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FENNTARTHATÓ DRÓNGYÁRTÁS: A GENERATÍV TERVEZÉS, AZ ADDITÍV GYÁRTÁS ÉS A KÖRFORGÁSOS GAZDASÁG INTEGRÁCIÓJA

SUSTAINABLE DRONE MANUFACTURING: INTEGRATION OF GENERATIVE DESIGN, ADDITIVE MANUFACTURING, AND CIRCULAR ECONOMY

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ABSTRACT

The rise of unmanned aerial vehicles in multiple sectors and the stricter environmental regulations initiate a growing need for sustainable design and manufacturing approaches in the drone industry.

The mass of components can be reduced using generative design, while the mechanical properties can be preserved or even improved. This optimization is useful in drones, where flight duration and payload capacity are important parameters. Generative design supported by additive manufacturing reduces raw material consumption, which is a key principle in the circular economy.

The aim of the paper is to explore how advanced technologies combined with circular principles can contribute to a more resource-conscious, sustainable future in drone manufacturing. These areas complement and enhance each other and together can form a powerful manufacturing solution that redefines engineering design while lowering environmental impact.

1. INTRODUCTION

As the technology advances, the use of drones (unmanned, remotely or autonomously controlled aerial vehicles) is further increasing. Nowadays, drones are used for many tasks, from precision agriculture to military operations [1]. In commerce, drones are revolutionizing traditional logistics systems: in 2024, the number of drone deliveries was 5 million, but this number is predicted to reach 808 million by 2034 [2]. As the usage of drones increases, the associated environmental issues are also on the rise.

According to the European Union's Circular Economy Action Plan, „*up to 80% of products' environmental impacts are determined at the design phase*" [3]. This emphasises that product design plays a crucial role in reducing resource use and creating a more sustainable future.

The aim of this paper is to explore the synergies between generative design, additive manufacturing, and circular product design principles in the context of drone manufacturing and to provide a conceptual framework.

First, generative design and additive manufacturing are defined, followed by the description of product design guidelines in circular economy, discussing in detail the advanced materials in the field of drones. Then, we analyse the synergies and possible integration of generative design and additive manufacturing with circular design principles in drone manufacturing. Finally, the current limitations and challenges are presented, pointing the way towards future research and innovation opportunities.

2. GENERATIVE DESIGN AND ADDITIVE MANUFACTURING

Generative design is an algorithmic design method that generates a large number of design solutions based on given input data as instructions and rules: constraints, loads, and performance goals, which are usually maximising strength or minimising weight. The steps of the generative design process are shown in Figure 1 [4].

Generative design is a genetic algorithm-driven process; genetic algorithms work similarly to selection and genetics observed in nature [5].

Generative design results in lightweight, organically structured parts with excellent mechanical properties. One of the most important goals in aerial vehicle design is to reduce mass. Lighter drone components improve flight performance, reduce power consumption, and thus extend battery life. Reducing energy consumption not only reduces operating costs but also supports sustainability. Generative design also promotes material efficiency by concentrating material only at structurally necessary points, reducing the raw material usage.

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Due to their unique geometry and complexity, parts created with generative design are typically made using additive manufacturing technologies. In traditional subtractive manufacturing, such as turning, material is removed from a solid mass to achieve the desired final shape. In contrast, additive manufacturing (AM) is a waste-saving production method, because it creates objects by combining material layer by layer [6].

The term *3D printing* refers to the process of building an object layer by layer. Additive manufacturing and 3D printing are often used interchangeably, but additive manufacturing refers to industrial applications and is a more complex process that includes postprocessing. There are different AM technologies; Figure 2 shows the core part of the fused deposition modelling (FDM) technology compared to subtractive manufacturing [7].

Because it enables the rapid and cost-effective production of unique parts, additive manufacturing is often used to reconstruct machine components thus produce replacement parts.[8].

The surface of the printed parts is staircase-like due to the layered structure, which results in poorer surface quality than if it had been made using subtractive technology [9]. Because of this, after the component is built up layer by layer, if necessary, post- processes can be performed to improve the surface quality. For example, in the case of FDM technology, this can be achieved by ironing post-processing, which can significantly reduce surface roughness [10].

