Industry Driven Analysis for AM Design and Green skills

Needs Analysis Report

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1. Purpose of this document

This document is the result from the collaborative effort of the members of the SINGforGREEN project. As part of the project's initial work, they conducted an initial identification of key aspects, aiming to explore the relationships between more sustainable production, advanced design techniques, additive manufacturing, and applicable training methodologies. This identification led to the development of a combined framework of topics and subtopics to be addressed as part of a review of the state-of-the-art concepts and tools within the identified areas. The purpose of this task is to establish a foundation of the various concepts and fields of knowledge potentially involved in the creation of future training materials, aiming to enable individuals undergoing training in additive manufacturing to internalize the concept of sustainability and implement it at both conceptual and technical levels.

2. Initial thoughts on sustainability, additive manufacturing and design

Concepts such as sustainability, circularity, green economy or similar are "usual talk", in a context in which awareness of the impact of human activity on the environment is growing in our societies. While these concepts are simple to understand in their most basic aspects, their implementation is not straightforward. Human activity as a whole can be seen in this sense as a set of processes, through which we consume energy and raw materials, and which can in turn lead to the generation of waste and emissions. Thus, all this activity can be seen as a "balance", where the objective is to reduce/absorb the net impact on the environment.

There is no doubt that, for this to be possible, industrial activity as a whole is the most critical "actor", as this area is mainly responsible for most of the impact generated by human activity. Thus, society's demand for products and services is satisfied through a whole series of industrial processes, which are the main consumers of resources and cause environmental impact. Reducing the impact of this industrial activity is therefore a key element of sustainability.

In any case, it must be borne in mind that, from an operational point of view, there are very different industries and sectors, and that beyond general prescriptions for increasing the sustainability of a process (consuming fewer resources and energy, increasing the recyclability of materials, recovering waste, etc.), it is not possible to establish "universal" technical measures, valid for any industrial process. However, this task can be tackled if we try to be a little more specific, and focus for example on manufacturing activities, that is, industries that transform raw materials into products.

In this field, which is precisely the main focus of ***SINGforGREEN***, additive manufacturing is currently playing a fundamental role from a technical point of view, as it allows us to tackle technical alternatives that would be unthinkable just 10 or 15 years ago. From a sustainability point of view, the use of additive manufacturing is not a mere substitution of one manufacturing technology for another, but its "upstream" and "downstream" repercussions can be very important as well. Thus, in a basic analysis of the issues that are relevant to the sustainability of products that can be supported by the use of additive manufacturing technologies, we can distinguish the following:

- **Relationship in the selection of an additive manufacturing technology and the modification of "upstream" and "downstream" processes.** The selection of an additive manufacturing technology does not only involve the substitution of one manufacturing process for another. Obvious modifications are the change in raw materials (type and quantity), recyclability of raw materials needed but not used in manufacturing, ability to generate designs that can be lighter, more durable or more efficient products, recyclability of materials once the product reaches the end of its life, etc.

- **Global concept of the product life cycle.** This concept is not exclusive to products developed through additive manufacturing technologies, but transcends any technology, product, field or sector. From a sustainability point of view, the product is not only understood as the cost/impact of its very manufacturing stages, but as a process that potentially begins with the extraction of the raw materials (what impact has the extraction and production of raw materials generated in the necessary format and quantity?), and can comprehend up to product lifespan and disposal (is the product manufactured through additive manufacturing more durable? does it consume less energy or consumables? does it require less maintenance? is it more easily recyclable/valuable when it has reached the end of its life?).

- **Specific knowledge of the development cycle associated with additive manufacturing.** The ability of this technology to reduce steps to move from the design to prototype and product stages is well known, but a deeper understanding of the particularities of the use of these technologies in the fields of design, development and testing allows further optimisations to be achieved.

- **Differentiation between additive manufacturing technologies.** Additive manufacturing is not a technology but a concept, based on the "layer-by-layer" manufacturing principle. This concept can be implemented through various technologies, which share the same principle but are radically different in terms of aspects that are relevant to design, manufacturing and sustainability. It is therefore important to know the particularities of each technology, as the differences can be very relevant.

- **Knowledge of raw materials for additive manufacturing.** Linked to the different technologies, each of them has the capacity to process materials of different nature and format. As a whole, additive manufacturing technologies have the capacity to process metals, polymers, ceramics, etc., but it is necessary to bear in mind that each technology demands different types of materials and processes them in different ways, which not only conditions the post-processing stages, but also gives rise to very different processes for obtaining and recycling (if possible) these raw materials.

- **Knowledge of design techniques particularly suitable for use in conjunction with additive manufacturing technologies.** Additive manufacturing is helping to overcome previous limitations in the field of design, where the possibility of manufacturing an object from a 3D file provides unparalleled possibilities. Techniques such as topological optimisation, generative design, lattice structures, etc., have the potential to result in products that not only make more rational use of raw materials, but are also able to perform better during their life cycle. The most obvious examples of this are the application of these design and manufacturing methodologies in sectors such as aerospace, where weight reduction is a known driver for lowering aircraft fuel consumption, in systems that are also designed to fly for decades.

- **Knowledge of techniques for identifying and accounting for impacts.** Unfortunately, most of the times the concept of sustainability is brought into conversation, it is handled in an excessively general or partial way, leading to preconceptions (positive or negative). As in any other field, analysis and evaluation are only possible if there is measurement in between, and this also applies to the field of sustainability. There are tools and databases that help to identify, quantify and calculate the impacts of a process/product, and these can be used to make a comparative and objective assessment between different manufacturing options. It is again necessary to bear in mind that a product, from the point of view of sustainability, is not so much the product itself, but its entire life cycle.

The aforementioned aspects make up an "amalgam" of wide-ranging and in certain points certainly complex knowledge. Although this can be covered by different professional profiles within the whole product chain, perhaps the most relevant one is that of the designer. The designer not only determines what must be manufactured, but has the potential to affect all the product chain:

- It conditions the selection of the manufacturing process, which in turn results in the consumption of a certain amount of energy and raw materials during the process.
- The selection of the manufacturing process, in turn, conditions the applicable post-processes.
- With the above, the designer conditions as well the selection of materials and raw materials, both in terms of format and quantity. This also conditions whether materials or raw materials not directly used in the manufacturing process can be (or not) reintroduced into the manufacturing process.
- The designer is key to the characteristics of the product, and is therefore decisive in aspects such as its weight, the life span of the product, its need for energy or other resources for its use, the ease of separating parts and materials for recycling once the product has reached the end of its use, etc.

- A design can even have an impact on the way products are shipped, as long as the manufacturing process can determine the implementation of central or distributed production systems.

Thus, although it is not the only profile with the capacity to influence the sustainability of a product, the designer has a totally critical role in the final sustainability of a product, and that is why the ***SINGforGREEN*** project makes this profile a central element. The intention of ***SINGforGREEN*** that professionals working in this field who want or are making use of additive manufacturing technologies can incorporate the sustainability variable from an operational point of view, far from preconceptions or generalisations.

The previous body of knowledge, which is eminently technical, must also be complemented with more general knowledge: general concept of sustainability, "green" competences, ethics in the use and consumption of resources, regulations associated with sustainability and eco-design, modern tools for learning about the aforementioned technical aspects, etc.

Based on this reasoning, the members of the ***SINGforGREEN*** project have tried to break down the topics listed in this section, as a means to detect and analyse the interactions between the concepts of design, additive manufacturing and sustainability, as a preliminary step for the future identification of a training curriculum in these areas, and the subsequent development and testing of appropriate training content.

We hope that you find this section of the document illustrative and enjoyable.

3. General concepts and context about Sustainability

3.1 Sustainability

3.1.1 Sustainability in the Industrial Context

In today's rapidly evolving industrial landscape, the concept of sustainability has transcended its environmental origins to become a cornerstone of strategic business planning and operational efficiency. The industrial sector, historically characterized by its significant environmental footprint due to resource-intensive operations and substantial waste generation, is now at a pivotal juncture. The drive for sustainability is not just a reaction to regulations or environmental activism, but a necessary strategy for long-term survival, risk mitigation, and the possibility of innovation and competitive edge.

The importance of implementing sustainable practices in industrial sector cannot be overstated. As global resources continue to diminish and the effects of climate change become increasingly apparent, industries are being forced to rethink their operational models. Sustainable practices offer a pathway not only to minimize environmental damage but also to enhance resource efficiency, reduce costs, and improve brand reputation. Furthermore, they align with the growing consumer demand for environmentally responsible products and services, thus opening new markets and opportunities for growth.

In the industrial context, sustainability is defined as the practice of managing enterprises and manufacturing processes in a manner that addresses current environmental, economic, and social needs without compromising the ability of future generations to meet their own needs.[1] It represents a holistic approach that seeks to integrate considerations for the natural environment, economic viability, and social equity into the operational strategies of industrial firms.[2] This approach stands in contrast to the traditional linear economic model characterized by a "take, make, dispose" mentality, advocating instead for a circular economy model where resources are utilized more efficiently, waste is minimized, and the lifecycle of materials is extended.[3]

The significance of sustainability within the industrial sector is profound and multifaceted. Industrially driven activities are among the leading consumers of natural resources and contributors to environmental degradation, through emissions, waste production, and water usage. By adopting sustainable practices, industries can significantly reduce their environmental footprint, conserving biodiversity and protecting

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[1] United Nations Sustainability. Link

[2] Hariram NP, Mekha KB, Suganthan V, Sudhakar K (2023) Sustainalism: An integrated socio-economic-environmental model to address sustainable development and sustainability. Sustainability 15:13-10682. Link

[3] Vogiantzi C, Tserpes, K (2023) On the definition, assessment, and enhancement of circular economy across various industrial sectors: a literature review and recent findings. Sustainability, 15:23- 16532. Link

ecosystems for future generations. Moreover, sustainability offers tangible economic benefits. Efficient resource use, waste reduction, and innovation spurred by sustainability initiatives can lead to substantial cost savings, while simultaneously opening new markets for green products and enhancing competitiveness.

Furthermore, sustainability is critical for ensuring regulatory compliance and effective risk management. As European Commission Europewide tighten environmental regulations such as European environment policy or Ecodesign for Sustainable Products Regulation (ESPR)[4] sustainable practices help industrial entities meet these legal requirements, thereby avoiding potential fines, sanctions, and operational disruptions. Beyond compliance, sustainability enhances a company's reputation, aligning with the growing consumer demand for responsible business practices and contributing positively to a brand's public image and consumer trust.

The move towards sustainability is also a catalyst for innovation, driving the development of new products, services, and processes that not only reduce environmental impact but also provide a competitive advantage in the marketplace. Additionally, the industrial sector's efforts to embrace sustainability are pivotal in the global fight against climate change, through measures aimed at reducing greenhouse gas emissions and implementing strategies for adaptation.

