Importance of Sustainable Product Design Through Additive Manufacturing Over Conventional Design

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Additive manufacturing (AM) is a process that fabricates components by adding material like plastic or metal layer by layer to obtain the required three-dimensional model. It is the reverse process of subtractive manufacturing, which involves cutting away a solid block of material into the required shape or size (Additive Manufacturing, Explained | MIT Sloan, 2017). According to Jayakrishna et al. (2023), additive manufacturing, also known as 3D printing, is a technology that has the potential to transform the manufacturing industry. It has enabled numerous advancements across various industries, including aerospace, automotive, healthcare, and consumer goods, due to its precision in producing complex and customized objects (p.p. 1-2). As industries worldwide face increasing pressure to reduce their environmental impact, sustainable manufacturing practices have gained significant attention.

Sustainability, as defined by Lin et al. (2009), means meeting the needs of the present without making it harder for future generations to do the same. Product designers must consider the product's impact on the world throughout its entire lifecycle. They must understand customer desires and develop products that fulfill those requirements while safeguarding the capacity of future generations to satisfy their own needs (p. 1506).

The traditional design methods have many problems, such as geometrical complexity, problems with making the designs, not caring about sustainability, oversimplification, limited design freedom, and a higher starting cost compared to new technologies like additive manufacturing, which help make better use of materials and reduce waste. It also increases efficiency of traditional methods if it is combined with new technologies. As Gebisa and Lemu (2017) have noted, “design for additive manufacturing” (DfAM) significantly outperforms the previously used “design for manufacturing” (DfM). They also present new methods and techniques that stand out when compared to traditional manufacturing processes, which led to the growth of additive manufacturing (p.p. 725-728). This literature review explores the critical role of AM in promoting sustainable product design by addressing the following questions:

1. How can mechanical design engineers use additive manufacturing to reduce plastic waste in industry?
2. What are the best methods for designing products to reduce plastic waste?
3. How do sustainable design methods overcome conventional design methods?

Although it requires addressing challenges such as recycling costs and material integrity to fully realize its advantages over traditional design methods, the implementation of additive manufacturing in product design holds the potential to significantly reduce lifecycle expenses and promote the growth of the circular economy through the use of recycled materials.

How Can Mechanical Design Engineers Use Additive Manufacturing to Reduce Plastic Waste in Industry?

Mechanical design engineers play a crucial role in managing industrial plastic waste; the application of efficient design and manufacturing techniques for products will reduce plastic waste generated in manufacturing processes. Lange (2021) reported that about 12% of plastics are recycled worldwide, while the rest end up going to landfills and oceans (p. 15723). Industrial plastics make significant contributions to waste production. According to Ncube et al. (2021), the logistics and packaging sectors account for 50% of plastic waste, which includes items such as "drinking bottles, bottle caps, food wrappers, grocery bags, lids, straws, stirrers, and foam take-away containers" (p. 4). Landfills may retain plastic waste for an extended period, leading to fires, sewer blockages, pest infestations, toxic gas emissions, and disturbances in the food chain that pose significant challenges. This is a call to all design and production engineers, as well as business professionals in the industrial sector, to promote awareness regarding the urgent need for strict regulations and policies to effectively manage industrial plastic waste.

Based on the evidence gathered to date, it is evident that the issue of unrecycled plastic waste represents a significant challenge for researchers in the field. It is now necessary to seek solutions that will gradually eliminate the problem. Failure to act will only worsen the situation and result in significant issues that contribute to environmental pollution. Additive manufacturing provides a solution by encouraging the direct recycling of plastic materials within the manufacturing process.

Engineers can use recycled plastic in 3D printing to produce prototypes, models, and final products, significantly lowering the amount of plastic waste that ends up in landfills. Additionally, additive manufacturing makes it easier to make highly optimized, light parts that use less material overall, which reduces plastic waste even more. By applying “design-for-additive manufacturing” (DfAM) principles, engineers can optimize material utilization and reduce plastic waste produced during manufacturing. When implemented across various industries, these practices might minimize the environmental consequences of plastic waste while preserving the performance and quality of final products (Gebisa & Lemu, 2017).

What Are the Best Methods for Designing Products to Reduce Plastic Waste?