The layered structure also weakens the mechanical properties, because the interlayer bonding is much weaker than the material structure within the layer. Since the new layer is placed on top of the previous, already solidified layer, the bond will not be as strong as in a homogeneous material. The mechanical properties of 3D printed objects are direction-dependent, they behave as a block of material within the layer, the bond along the layers is weaker, so they can separate from each other more easily. On the other hand, microscopic voids, defects and poorly adhered parts can form between the layers. These act as stress accumulation sites and promote the formation of cracks, and they appear quickly especially under dynamic loads.

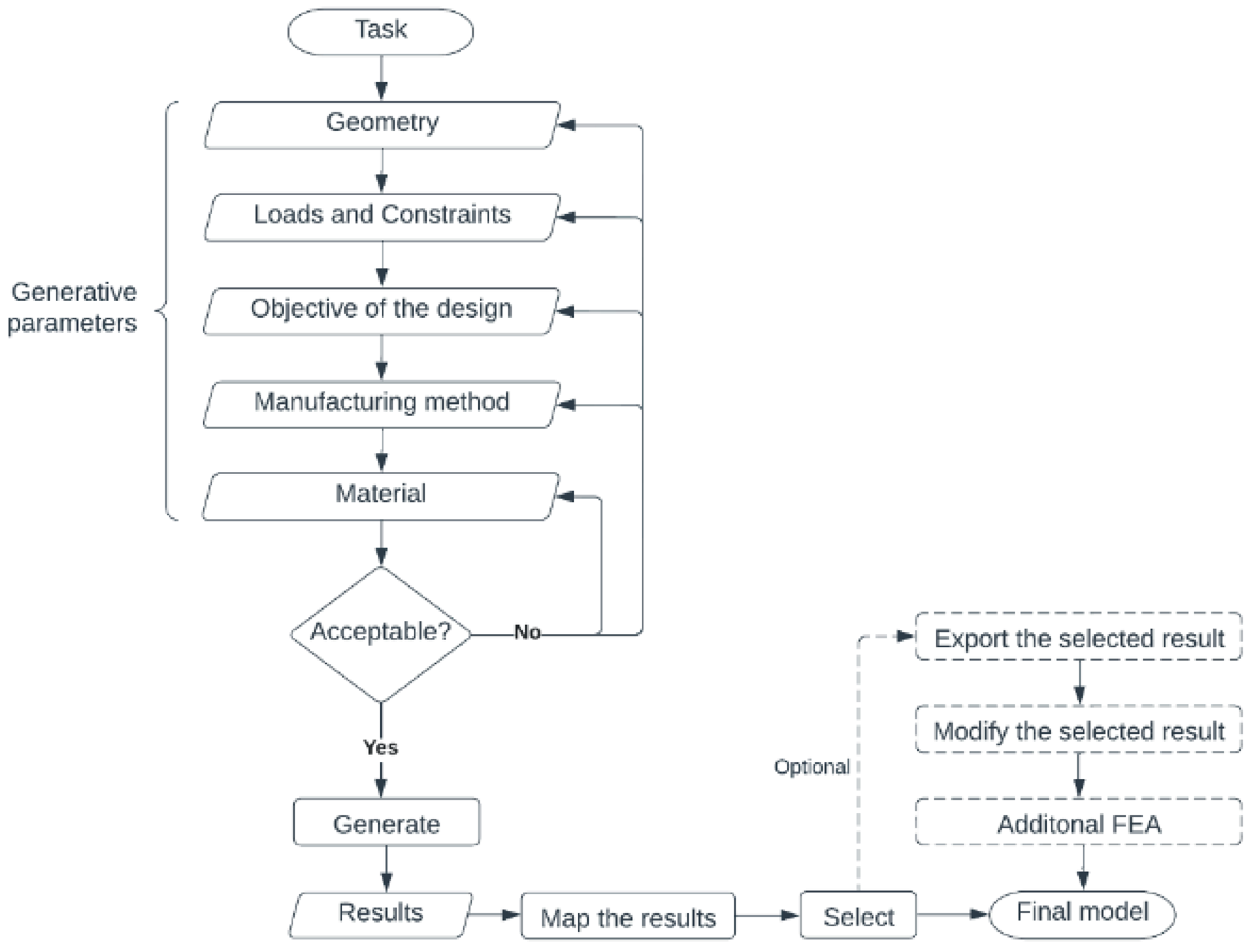

Figure 1. The process of generative design [4]

To solve these problems, it is very important to set the correct printing parameters and examine how they influence the mechanical properties.