Importantly, sustainable industrial practices ensure that the benefits of economic development are equitably distributed, fostering social equity and improving the quality of life in communities worldwide. This approach to industrial operation emphasizes not just the ethical imperative of sustainability but also its role as a comprehensive strategy that secures long-term business viability, environmental preservation, and societal well-being.

The integration of sustainability within the industrial sector presents a complex mix of challenges and opportunities. On one hand, adopting sustainable practices can be difficult due to the initial costs of green technology investments, retrofitting existing systems for improved environmental performance, and the need for skilled personnel to manage and implement sustainability initiatives. Regulatory pressures and market demands for sustainability also present challenges in terms of compliance and keeping pace with evolving standards. On the other hand, the push towards sustainability opens up numerous opportunities for innovation and competitive advantage. Companies can achieve cost savings through resource efficiency, waste reduction, and energy conservation, while also tapping into new markets driven by consumer demand for sustainable products.[5] The shift towards a circular economy model further presents

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[4] European Commission. (2022). Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. Link

[5] Barros MV, Salvador R, do Prado GF, de Francisco AC, Piekarski CM (2021) Circular economy as a driver to sustainable businesses. Cleaner Environmental Systems, 2 -100006. Link

opportunities for businesses to redefine value creation through closed-loop processes and services that extend product lifecycles and reduce environmental impacts. Moreover, embracing sustainability can enhance corporate reputation, attract investment, and foster stronger relationships with stakeholders. Ultimately, the successful integration of sustainability in the industrial context requires a balanced approach to navigating these challenges while seizing the opportunities to build resilient, efficient, and environmentally responsible operations.

Integrating sustainability into industrial operations involves embedding environmental, economic, and social considerations into the core business processes and decision-making frameworks of industrial entities. This integration is crucial for transitioning towards more sustainable production methods, which not only mitigate environmental impacts but also enhance economic performance and contribute to social well-being.[6] The process begins with the assessment of current operations to identify areas where sustainability improvements can be made, such as energy use, waste management, resource efficiency, and the health and safety of workers. Industries then adopt practices like using renewable energy sources, recycling materials, and implementing more efficient production techniques to reduce waste and emissions. Sustainability integration also involves redesigning products from the outset to minimize environmental impact, known as eco-design, and adopting circular economy principles. This might include creating products that are easier to repair, upgrade, or recycle, thereby extending their lifecycle and reducing waste.

In addition to operational changes, integrating sustainability requires a cultural shift within the organization. This involves training employees at all levels to understand and commit to sustainability goals, as well as engaging stakeholders such as suppliers, customers, and local communities in these initiatives. Technological innovation plays a key role, with advancements in green technology offering new opportunities to improve sustainability. Digital tools like the Internet of Things (IoT) and big data analytics can optimize resource use and energy consumption, while innovative materials can replace those that are hazardous or non-recyclable.

3.1.2 Beyond the Impact of the Manufacturing Process: Product Lifecycle

Understanding the stages of a product lifecycle is fundamental for businesses aiming to enhance performance, ensure sustainability, and secure profitability. The lifecycle of a product encompasses its journey from the drawing board to disposal, each phase presenting unique attributes and challenges. It begins with the concept and design phase, where market needs are identified, and products are conceptualized to meet these needs (see *Figure 1*)[7]. This early stage is critical for integrating sustainability

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[6] Embedding Sustainability in Corporate Strategy: Benefits, Challenges, and Success Stories. Link

[7] Lenar K (2023) Establishing a product life cycle: the crucial design phases in the ideation stage. Link

through eco-design principles, aiming to minimize the product's environmental impact throughout its life.

Figure 1: Product lifecycle[8]

Following concept and design, the product enters the raw material extraction and sourcing stage, involving the procurement of necessary materials. Sustainable practices here include choosing recyclable, renewable, or sustainably sourced materials and considering the environmental effects of the extraction processes.[9] The manufacturing and production phase then transforms these materials into the final product. Emphasizing efficiency and sustainability, this stage focuses on reducing waste, conserving energy, and minimizing emissions through lean manufacturing processes and the use of eco-friendly materials and technologies.[10]

Once the product is ready, it moves to the distribution and logistics phase, where it's packaged, stored, and transported to retailers or directly to consumers. Optimizing logistics for fuel efficiency, minimizing packaging materials, and reducing the transportation methods' carbon footprint are central to sustainability at this stage. The use and operation phase sees the product in the hands of the consumer, where designs that promote energy efficiency, durability, and repairability are key to extending the product's lifespan and reducing the need for replacements.

Maintenance and repair play a crucial role in prolonging product usability, emphasizing the importance of designing products for easy repair, providing spare parts, and offering maintenance services to decrease environmental impact. Finally, the product reaches its end-of-life stage, where it's disposed of, recycled, or reused. Sustainable practices involve designing products for easy disassembly, creating take-

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[8] Philips Innovation. Link

[9] Ljungberg LY (2007) Materials selection and design for development of sustainable products. Materials & Design, 28:2-466-479. Link

[10] How to Apply Design for X (DFX) Principles in Product Engineering. Link

back schemes, and exploring opportunities for reuse or repurposing, embodying circular economy principles to keep resources in use for as long as possible and regenerate products and materials at the end of their service life.[11]

By comprehensively understanding these lifecycle stages, companies can pinpoint sustainability improvement opportunities, develop strategies to lessen environmental impact, and align with the increasing consumer demand for environmentally responsible products, all while reducing costs and contributing to a sustainable future.

3.1.3 Circular Economy

The circular economy represents a shift in economic activity, moving away from the traditional linear model of 'take, make, dispose'. It aims to redefine growth by focusing on positive society-wide benefits. The circular economy model is shown in *Figure 2*. The circular economy operates on three core principles:

1. **Design Out Waste and Pollution:** By rethinking how resources are harvested, used, and disposed of, the circular economy seeks to design systems that prevent waste and pollution from being created in the first place.

2. **Keep Products and Materials in Use:** This principle focuses on designing products for durability, reuse, remanufacturing, and recycling, ensuring that they can be continuously circulated in the economy without entering the waste stream.

3. **Regenerate Natural Systems:** Unlike the linear model that often degrades natural resources, the circular economy emphasizes enhancing natural systems through practices that restore and rebuild environmental health and resilience. These principles aim to transform a linear system into a circular one, emphasizing the retention of value in the form of energy, labour and materials.[12]

The circular economy model offers several advantages over traditional linear models. Economically, it can lead to significant cost savings for businesses through efficient resource use and by transforming waste into a resource. Environmentally, it greatly reduces the negative impacts of production and consumption by minimizing waste and conserving natural resources. Socially, it has the potential to create new job opportunities in sectors related to recycling, remanufacturing, and product service systems, contributing to a more sustainable and equitable economic system.[13]

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[11] Circular economy introduction. Link

[12] Circular economy: definition, importance and benefits. Link

[13] Elisha OD (2020) Moving beyond take-make-dispose to take-make-use for sustainable economy. Int. J. Sci. Res. Educ, 13:3-497-516. Link

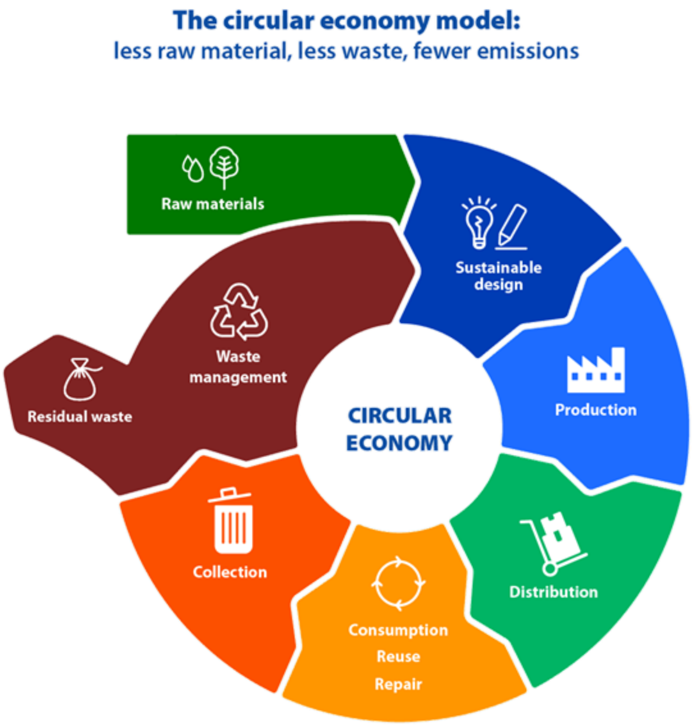

Figure 2: The circular economy model

Industries can implement circular economy practices through various strategies. One of these strategies is through product design as developing products with circular principles in mind, such as modularity, repairability, and materials that are easy to recycle or biodegrade will contribute to circular economy.

3.1.4 Digital Product Passport

The European Union's Digital Product Passport (DPP) represents a groundbreaking initiative aimed at enhancing sustainability and transparency across product life cycles and supply chains. Envisioned as a comprehensive digital platform, the DPP provides detailed information about products' environmental footprint, composition, origin, and recycling instructions, accessible throughout the product's life cycle. This initiative aligns with the broader goals of the EU's Circular Economy Action Plan[14], intending to facilitate the transition towards a circular economy by ensuring products placed on the EU market are increasingly sustainable and circular.[15]

The benefits of the Digital Product Passport extend beyond regulatory compliance and consumer information, playing a crucial role in enhancing the sustainability and transparency of supply chains. It enables better tracking of materials and components, thus facilitating the reuse, recycling, and recovery of products. This

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[14] Circular economy action plan. Link

[15] Neligan A, Schleicher C, Engels B, Kroke T (2023) Digital product passport as enabler for the circular economy. Link

comprehensive tracking system aids in identifying inefficiencies and opportunities for improvement in product design and manufacturing processes, encouraging the adoption of more sustainable practices from the design phase. Furthermore, the DPP fosters greater collaboration among stakeholders across the supply chain, promoting the sharing of best practices and innovation in sustainable product design.

In essence, the EU Digital Product Passport serves as a cornerstone in the EU's strategy to promote a circular economy, embodying the principles of transparency, sustainability, and consumer empowerment. Its role in redefining product design and supply chain practices marks a significant step towards achieving a sustainable market where economic activities are in harmony with the planet's ecological boundaries.

The challenges associated with product disposal and waste management are multifaceted and significant, stemming from the ever-increasing volume of waste generated by contemporary consumption patterns and the complexity of modern products, which often contain materials that are difficult to recycle or hazardous to the environment (Perkumiené, 2023)[16]. The ethical disposal of products has thus become a critical concern, as improper waste management practices can lead to severe environmental pollution, harming ecosystems and human health. Ethical disposal practices are crucial not only for minimizing the environmental impact of waste but also for conserving resources by enabling the recovery and recycling of materials. They ensure compliance with regulatory standards, protect brand reputation, and meet the growing consumer demand for responsible corporate behaviour.

