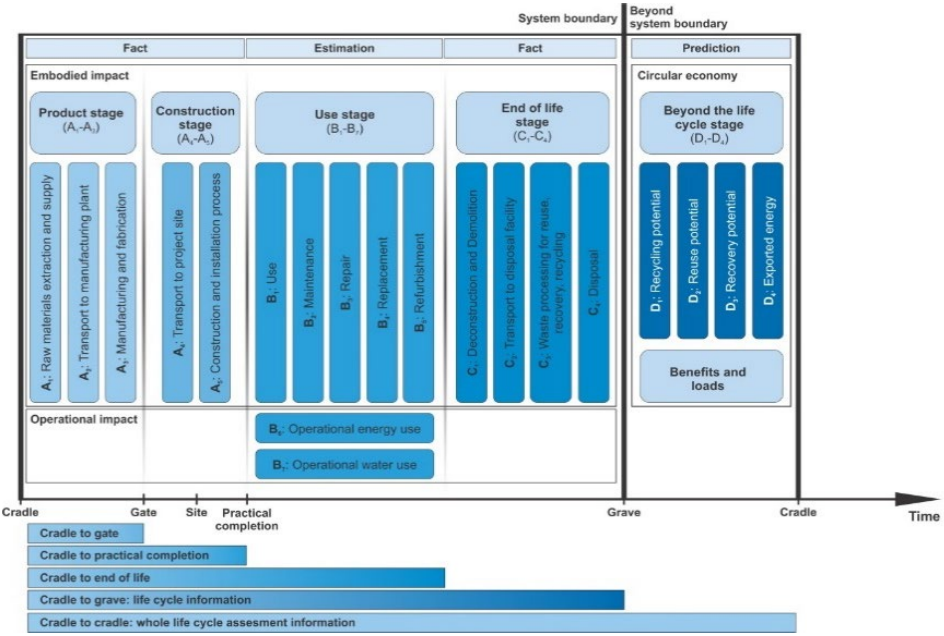

Figure 1: The main stages of LCA

The CFF technique has been found to be more material efficient, as continuous fiber manufacturing can reduce material consumption by 30-50% compared to traditional manufacturing methods due to its ability to optimize material placement and reduce waste. Studies have shown that this technique can lead to a solids-to-envelope ratio of less than 1:7, which is beneficial for reducing environmental impacts (Jung et al, 2023). However, it is also important to note that the production of synthetic fibers (e.g. carbon fibers), which is energy intensive and can emit up to 20 kg of CO_2 per kilogram produced, also has a large impact on the environment. This emphasizes the need for sustainable sourcing of materials for CFF technology as well (Faludi et al, 2015). So, an important part of the impact on the environment is also the possibility of using recycled materials and the ability to recycle a newly designed product, as this contributes to the circular economy, reduces the demand for raw materials and reduces the amount of waste (Sanchez et al, 2020). Many of the thermoplastics used in the CFF process can be recycled (Sola et al, 2023). Often the environmental challenge is the energy consumption of CFF. The energy required for CFF ranges from 0.5 to 2 kWh per kilogram of material produced. If sourced from non-renewable energy, this can significantly impact the overall carbon footprint of the process (Gopal et al, 2023).

We have also high energy demand in DMLS additive manufacturing techniques. The energy consumption for DMLS ranges from 5 to 10 kWh per kilogram of metal powder processed (Gopal et al, 2023). The carbon footprint associated with this energy use can be significant if derived from fossil fuels (Macheter et al, 2023). There is certainly room for manoeuvre here to reduce the impact on the environment, as well as in the handling of metal dust. Effective management strategies can mitigate the safety and environmental risks in AM posed by the production and challenging handling of metal dust (Modupeola et al, 2024, Chen et al, 2020). A positive characteristic of DMLS technique is the huge ability to reduce material waste. DMLS can achieve a material waste reduction of up to 90% compared to traditional machining processes (Mecheter et al, 2023). This is due to its additive nature, where only the required amount of material is used. Also, DMLS has Life cycle benefits. Parts manufactured with DMLS often have superior mechanical properties, leading to longer life and reduced resource consumption over time. For example, DMLS components can be designed to be lighter, which in turn reduces energy consumption during product use – which is especially critical in industries such as the aerospace industry (Markforged and Metalcraft solutions, assessed on 19.9.2024).