The manufacturing challenges can be critical in industrial applications, for instance in the case of 3D printed gears they can affect the reliability and performance of the gears [11]. This draws attention to the fact that additive manufacturing has limits, and the production technology and material of the part must be selected with great care, in accordance with the application.

3. CIRCULAR PRINCIPLES

The circular economy (CE) differs from the traditional linear model of economy. The main goals of the circular economy are to reduce the use of primary raw materials and the loss of resources. The circular economy is a system-based model, called „circular", because it preserves the value integrated into products by keeping them in a closed loop for as long as possible.

Value preservation can be achieved through reuse, repurposing, repair and maintenance, recycling, refurbishment, remanufacturing and recovery.

3.1. Circular design principles

When applying the principles of the circular mindset to drone manufacturing, it requires drastic changes throughout the life cycle of the product, such as how materials are chosen, the design process, production methods, utilization, and management after the servicing life of the product.

Considering this, product design guidelines aligned with the goals of the circular economy can be summarised as follows:

Product life extension related principles:

- Creating durable products,
- Designing modular products,
- Designing products that are easy to maintain and repair,
- Designing products that can be easily upgraded,
- Designing products that can be easily disassembled and reassembled.

Material related principles:

- Incorporating recycled and/or recyclable materials,
- Designing for easy material recovery,
- Minimising material use with not completely filled internal areas,
- Minimising material use with proper geometry,
- Minimising material consumption by using advanced materials with improved mechanical properties.

In addition, the choice of manufacturing technology is also an important aspect. Circular guidelines require the use of energy-efficient and low-waste production technologies, and generative design combined with additive manufacturing fits well into these sustainable engineering principles.

3.2. Business model related principles

The circular economy model forces manufacturers to take responsibility for their products throughout the entire product life cycles. Manufacturers can support this by:

- Operating a service network,
- Creating repair manuals and tutorials for consumers,
- Producing spare parts,
- Operating return logistics systems,
- Ensuring the integration of waste into the secondary raw material stream.

3.3. Sustainable materials in drone manufacturing

Carbon fiber composites are now widely used in drone manufacturing due to their remarkable stiffness, durability, and strength-to-weight ratio.

However, the production of conventional carbon fibre requires a lot of resources and is challenging to recycle, which causes problems for the environment and the economy. Recent efforts have shifted toward utilising Recycled Carbon Fiber Composites (rCFCs) to enhance sustainability in drone design and production [12].

The RECICOM project is one of the most prominent efforts in this field. Its goal is to develop hydrothermal recycling methods for recovering high-quality carbon fibres from thermoset composite waste [12]. The mechanical qualities of the fibres can be preserved for use in new components by using this technique to separate the resin and fibres under controlled heat and pressure. Examples of non-structural and semi-structural drone components that can be repurposed from these recycled fibres include arms, landing gear, and housing panels. Their performance is sometimes comparable to that of virgin carbon fibres when used in non-woven or short-fiber mat formats [12]. Because they can retain 80 – 90 % of their initial mechanical strength, rCFCs are a good substitute for other materials. rCFCs not only provide advantages for the environment, but they are also cost saving alternatives. This is especially beneficial for drone producers who want to scale sustainably or who work under strict financial limits.

There are still difficulties, especially when it comes to preserving fibre alignment, scaling up recycling procedures, and guaranteeing matrix bonding homogeneity.