In response to these challenges, industries are exploring innovative approaches to waste management, aiming to reduce waste generation and enhance the efficiency of recycling processes. One such approach is the adoption of circular economy principles, which encourage the design of products with their end-of-life in mind, facilitating disassembly and material recovery. Advanced recycling technologies, such as chemical recycling, offer new possibilities for processing materials that were previously considered non-recyclable.[17] Additionally, industries are implementing extended producer responsibility (EPR) schemes, where manufacturers take on the responsibility for the entire lifecycle of their products, including disposal and recycling. Digital tools, like the EU Digital Product Passport, are emerging to improve traceability and information sharing across the product lifecycle, supporting better waste management practices.

These innovative approaches reflect a broader shift towards sustainability in industries, recognizing that effective waste management is not only an environmental

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[16] Perkumienė D, Atalay A, Safaa L, Grigienė J (2023) Sustainable waste management for clean and safe environments in the recreation and tourism sector: a case study of Lithuania, Turkey and Morocco. Recycling, 8:4-56. Link

[17] Closing the Loop: The Gap in the Circular Economy. Link

imperative but also an opportunity to create value and drive economic growth.[18] By embracing ethical disposal practices and investing in innovative waste management solutions, industries can contribute to a more sustainable future, mitigating the environmental impacts of waste and fostering a more circular economy.

The United Nations Sustainable Development Goals (SDGs) constitute a global blueprint adopted to eradicate poverty, protect the planet, and ensure prosperity for all as part of a new sustainable development agenda.[19] Each of the 17 SDGs, with their 169 targets, provides a comprehensive framework addressing the critical environmental, social, and economic challenges facing the world today. For the industrial sector, aligning practices with the SDGs is not just a matter of corporate social responsibility but a strategic imperative that underscores the interconnectedness of industrial activities with global sustainability objectives. This alignment is crucial as it enables industries to contribute effectively to combating climate change, conserving natural resources, ensuring equitable economic growth, and fostering innovation for sustainable solutions. By integrating SDG principles into their operations, industries can drive positive change, enhancing their resilience, opening up new markets, and building a sustainable competitive advantage, all while playing a pivotal role in achieving the ambitious targets set for a more sustainable and equitable global future.

3.2 General Green Competencies for AM Designers

For an employee working in additive manufacturing as a designer, cultivating a suite of competencies that align with sustainability can significantly enhance the contribution to both the industry and the broader environmental goals. These competencies integrate deeply with the principles of sustainable design, ensuring that products not only meet current needs but do so without compromising the ability of future generations to meet theirs. Here’s how these competencies unfold in the context of AM:

- **Promoting Nature through Nature-Based Solutions:** In additive manufacturing, incorporating nature-based solutions means leveraging biomimicry and natural processes to innovate in product design and manufacturing processes. Designers can draw inspiration from the efficiency and resilience of natural systems, leading to solutions that minimize waste and energy use while enhancing the functionality and lifecycle of products.[20]

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[18] Circular Economy: A Sustainable Solution for Effective Waste Management. Link

[19] Sustainable Development Goals. Link

[20] Kennedy, E. B., & Marting, T. A. (2016). Biomimicry: Streamlining the Front End of Innovation for Environmentally Sustainable Products: Biomimicry can be a powerful design tool to support sustainability-driven product development in the front end of innovation. Research-Technology Management, 59(4), 40-48. Link

- **Critical Thinking to Evaluate Environmental Impacts:** A designer with strong critical thinking skills can assess the environmental impacts of design choices, from the selection of materials to the manufacturing process itself. This involves evaluating the sustainability of different materials, understanding the energy consumption of manufacturing processes, and considering the product's end-of-life, aiming to minimize negative environmental impacts.[21]

- **Futures Literacy for Anticipating Trends:** Futures literacy empowers designers to anticipate and adapt to trends, technologies, and regulatory changes that could impact additive manufacturing. By staying informed about potential future scenarios, designers can proactively incorporate sustainable practices and materials that align with emerging trends and expectations.[22]

For designers in additive manufacturing, developing these competencies is not just about enhancing personal skill sets but also about contributing to the industry's transition towards more sustainable practices. By embedding these principles into their work, designers can play a pivotal role in shaping a future where industrial processes are harmonious with our planet's ecological systems. Besides these soft skills, there are also technical green competence useful for designers especially working in AM sector:

- **Life Cycle Assessment (LCA) Knowledge:** Understanding the environmental impacts of products throughout their entire life cycle—from raw material extraction through manufacturing, use, and end-of-life disposal or recycling—is crucial. This knowledge allows designers to make informed decisions that minimize negative impacts on the planet.[23]

- **Material Science Expertise:** A deep understanding of both traditional and emerging materials, including their environmental impact, recyclability, and life cycle performance. This enables designers to select the most appropriate and sustainable materials for their projects.[24]

- **Energy Efficiency Understanding:** Knowledge of how to design products and components that require less energy to manufacture, use, and dispose of. This includes understanding energy-saving manufacturing processes and designing products that consume less energy during use.[25]

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[21] How can you evaluate environmental impact when planning projects? Link

[22] Ngida S (2023) Sustainable Product Design: Balancing Functionality and Environmental Impact. Link

[23] Bashyal J (2023) Life Cycle Assessment (LCA): 4 Phases, Importance, Limitations. Link

[24] Shahhoseini, A., Heydari, S., & Pedrammehr, S. (2023). Manufacturing and Assembly for the Ease of Product Recycling: A Review. Designs, 7(2), 42. Link

[25] Energy Efficiency: Buildings and Industry. Link

- **Water Stewardship:** Awareness of water usage and conservation within the manufacturing process, as well as designing products that minimize water consumption throughout their life cycle, is an increasingly important competence as water scarcity becomes a more pressing global issue.[26]

- **Digital Proficiency:** Proficiency in digital tools and platforms that support sustainable design, such as CAD software for efficient material use, platforms for sharing and collaborating on circular economy solutions, and tools for simulating product performance and environmental impact.

- **Regulatory and Standards Knowledge:** Staying informed about relevant environmental regulations, standards, and certifications can guide sustainable design practices and ensure compliance. This includes international, national, and industry-specific environmental standards.

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[26] Advancing water stewardship. Link

4. Additive Manufacturing: a process perspective

This chapter explores Additive Manufacturing (AM) as a process. It presents a general AM knowledge, introducing basic, most used AM and 3D technologies. This part is divided in three parts, unpacking the i) design for process chain, the ii) design for additive manufacturing, the iii) selection of materials and post-processing. In light of conversations throughout this report on useful sustainability tools, such as the EU digital product passport or the Life Cycle Assessment, the second part of this chapter focuses on other processual sustainability methods. Specifically, it explores sustainable methods of production for additive manufacturing, covering topics like include, the i) role and definition of relevant standards, ii) the design for disassembly-design for repair and end of life, and iii) the ethical product disposal and waste management. The third and final installment of the chapter explores industrial applications within the context of sustainable manufacturing/post-processing, highlighting examples and case-studies where applicable.

4.1 Additive Manufacturing Knowledge

"Additive manufacturing," is a term encompassing a range of different technologies.[27] According to ISO/ASTM 52900, "process of joining materials to make parts layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies".[28] The technologies are categorized below based on the most fundamental manufacturing concepts, according to [29] and [30].

4.1.1 Material Extrusion Process

Material Extrusion, or MEX for short, is the most widely used type of 3D printing. MEX is the process of extruding material through a nozzle. The material is usually a plastic filament that is pushed into a heated nozzle, almost melting it in the process. Following a path specified by the build preparation software, the printer deposits the material on a build platform. A solid object is then formed when the deposited material cools and solidifies. Although this technology has been based on using plastic materials, it is a viable technology for the deposit of various kinds of materials that can be fluidly injected and then solidified. As a result, bio-printing—the 3D printing of items including food, bioabsorbable polymers and concrete also uses this technique.

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[27] Santos Gonzales, D. and Gonzalez Alvarez, A. (2018). Additive Manufacturing Feasibility Study & Technology Demonstration: EDA AM State of the Art & Strategic Report. [online]. Link

[28] ISO/ASTM 52900:2021 Additive Manufacturing – general principles – fundamentals and vocabulary.

[29] What are the 7 Types of Additive Manufacturing Technologies? Link

[30] About Additive Manufacturing. Link

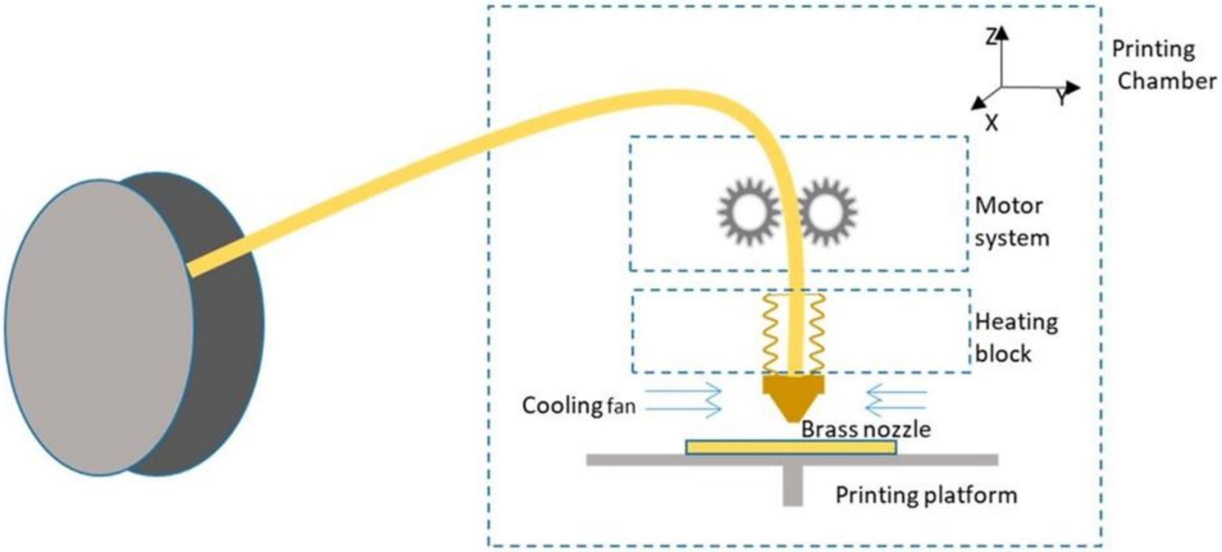

Figure 3: MEX Technology Operating Principle

4.1.2 Vat-photo-polymerization

Vat polymerization, or resin 3D printing, is actually a family of 3D printing techniques that selectively cures - or hardens - photopolymer resin using a light source. Photopolymers are light-responsive polymers. To harden the resin, light is precisely directed towards a particular spot or portion of the material in accordance with the corresponding slice of the 3D model. Depending on the machine being used, the build platform is either raised or lowered by the height of a single layer to generate subsequent layers. This process is continued until the desired 3D part is achieved.