The design phase is crucial in minimizing plastic waste and ensuring the sustainability of the manufactured products. Researchers have identified various methods to optimize materials used in additive manufacturing. Babagowda et al. (2018) claimed that fused deposition modeling (FDM) yields beneficial features for polylactic acid (PLA) filament used for 3D printing. Their experiments reveal that mixing virgin PLA filament with recycled PLA materials in specific ratios was outlined in a table, which provides precise data for determining the optimal mixture ratio, resulting in enhanced products suitable for additive manufacturing (p. 6). Manufacturers can reduce their reliance on virgin materials while maintaining product quality by incorporating recycled PLA, a significant development given the widespread use of PLA in 3D printing.

Maldonado-García et al. (2021) conducted an additional study that introduced a composite material composed of a blend of 100% recycled high-density polyethylene (HDPE) and polypropylene (PP) plastics, as well as soy-hull-derived biocarbon. The mechanical properties of the 3D-printed composite material specimens were superior, as evidenced by a 34% increase in Young's modulus obtained through fused filament fabrication (FFF). Ultimately, this enabled them to resolve the challenges they encountered during their investigation (p. 15). This method illustrates the potential of utilizing recycled materials to manufacture high-performance, durable components while simultaneously minimizing the environmental impact of the manufacturing process.

In a recent study, Mishra et al. (2023) proposed a method to enhance the quality of filament by adhering to “Table 1's recommended processing parameters for extrusion of recycled feedstock filament for 3D printing” (p. 761). They also provided numerous other tables and methods that explain how to implement these parameters and achieve superior material properties for filament. These methods enable the recycling of various thermoplastics, thereby promoting a circular economy by repurposing materials that would otherwise go to waste. Individuals can also contribute to the circular economy by using desktop 3D printing FDM-based printers at home, which can print toys, key chains, smartphone stands, pencil holders, bowls, and other easily designed products. By synthesizing the findings of numerous researchers and experts, the outlined methodologies aim to overcome the deficiencies in additive manufacturing, offering a comprehensive approach to address existing challenges.

How do Sustainable Design Methods Overcome Conventional Design Methods?

Sustainable design through additive manufacturing addresses many of the limitations associated with traditional manufacturing methods. Traditional methods, such as subtractive manufacturing, are often inefficient in terms of material use and generate significant plastic waste due to the removal of material from a solid block. In contrast, additive manufacturing allows for precise material deposition, resulting in less material waste and greater design flexibility.

According to Jayakrishna et al. (2023), additive manufacturing can be used in many areas of manufacturing, like supply chain optimization, customization and personalization, spare parts and aftermarket services, complex geometries and lightweight structures, prototyping, and product development (p. 2). One of the key advantages of AM is its ability to create complex geometries that would be difficult, if not impossible, to achieve with traditional methods. This capability allows designers to minimize material usage without compromising the strength or functionality of the product. For instance, the aerospace and automotive industries use AM to create lightweight, high-strength parts that reduce the overall weight of vehicles and aircraft, leading to fuel savings and lower carbon emissions. Additionally, the use of recycled materials in AM further supports sustainability efforts by decreasing the demand for virgin resources.

By creating durable products, the impact of plastic waste can be reduced, and industries can be encouraged to adopt recycled materials. They also discuss eight significant advantages of 3D printing, including improved accuracy and precision, faster production, reduced costs and waste, increased customization, design versatility, and rapid design and production. On the other hand, they list some problems with 3D printing, such as the high cost for recycling materials, structural issues, limited building sizes, design flaws, and health and safety risks and limitations related to mass manufacturing (p.p. 15–16).

Further research is necessary to overcome these flaws. Gradually, the advantages surpass the limitations, resulting in a positive environmental impact. As the industry continues to evolve, the benefits of AM in sustainable design will likely outweigh the drawbacks, leading to a more environmentally responsible manufacturing process.

Conclusion

From the perspective of additive manufacturing technology, the implementation of sustainable designs addresses the limitations associated with traditional designs. The integration of design for additive manufacturing (DfAM), fused deposition modeling (FDM), and fused filament fabrication (FFF) with recycled plastics, such as ocean plastic composites with pyrolyzed soy hulls, PLA blends with recycled PLA, and recycled thermoplastics, enhances waste utilization, thereby reducing waste generation, promoting the circular economy, and improving sustainable product design. Additive manufacturing significantly reduces material waste and promotes the circular economy.

The findings underscore the potential of additive manufacturing to address environmental challenges and foster sustainability across various sectors. As a result, implementing sustainable product design through additive manufacturing is essential for minimizing the adverse impacts of plastic production and ensuring a more sustainable future.

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