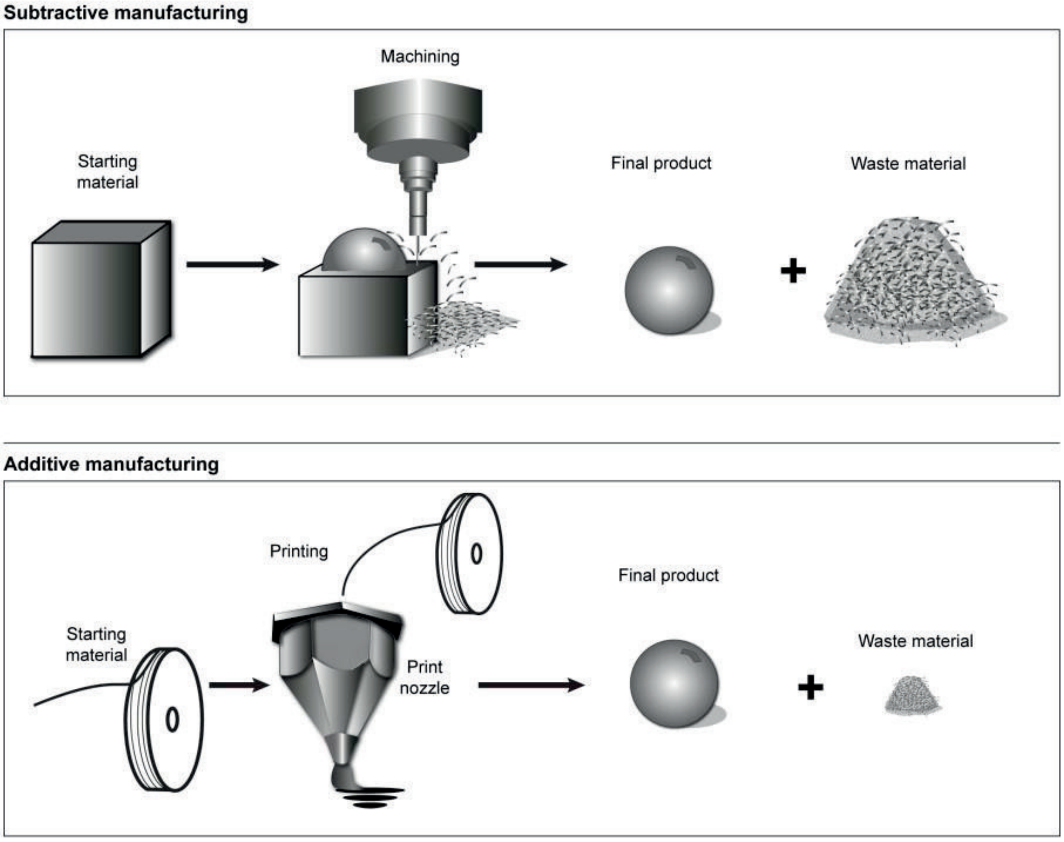

Figure 2. Subtractive and additive manufacturing [7]

However, these problems are progressively being lessened thanks to developments in preprocessing, automated layup, and material handling.

By encouraging material recovery, lifecycle extension, and a decrease in embodied energy, the incorporation of rCFCs into UAV production is in line with the concepts of the circular economy.

With a focus on incorporating recycled materials to lessen environmental effect, improve material efficiency, and advance sustainability, circular economy principles have progressively influenced drone manufacturing processes over the past five years.

Roboze, producer of industrial 3D printers, has a circular economy initiative: recycling broken or unused 3D printed parts into affordable filaments [13]. These types of initiatives support circular drone manufacturing at both ends of the raw material-production-use-waste cycle. On the one hand, it provides an opportunity to recycle the material of worn drone components, and on the other hand, it allows drone parts to be manufactured from recycled materials.

One major issue with drone systems is electronic waste. In 2024, a study presented vitrimer-based PCBs (vPCBs), which are recyclable, repairable, and physically and electrically stable [14]. The environmental impact of e-waste in drones can be reduced by using this type of PCB.

Bio-based and/or bio-waste-containing materials could be potential materials for sustainable drone production. Bio-based materials offer improved sustainability metrics due to their biodegradability. Furthermore, enriching bio-based polymers with nature-derived materials can even enhance mechanical properties, as demonstrated in a study, where a PLA matrix material containing hemp powder was produced for 3D printing: 3D printed specimens made of PLA/hemp composite showed a higher elastic modulus than pure PLA samples [15].

A peer review by Kordos et al. claims that the study tackles issues with UAV recycling, including the processing of complicated electronics and carbon fibre composites [16]. For smaller drones, it advises using biodegradable parts and switching to materials that are simpler to disassemble and recycle.