Following the completion of the 3D printing process, the part is cleaned to get rid of any leftover liquid resin and post-cured to improve the part's mechanical qualities (either in a UV chamber or outside). Without these post-printing procedures, the part is not functional. Stereolithography (SLA), digital light processing (DLP), and liquid crystal display (LCD), sometimes referred to as masked stereolithography (MSLA), are the three most used vat polymerization techniques. The light source and the method by which it cures the resin are the primary distinctions between various kinds of 3D printing technologies.

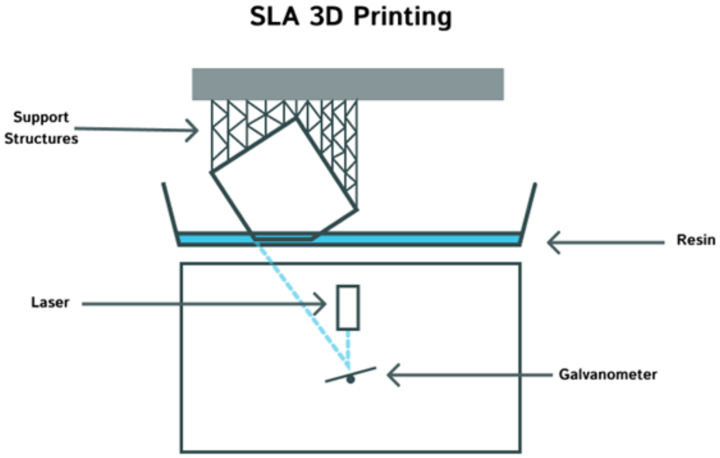

Figure 4: SLA Technology Operating Principle

4.1.3 Material Jetting

With material jetting technology, liquid photopolymer is jetted in thin layers by a nozzle that moves horizontally across the build platform on which the object is formed. As the material is deposited in the desired form of the 3D design pattern, an ultraviolet lamp shines over the object, solidifying the polymer right away. The platform descends once the initial layer is created, and other layers are added on top of it to create the three-dimensional object. The machine jets a separate, gel-like substance when support material is needed for certain difficult geometries and overhangs. To get the final product, the support material is removed using water or a solution bath once the entire part is printed.

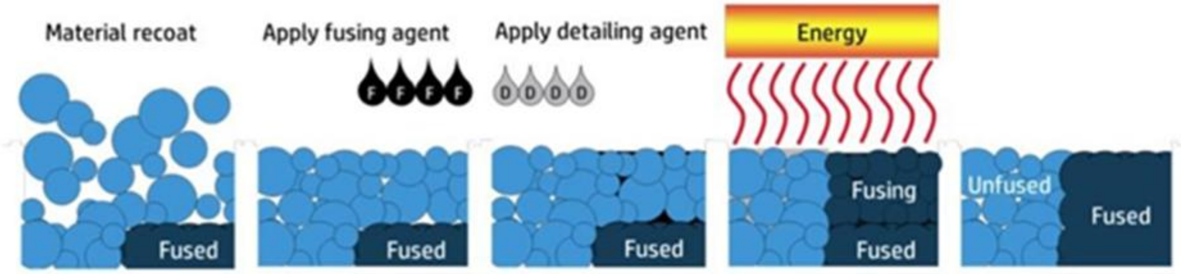

Figure 5: Material Jetting Technology Operating Principle

4.1.4 Binder Jetting

Binder jetting is a 3D printing process where a liquid bonding agent selectively binds regions of a layer of powder. This process spreads a thin layer of powder material over a build platform. A print head then directly deposits a binding agent onto the layer in the desired pattern, binding the powder together. Once the first layer is completed, the build platform descends, and a levelling roller spreads another layer of powder material. the process is repeated until the entire part is finished. After the process is complete, the part is cleaned of any extra powder. Some additional post-processing may be necessary from this point on, depending on the material.

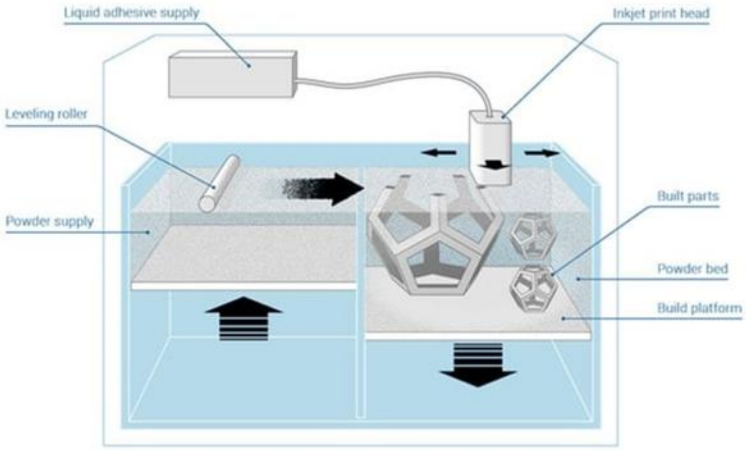

Figure 6: Binder Jetting Technology Operating Principle

4.1.5 Powder Bed Fusion Process

In powder bed fusion (PBF) 3D printing, powder particles (ceramic, metal, or plastic) are selectively melted inside a build area by a thermal energy source (Laser or Electron Beam), layer by layer forming a solid object. 3D printers spread a thin layer of powdered material over the print bed, typically with a type of blade, roller, or wiper. Using a blade, 3D printers typically apply a thin layer of powdered material to the print bed. A powder layer is fused at certain spots by thermal energy. A second powder layer is then placed and fused to the first layer. Until the entire part is manufactured, this process is repeated. The finished product is supported and covered in a bed of unfused powder. After completion, the bed is elevated, the object is allowed to cool, and the parts are removed. Lastly, bead blasting is used to remove any residual bits of material from the product. The unused powders can be recovered and reused.

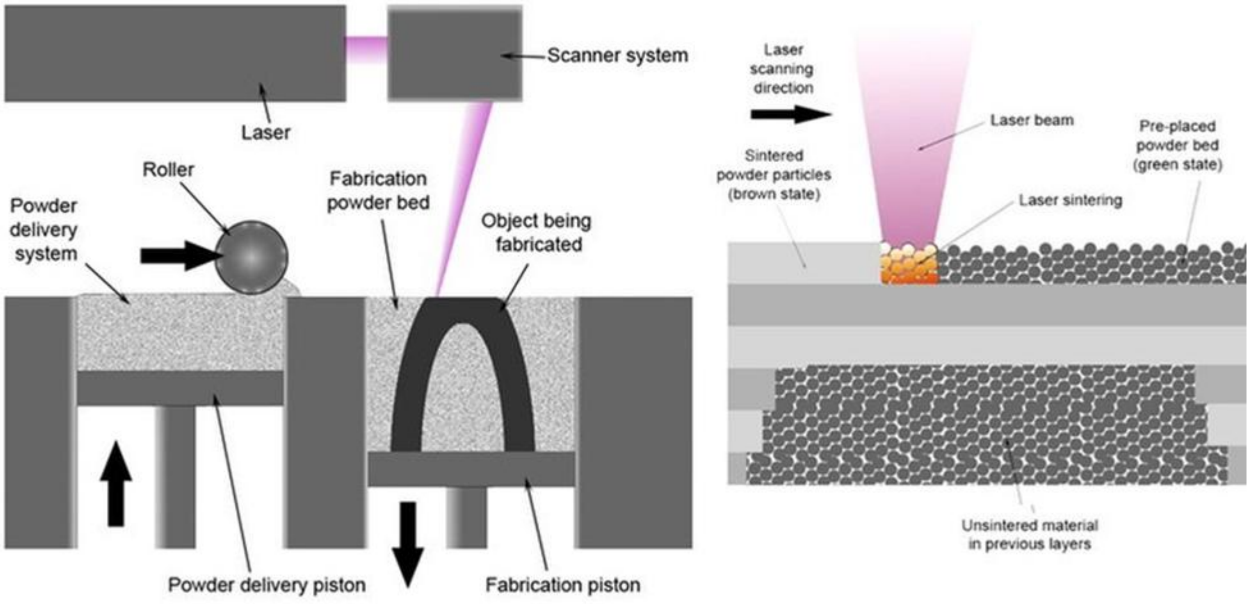

Figure 7: PBF Process Operating Principle

4.1.6 Direct Energy Deposition (DED)

This method creates metal components by directly depositing melted metal powder. A high-power laser melts the metal powder after it is fed to the deposition head using either gravity or pressurised gas. Generally, the powder supply direction is coaxially aligned with the laser beam's focus point through the center of the supply head. The table onto which the object is printed moves horizontally to create the desired pattern of the layer and when complete, the deposition head moves vertically to generate the next layer. The procedure is carried out in a regulated environment with an inert gas (argon) and no oxygen to enhance layer adhesion and regulate the product's qualities.

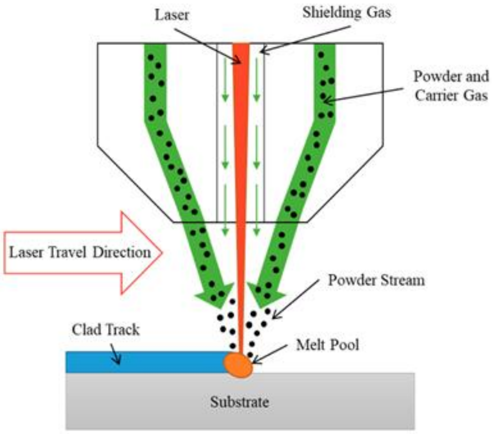

Figure 8: DED Technology Operating Principle

4.1.7 Laminated Object Manufacturing

Rolls of material coated with adhesive are used in laminated object manufacturing. Before the material is transferred to the build platform, it is heated by a second roller, which melts the glue. A laser or blade is used to cut the chosen shape, cross hatches are drawn on the remaining surface to aid in the removal of waste, and the sheet is then placed onto the platform and adhered to the previous layer. The platform drops after this phase is complete. The previously used material is gathered onto a waste roll as the sheet travels and new material is placed on top of the object simultaneously. Layer by layer, this process is done until the desired object is achieved.