As with DMLS, the source of energy required for SLS has a strong impact on the overall sustainability of the process, as the energy consumption rate for SLS is approximately 3-6 kWh per kilogram of processed material (Hegab et al, 2023). However, SLS technology also has advantages such as design flexibility and a good ability to recycle the material. SLS enables the production of complex geometries that would be difficult or impossible with conventional techniques. This flexibility can lead to more efficient designs that use less material overall while improving performance. At the same time, SLS enables the recycling of unused powder, with studies showing that up to 70% of unused material can be recovered and reused in subsequent builds (Peng et al, 2018). This significantly improves the sustainability profile of SLS compared to traditional production methods. However, we must also pay attention to the fact that some powders can release harmful particles or volatile organic compounds (VOCs) during processing, which requires adequate ventilation and filtration systems to mitigate the impact on air quality.

Table 1: Energy consumption and material waste reduction for CFF, DMLS and SLS.

A type of additive manufacturing technique	Energy Consumption [kWh/kg]	Material Waste Reduction [up to %]
CFF	0.5-2	50
DLMS	5-10	90
SLS	3-6	70

LCA is a method supported by international standards (ISO 14040 and ISO 14044). LCA provides a comprehensive framework for assessing the environmental impacts associated with all stages of a product's life cycle – from raw material extraction to production, use and disposal. Some comparative LCA results are available in open access and provide conclusions regarding AM technologies. In line with LCA findings, AM processes generally exhibit lower greenhouse gas (GHG) emissions than traditional manufacturing when production volumes are small (under approximately 1,000 parts per year). For example, AM can reduce emissions by approximately 35-80%, depending on part geometry and production volume. AM also has the advantage of lower production volumes (below ~1000 units per year) due to cost efficiency and environmental benefits. In contrast, traditional methods become more favorable due to economies of scale when production exceeds approximately 42,000–87,000 units annually (Jung et al, 2023).

In Figure 2, we present a schematic illustration that highlights the relationship between production volume and production costs in additive manufacturing, juxtaposed with traditional manufacturing methods.

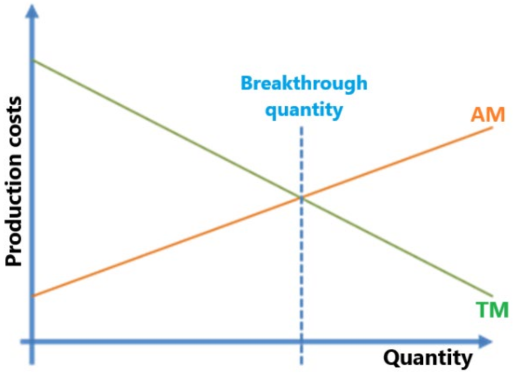

Figure 2: Relationship between production volume and production costs in additive manufacturing vs. traditional manufacturing.

The net environmental benefit of AM therefore depends on various factors. LCA has indicated that AM can reduce transportation distances with smarter logistic (Pilz et al, 2020, Kayikci, et al, 2018), as well as the associated transportation emissions. Traditional manufacturing (TM) often requires transporting goods over long distances, which can account for approximately 30% of a product's total carbon footprint (Nagabandi, 2023). AM and TM may also involve high energy consumption during production phases, where the important parameters are production scale and energy sources used during manufacturing.

The review identifies that AM has a big potential to contribute to sustainable development. Also, for small and medium-sized enterprises (SMEs), adopting AM can lead to substantial improvements in productivity, product quality, and environmental performance (Forth et al, 2018, Surya et al, 2021, and OECD 2019). However, successful implementation requires careful consideration of best practices to maximize the technology's benefits while mitigating its potential environmental drawbacks.

3 Conclusions

While AM can be seen as a sustainable alternative to TM, the degree to which the AM technique is environmentally friendly in the production of a certain product is specific for each individual case. If LCA output of AM can be lowered depends on its ability to accept environmentally friendly inputs from all LCA phases and the consistency of following the recommendations. Certainly, a case-by-case LCA analysis is recommended.

To increase the sustainability potential of AM, future research should focus mainly on improving the energy efficiency of printing processes, on the development of more sustainable AM input materials, on choosing the energy sources with the smallest environmental impact, and on further minimizing the environmental impact coming from the energy production of the selected energy source. By addressing challenging areas with innovative approaches, like by using renewable energy sources, digitalization of supply chains, and improving recycling capabilities, AM can play a key role in advancing sustainable manufacturing practices worldwide while meeting increasing demands in various technology industries.

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