Vedrtnam et al. conducted a comprehensive life cycle assessment study that examines the environmental and energy impacts of several drone materials [17]. According to the findings, thermoplastic matrices and modular designs are thought to be crucial components for improving recyclability and reducing embodied energy.

4. SYNERGY BETWEEN GENERATIVE DESIGN, ADDITIVE MANUFACTURING AND CIRCULARITY IN DRONE MANUFACTURING

The combination of generative design, additive manufacturing, and circular economy principles offer a highly compelling opportunity for more environmentally friendly and efficient drone manufacturing by creating a sustainable design for manufacturing system. Each of these areas has an impact on sustainability on its own but pairing them maximises the sustainability outcome. This systems-based approach reduces the environmental impacts of drone products throughout their entire life cycle, thereby achieving the goals of the circular economy model.

Figure 3 illustrates the interactions between the three investigated areas. The overlapping areas in the diagram highlight the synergistic benefits of the integration.

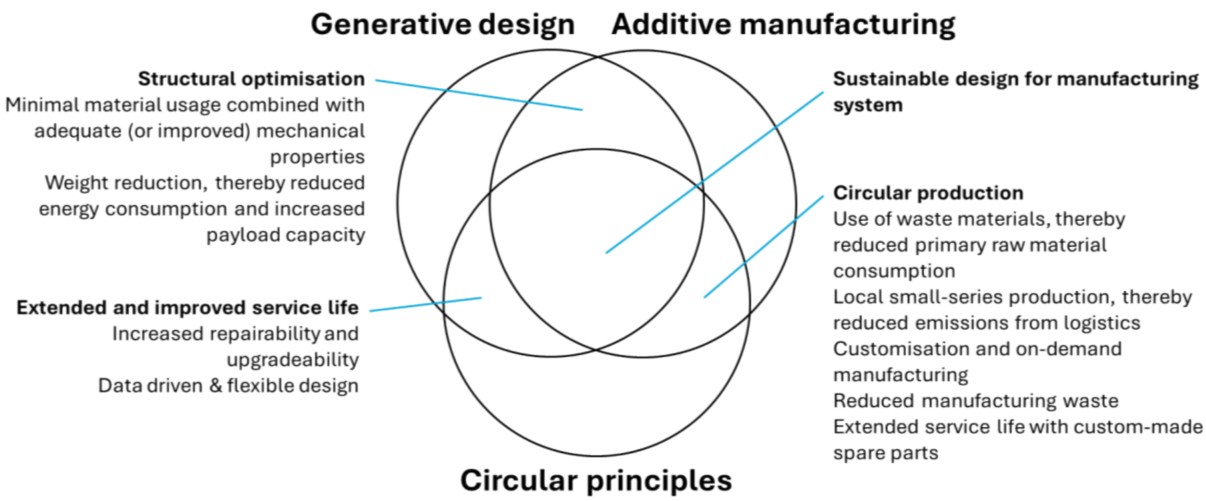

Figure 3. Intersections of generative design, additive manufacturing, and circular principles in drone production

Additive manufacturing can realize structurally optimized, weight-reduced, generatively designed parts with minimal material use and waste generation, increasing material efficiency. Weight reduction is not only carried out through structural optimization, but also through the possibility of creating hollow structures. Lightweight components designed with these considerations help reduce the energy consumption of drones, which can increase flight time and payload capacity.

Additive manufacturing also supports circular production, with the possibility of small-series, local production, thereby reduced environmental pollution from transportation. Additive manufacturing is a low-waste technology, that reduces manufacturing waste. The use of recycled materials can reduce the consumption of primary raw materials. This combination preserves the value stored in the material on both sides of the production cycle. Finally, service life extension can be achieved with additively manufactured custom-made spare parts.

Integrating circular principles into the generative design process could be a future goal and research direction. This can be accomplished, for example, by incorporating life cycle data or assembly/disassembly considerations into the design process.

5. SUMMARY

The emergence of drones in more and more industries makes it necessary to investigate their sustainability. The framework presented in this article can help to produce more environmentally friendly drone components.

The integration of generative design, additive manufacturing, and circular principles enables sustainable drone production and even the realization of a closed-loop, design for manufacturing system.

A continuation of the research could be the design and testing of drone components that fit this framework.

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