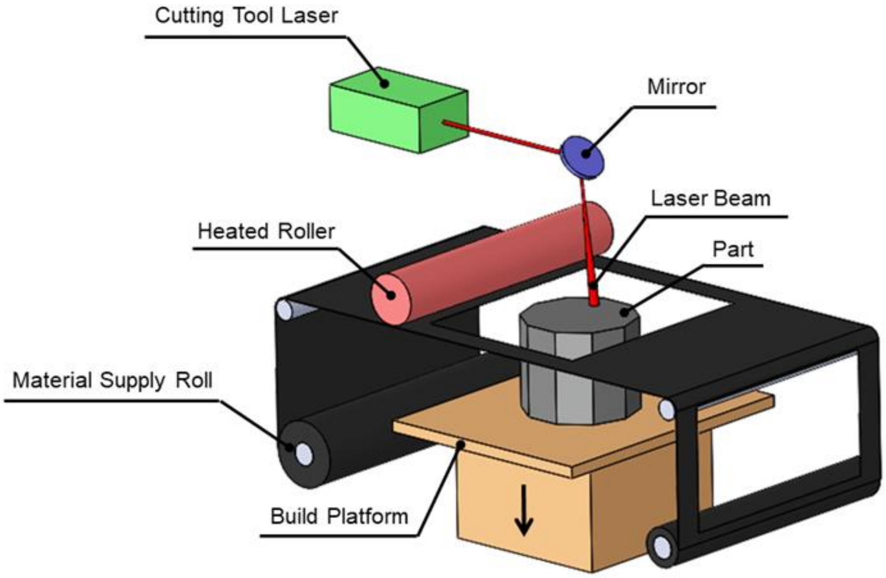

Figure 9: LOM Technology Operating Principle

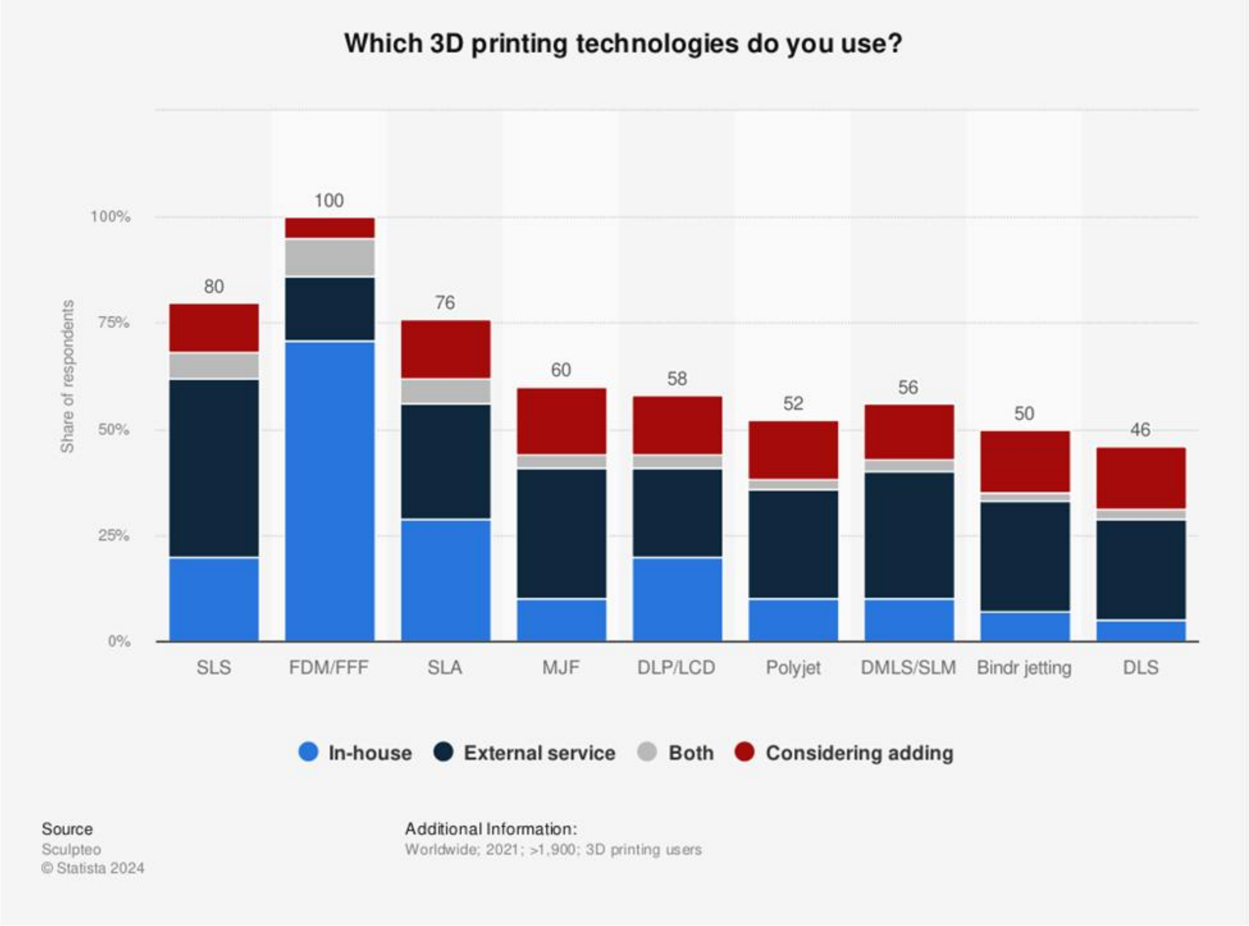

Figure 10: Use of 3D printing technologies[31]

The most popular in-house process is still fused deposition modelling (FDM), followed by SLS, Multi Jet Fusion, and metal additive manufacturing are still popular but more so through printing services (*Figure 10*).[31] The fact that many structures still have excessively high investment costs could be one explanation for this. Finally, when it comes to materials, plastic filaments are used by the great majority of users, closely followed by resins and metals.

4.2 Design for process chain

The Additive Manufacturing (AM) process chain involves 8 (eight) steps.[32] These steps are:

- creating the CAD model

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[31] Alsop, T. (2017). Most used 3D printing technologies 2017-2018, Statistic. [online] Statista. Link

[32] Gibson, I. Rosen, D. and Strucker, B. (2015). Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing. Springer. Link

- conversion to STL/AMF file,
- file transfer to AM machines
- machine set up
- build
- part removal
- post-processing
- application

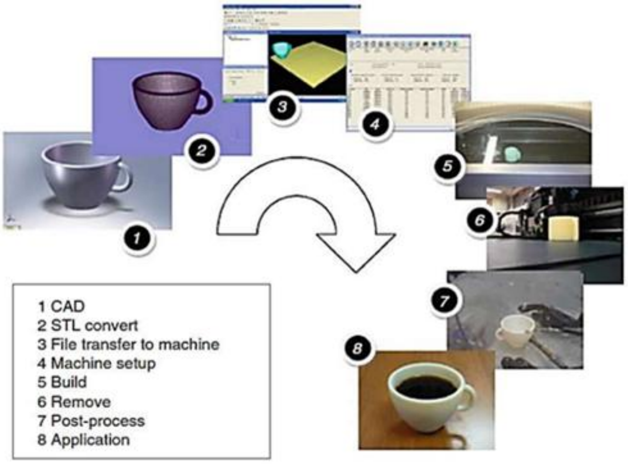

Figure 11: The AM design for process chain[32]

4.2.1 Creating the CAD model

The first step in every product development process is to establish an idea for the product's functionality and look. Therefore, 3D CAD data must be the starting point for the general AM process. There could be several approaches for producing the 3D source data. A designer could develop this model description using 3D CAD software or 3D scanning a physical component that already exists, or a combination of all of these.

4.2.2 Conversion to STL/AMF file

The 3D CAD model is converted into an STL file. The surfaces of the CAD model are represented by a series of triangular facets. Other file formats like AMF/3MF can also be used for AM.

4.2.3 File transfer to AM machines

The STL file is then converted into G-code by the slicing software and then sent to the targeted AM machine. The machine should be able to create the part immediately when a user presses the "print" button after setting up the printing parameters. But there might be a few things to do before the part is built. The initial step would be to ensure that the part is placed correctly. The user can move the item or even alter its orientation. To account for shrinkage, some of the AM parts need to be somewhat bigger or smaller than the original.

4.2.4 Machine Setup

There will be at least a few configuration settings for each AM machine that are unique to that machine or process. Some machines only support the use of one or two materials, and they don't support variations in layer thickness or other build parameters. To speed up machine setup and minimize errors, default settings or file saves from previously established setups can be used. The operator must ensure that the machine has been loaded with enough building material to finish the build.

4.2.5 Build

The first few stages of the AM process include semiautomated processes that may involve significant manual control, interaction, and decision making even while they benefit from computer assistance.[33] Layer control using a height-adjustable platform, material deposition, and layer cross-section creation will occur in a similar order on all AM machines. All AM machines will repeat the process till the part is built.

4.2.6 Part removal

The part must be removed from the build platform. A lot of manual labor is frequently needed at this stage to remove support from the bed. The part should be carefully removed otherwise the tools which are used to remove the part can damage it.

4.2.7 Post processing

Post-processing describes the (often manual) steps of finishing the parts for applications. This may involve coating application or abrasive finishing techniques like polishing and sanding. However, the use of power tools, CNC milling, and extra instruments like polishing tubs or drying and baking ovens might be advantageous for certain activities. To attain final part qualities, some post-processing may entail chemical or heat treatment of the component.

4.2.8 Application

Parts are ready for use after post-processing. Some AM techniques naturally produce components with tiny gaps trapped inside of them, which may be the cause of part failure when subjected to mechanical stress. Parts need to undergo inspection and quality check before they reach the customer.

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[33] Chua, C. K., Leong, K. F., Lim, C. S. (2003). Rapid Prototyping: Principles and Applications. World Scientific. Link

4.3 Design for Additive Manufacturing

Like other established manufacturing technologies, the fabrication capability for Additive Manufacturing (AM) depends on the design that has been implemented. Because of AM technologies' unique features, there are more opportunities for customisation, major improvements in product performance, multifunctionality, and reduced manufacturing costs. The process of designing a product to maximise additive manufacturing (AM) capabilities while adhering to specific manufacturing limitations is known as *Design for Additive Manufacturing (DfAM)*.[34]

AM makes it possible to implement several design features that would be extremely costly or impossible to accomplish with traditional manufacturing; for example, it is tough to produce conformal cooling channels for moulding dies in conventional manufacturing.[35] To ensure that the design concept is feasible, it is essential to consider the limits of the AM process during the preliminary design stage:

1. **Functional areas and design space** - Functional areas directly enable the delivery of a functional requirement (e.g., mating pins on a Lego block). This is mostly untouched in the DfAM process, and the remaining area of the part is known as design space (e.g., the body of the Lego block). This space can be optimized to reduce the weight of the part.[36]
2. **Design on print orientation** - Component orientation determines the direction of anisotropy, mechanical properties, surface finish, roundness of holes, support material, etc., so when designing for additive manufacturing, one should always plan around the precise orientation in which the component will be printed.
3. **Support material** - Support material is a temporary sacrificial material that is used for a specific reason during the printing process and then removed after the print is completed. During the design stage it is worth considering where these supports are added and how to minimise it by redesigning certain features of the part and how it is built (e.g. orientation, type of AM process used, material used etc.)
4. **Design Guidelines** - Guidelines for DFAM vary with different AM processes and materials used, so it is important to choose the right design guidelines.

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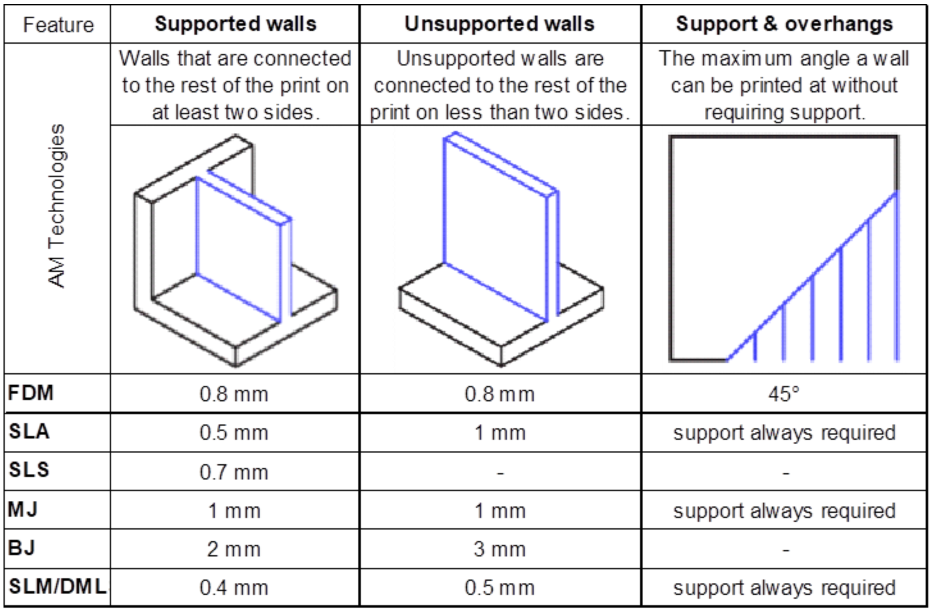
[34] Diegel, O., Nordin, A., Motte, D. (2020). A Practical Guide to Design for Additive Manufacturing. Springer, 2019/2020. Link
[35] Godec, D., Gonzalez, J., Nordin, J., Pei, E., Alcázar, J.U. (2020). A Guide to Additive Manufacturing. Springer. Link
[36] Gen3d. (n.d). Design for Additive Manufacturing. Link

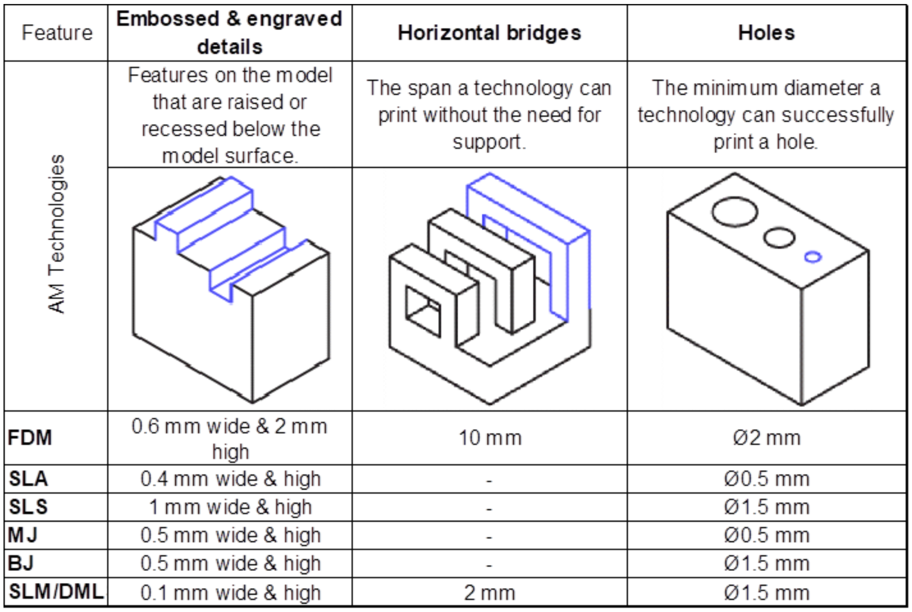
4.4 Design Constraints

Table 1: Design Constraints[37]



Feature	Supported walls	Unsupported walls	Support & overhangs
AM Technologies	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.
FDM	0.8 mm	0.8 mm	45°
SLA	0.5 mm	1 mm	support always required
SLS	0.7 mm	-	-
MJ	1 mm	1 mm	support always required
BJ	2 mm	3 mm	-
SLM/DML	0.4 mm	0.5 mm	support always required

Table 2: Design Constraints[37]



Feature	Embossed & engraved details	Horizontal bridges	Holes
AM Technologies	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.
FDM	0.6 mm wide & 2 mm high	10 mm	Ø2 mm
SLA	0.4 mm wide & high	-	Ø0.5 mm
SLS	1 mm wide & high	-	Ø1.5 mm
MJ	0.5 mm wide & high	-	Ø0.5 mm
BJ	0.5 mm wide & high	-	Ø1.5 mm
SLM/DML	0.1 mm wide & high	2 mm	Ø1.5 mm

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[37] 3D Hubs. Design rules for 3D printing poster. Link

Table 3: Design constrains[37]

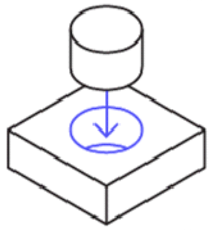
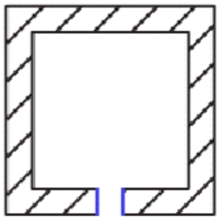
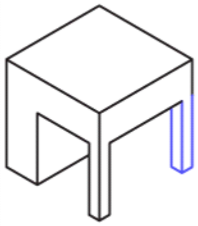
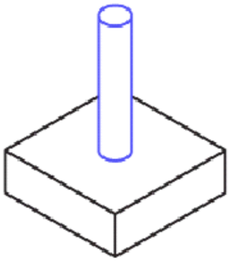
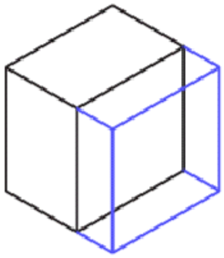
Feature	Connecting/moving parts	Escape holes	Minimum features
AM Technologies	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.
			
FDM	0.5 mm	-	2 mm
SLA	0.5 mm	4 mm	0.2 mm
SLS	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8mm
MJ	0.2 mm	-	0.5 mm
BJ	-	5 mm	2 mm
SLM/DML	-	5 mm	0.6 mm

Table 4: Design constrains[37]

Feature	Pin diameter	Tolerance
AM Technologies	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
		
FDM	3 mm	±0.5% (lower limit ±0.5 mm)
SLA	0.5 mm	±0.5% (lower limit ±0.15 mm)
SLS	0.8 mm	±0.3% (lower limit ±0.3 mm)
MJ	0.5 mm	±0.1 mm
BJ	2 mm	±0.2 mm for metal & ±0.3 mm for sand
SLM/DML	1 mm	±0.1 mm

4.5 3D Slicer

A slicer is a software that converts digital 3D models into printing instructions for an 3D printer to build an object.[38]

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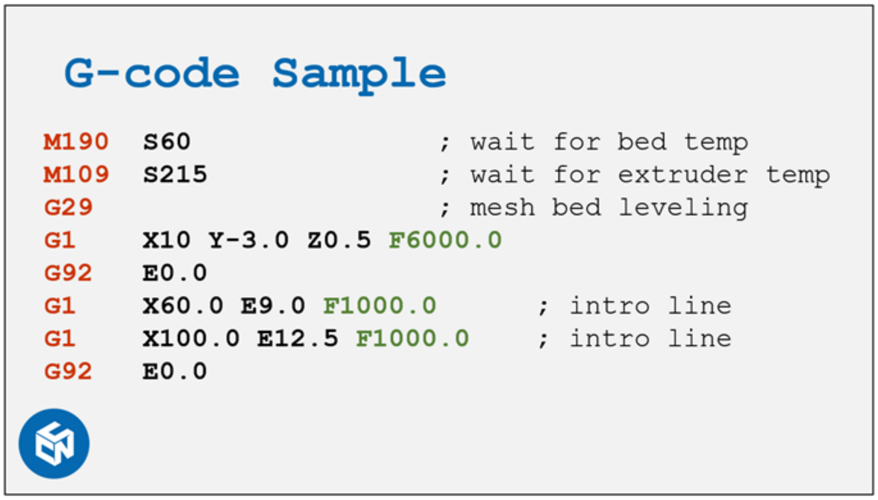
[38] Carolo L. (2024). What Is a 3D Slicer? – Simply Explained. Link

Every 3D printing technology creates 3D objects by adding material layer by layer. Slicer softwares are therefore appropriately named because it virtually "cuts" 3D models into many horizontal 2D layers that will later be printed, one at a time.[38]

A slicer acts as a bridge between a digital 3D model and a 3D printer by translating the design into instructions for movement. These instructions are transmitted in the form of command lines – G-code.[38] A sample of G-code is shown on *Figure 12*.



G-code Sample

```
M190   S60                  ; wait for bed temp
M109   S215                 ; wait for extruder temp
G29                         ; mesh bed leveling
G1     X10 Y-3.0 Z0.5 F6000.0
G92    E0.0
G1     X60.0 E9.0 F1000.0         ; intro line
G1     X100.0 E12.5 F1000.0       ; intro line
G92    E0.0
```

Figure 12: G-code sample[39]

The most popular 3D slicers are:

- Cura
- PrusaSlicer
- Simplify3D
- OctoPrint
- Simplify3D
- Creality Print
- GrabCAD

Figure 13 shows sliced CAD model in slicing software PrusaSlicer. Slicer informs operator (user) about estimated printing time and weight of used filament.

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[39] CNC Kitchen (2021). G-code Basics for 3D Printing. Link

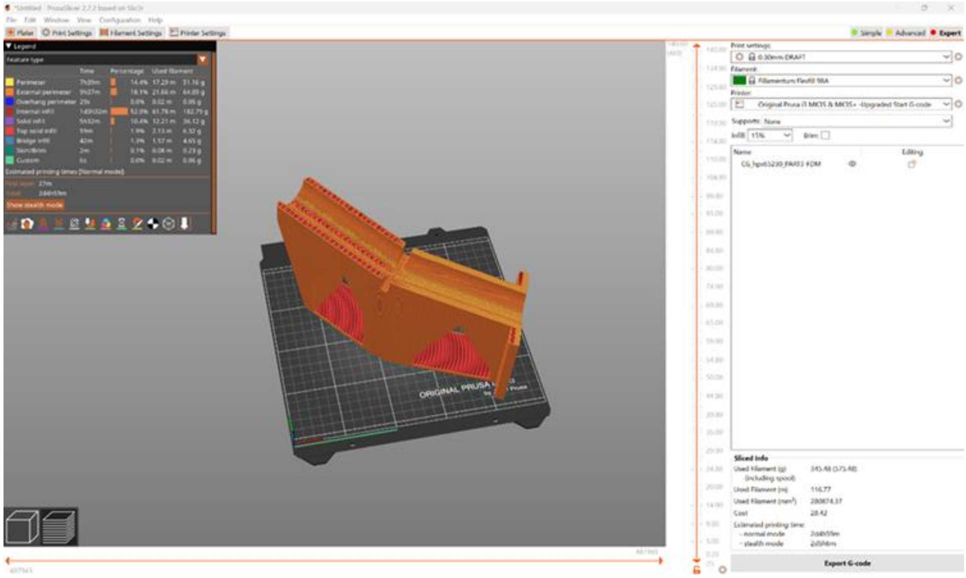

Figure 13: Sliced CAD model in slicing software PrusaSlicer

For successful preparation of a model for 3D printing and generating the G-code, the slicing software requires two inputs:

1. 3D model
2. set of printing parameters

4.5.1 3D model

A digital 3D model can be created in number of CAD software. Specific CAD software designs the digital 3D model in particular format.

If 3D slicers were to process all these different formats, they would require a huge support base, and even so, they surely couldn't cover all the CAD software out there. For this reason, a standardized file format is used. The most common associated with 3D printing is STL (.stl).[39]

STL is a file format commonly used for 3D printing and computer-aided design (CAD). The name STL is an acronym that stands for *stereolithography* — a popular 3D printing technology. You might also hear it referred to as *Standard Triangle Language or Standard Tessellation Language*.[40]

STL file is made up of a series of linked triangles that describe the surface geometry of a 3D model or object (*Figure 14*). The more complex the design, the more triangles used and the higher the resolution.[40]

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[40] STL files. Link

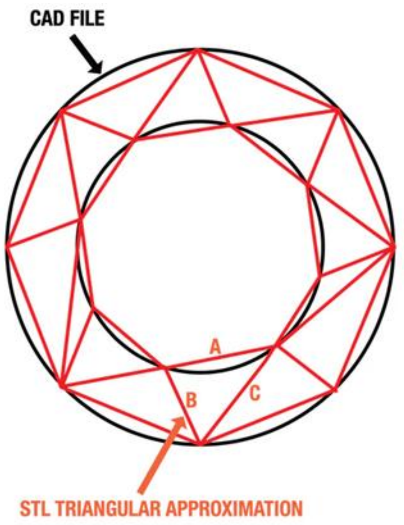

Figure 14: STL file visualization[41]

4.5.2 3D printing (slicing) parameters

The 3D printing parameters will differ depending on the type of technology, the type of material, the object to be printed, and its intended use. The most important parameters are:

- layer height
- infill density
- infill pattern
- wall thickness
- support structure
- print orientation

4.5.2.1 Layer height

The choice of layer height affects the quality of the surface of the model, the printing time and the amount of material needed (*Figure 15*). The lower the layer height, the better the quality of the surface, but the printing time is slower, and the amount of needed material increases.[42]

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[41] 3D Printer Academy (2023). What Exactly are STL Files? Link

[42] Valjak, F., Kapetanović, A., Taradi, I., Bojčetić, N. (2023) 'Work in Progress: Development of Educational Kit for Teaching Additive Manufacturing', in Proceedings of the International Conference on Engineering Design (ICED23), Bordeaux, France, 24-28 July 2023. Link

Figure 15: Effect of layer height on quality of 3D-printed part[43]

4.5.2.2 Infill density

AM enables the selection of the infill density in percentage (*Figure 16*). A lower percentage of the infill saves material and print time, while higher percentages result in stronger models.[42]

By adjusting the infill percentage, the model's mass is directly affected while maintaining or improving the model's properties. AM enables the printing of completely hollow, very light models.[42]

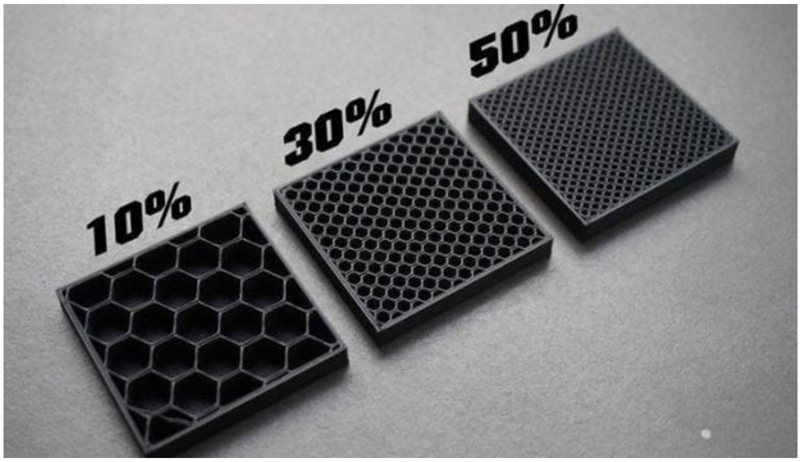

Figure 16: Infill density[44]

4.5.2.3 Infill pattern

The infill pattern is the structure and shape of the material inside the model. There are different shapes, from simple lines to complex geometric shapes (*Figure 17*). The infill pattern choice can affect the model's strength, print time, weight, and flexibility.[42]

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[43] Prusa Research a.s. Layers and perimeters. Link

[44] Avery S. (2023). The Infill Puzzle: Cracking the Code for Perfectly Balanced 3D Prints. Link

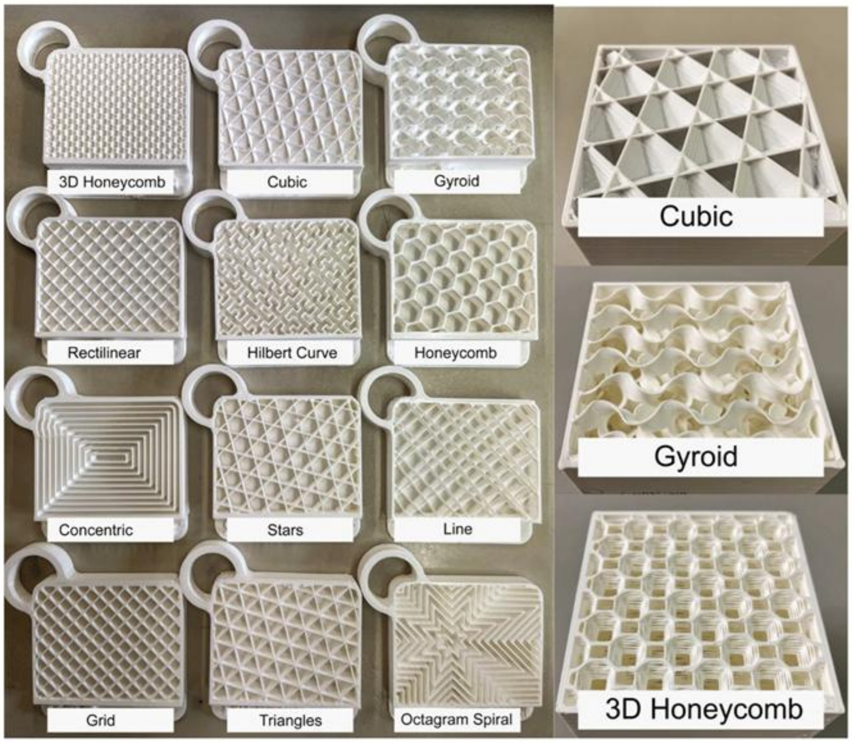

Figure 17: Infill patterns[45]

4.5.2.4 Wall thickness

Setting for walls and top and bottom layers is the thickness of the shell features. Usually there's no one slicer setting for shell thickness, as it's split into wall thickness and top and bottom layer thickness.[46]

The shell thickness or number of perimeters should change based on the purpose of a model and an used material. The bigger wall is, the longer print will take, and the more material will be consumed. However, model will be stronger.[46]

4.5.2.5 Support structure

The support structure (*Figure 18*) is the structural support for the hanging part of a model that prevents shape deformation. It consists of a flat base and vertical support that can be made of the same or sacrificial material. After manufacturing, the support structure is completely removed. Therefore, the support structure's choice affects the surface's quality.[42]

If there are hanging parts with a low angle of inclination, the material gives way and collapses at the overhangs (*Figure 18*). Reducing the angle leads to increasing

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[45] Lopes, L.; Reis, D.; Paula Junior, A.; Almeida, M. Influence of 3D Microstructure Pattern and Infill Density on the Mechanical and Thermal Properties of PET-G Filaments. Polymers 2023, 15, 2268. Link

[46] O'Connell J. Wall Thickness (3D Printing): How to Make It Perfect. Link

deformation of the model. It is recommended to use support structures or change the print orientation to prevent deformation of the model.[42]

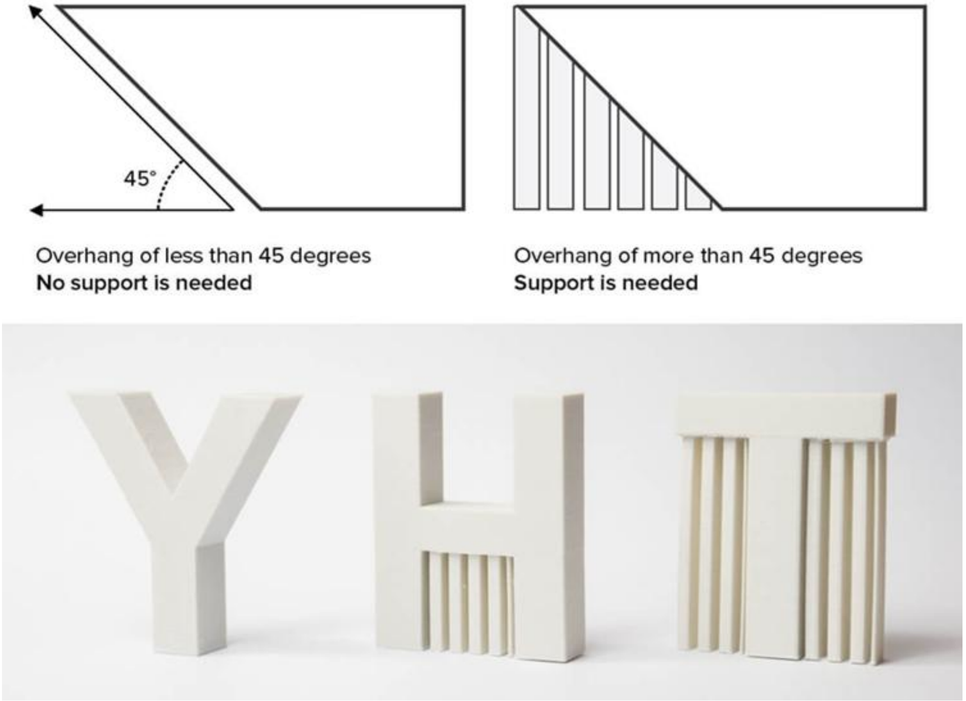

Figure 18: Support structures and overhangs[47]

4.5.2.6 Print orientation

Print orientation is possible in the x, y and z-axis. Depending on the shape of the product, by choosing the orientation, we can influence the quality of the surfaces, the amount of supporting material, and thus the production time (*Figure 19*).[42]

Figure 19: Effect of printing orientation on the amount of supporting material[48]

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[47] Gambody Team (2022). Two Main Types of 3D Printing Supports and Tips for Beginners. Link
[48] Tyson M. (2018). Starters guide to 3D Printing: Orientation. Link

4.6 Selection of Materials and Post-Processing

Selecting the appropriate material depends upon several criteria. Keeping track of each property required for a part's material and figuring out which one meets the profile can be challenging. There are a few considerations for choosing the right material:

- application
- precision and detail
- cost
- material properties
- certification
- post-processing

4.6.1 Application

The material needs to match the essential characteristics required for the application (prototypes, spare parts, etc) when selecting a material and AM method for the project.[49] The need for durability will vary depending on the stage of the product life cycle at which the part is. For example, a concept model has to mimic the final product's appearance and feel, but it does not have to be as durable.

4.6.2 Precision and detail

AM technology and materials are intertwined, each technology builds parts at a range of resolutions. While certain materials work better for larger, less complex prints, others are better suited for making intricate and detailed designs. For example, the use of Material Jetting creates extremely detailed cosmetic parts by using the thinnest layer possible and full CMYKW colour. Different levels of post-processing, such as sanding, painting, or polishing, may be required for different materials. Be aware of the post-processing requirements for each material.

4.6.3 Cost

The cost of materials can vary significantly, with some being more expensive than others. Selecting materials that fit the budget will help in controlling the project expenses without compromising project quality.

4.6.4 Material properties

Materials for AM are put through a rigorous testing process to determine the kinds of pressures they can withstand and the ability to excel in harsh environmental conditions.[50] Therefore, it is useful to consider material properties, impact resistance,

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[49] Stratasys. (n.d). 4 Considerations for Material Selection. [online]. Link

[50] Wevolner. (n.d). The Ultimate Guide to Types of 3D Printing Materials. [online]. Link

flame retardancy, toughness, and other key characteristics to identify the material that best fits the main purpose of the application.

4.6.5 Certification

Some AM materials come with certificates that may be essential for the project, such as flame smoke and toxicity certifications, chemical resistance, biocompatibility, sterilisation capabilities, and FDA certifications for skin contact. Make sure your material can meet your needs when selecting an AM process and material for your project.

4.6.6 Post-Processing

Practically all 3D prints need to undergo some post-processing. A printed part's strength and other characteristics can be increased in addition to its appearance by post-processing.[51] The post-processing methods vary for different 3D printing technologies. The following are a various categories of post-processing methods that are widely used in various 3D printing technologies.

The parts need to be cleaned first. This covers all the methods like de-soldering, rinsing, brushing, blowing, etc. that will make the part clean. Eliminating any excess material (powder or resin) is the aim. This phase will take more or less time, depending on the printing method that is being utilised. This is a time-consuming phase that lengthens the manufacturing time.

The next category is curing or sintering. For the resin process, the parts are UV-cured to attain their full properties. Sintering is a process where the green part produced by some AM processes is heated in a furnace under a controlled atmosphere. This will burn away the binding agent and fuse the metal particles together to reduce the porosity.

Some heat treatment operations like annealing are done to enhance the mechanical properties. Annealing involves increasing a part's temperature to a certain specific temperature which varies for different materials and then cooled. This will enhance its thermal stability, as well as its resistance to heat, traction, and UV light. This process is used for high-performing polymers and metals.

Surface finishing and colouring are the two areas where the parts' aesthetics are maximised. All techniques used to enhance appearance fall under the first category, including sandblasting, polishing, infiltration, smoothing, and milling. Part's surface can be modified by adding or removing material. For instance, sanding will eliminate surface irregularities, but spraying will apply a coating of substance to improve the shine. Painting and Dyeing are used to add colour to the finished part.

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[51] 3dnatives. (n.d). An Introduction to Post-Processing in 3D Printing. [online]. Link

4.7 Sustainable methods of production in Additive Manufacturing

This part focuses on three methods of sustainability in the production phases of AM. These are the design for disassembly – repair and end of life, ISO/ASTM 52900 standards and definitions, and ethical product disposal and waste management. However, it should be briefly acknowledged – reminded, even – that there are other ways to ensure sustainability considered in the AM processes, as seen throughout this report.

First, this includes life cycle assessments. These evaluations might aid in offering an in-depth understanding of the environmental effects of additive manufacturing.[52] To give an extensive overview of how the materials, equipment, and procedures used in additive manufacturing affect the environment, manufacturers should follow standardised reporting procedures. To learn more about the environmental consequences of various additive manufacturing materials and equipment, manufacturers should include information about recycling and zero-waste possibilities.

However, Lifecycle evaluations are expensive and time-consuming, so additive manufacturers should think about creating an appropriate database for lifecycle analysis.[53] Creating these databases will encourage openness and assist manufacturers in evaluating and validating the energy usage and carbon dioxide emissions of their products over time. They might also share this information with clients who might be more likely to convert to items made through additive manufacturing if it turns out to be a long-term viable solution. Furthermore, anticipating the environmental impact before printing can assist manufacturers in identifying equipment and process defects related to additive manufacturing, enabling them to address these issues in the future to reduce carbon emissions and environmental effects. Therefore, it is important to optimise workflows and procedures to minimise the ecological footprint. Creating a well-defined plan of action can contribute to the long-term sustainability of AM.

Next, the AM designer can make use of design freedom to reduce carbon footprints. Highly functional components that have prolonged life can be made possible by generative design or topology optimisation. Further infill patterns/lattices can be used to reduce the weight of the part. Part consolidation can save material wastage and eliminate the assembly process. A modular design approach can be employed in the products where there is a difference in life span of each sub-part. That is only the damaged portions need to be replaced, which saves energy and resources when compared to remanufacturing the entire part. Reusability of subsequent products could be made possible by standardising certain aspects of the design. Part orientation has an

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[52] FTI. (n.d). 4 Steps to Sustainable Additive Manufacturing. Link

[53] Materialise. (n.d). Reduce and Rethink: How to Take a Proactive Approach to Waste Reduction with Additive Manufacturing. [online]. Link

impact on a product's environmental impact because it directly affects the material's printing speed.

Finally, new manufacturing methods like hybrid manufacturing and 5-axis printing can be employed wherever possible as it eliminates the need for support structures. The environmental benefits of various materials should be considered when choices are available. Low-density materials can be used in place of high-density ones to replace them, saving energy and improving operation. Try to use materials that are recycled and biodegradable. Nowadays even metal powders are prepared from scrap materials.

4.7.1 Design for Disassembly: Repair and End of Life

Environmental requirements are becoming increasingly stringent today, so when developing a product, it is necessary to consider the possibilities of its recycling and/or disposal. This can be done through the use of models and prototypes. For example, using appropriate models, it is possible to analyse the disassembly of a complicated product or examine the ecological packaging of such a product, all at a very early stage in product development.[35] However, during the design stage of a product in AM, one should consider the following aspects in order to achieve longer usability of the product:

- Doing part consolidation in AM reduces the chances of disassembly, especially in case of single-body designs from converted multi-body parts. For such cases, one has to properly consider movement of components in assembly designs and also if the materials are different. The blueprints of the parts should be readily accessible for AM to avoid longer delays in assembly breakdowns, and to avoid recreating, designing and manufacturing all components from beginning. In contrast, multi-body parts can be disassembled easily.

- With multi-materials such as metal-polymer locking or interfaces, designers should aim for shape memory or special designed fasteners which upon heat can detach easily for disassembly purpose. These should only be used where firm contacts are not required or heat transfer is not essential. Another metal-polymer easy assembly and disassembly is possible by using heat degradable adhesives in interfaces.[54]

- Use of micro protrusions outward and inward in metal-polymer interface also exhibits improved mechanical interlocking and disassembly.

- At the End-of-Life cycle, material recovery is also possible by the heat treatment of metal-polymer joined parts. In case of polymers or composites, cutter mills,

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[54] Abuzied, H., Senbel, H., Awad, M. and Abbas, A. (2019). A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal. Link

choppers or shredders coupled with heat extruders can assist recycling of polymer material where actual polymer part is broken into tiny pieces which then on molten and extrusion stages can be reconverted into 3D printable filaments.[55] Recycled materials should be tested for printability (maintaining extrusion and shape) and should pass minimum limits for strength.

- Use of thermosets such as silicone or polyurethane (PU) should be avoided as these get hardened in AM VAT Photopolymerization process and cannot be recycled. Use of thermoplastics is recommended for Material Extrusion process.[56]

AM is advantageous in repairing parts as spares whether individuals or in assemblies which could be out-dated or discontinued from production. This improves the circularity of the part or equipment as it prolongs functionality, decreases need of inventory and time and money on spares. The damage should be assessed through a decision process where potentiality of repair can be grouped as 'repair via AM', 'repair excluded of AM' or 'totally reject or replace'.[57] Apart from traditional bonding means, some FDM printers can be used to repair shallow cracks as long as the depth suffice the nozzle size and the material get bonded. 3D scanners can also be used for reverse engineering purpose which can produce CAD models of damage parts and/or after tweaking can readily be 3D printed for use /replacement.

4.7.2 ISO/ASTM 52900 Standards and Definitions

The ISO/ASTM 52900 is a standard written with the main goal of supporting communication between various parties involved in the field of additive manufacturing technology. This standard enumerates and defines principles and terminology associated with additive manufacturing. It breaks down the field of AM into its various process categories, data terminology and part terminology. Here are just a few different areas that it covers:

- **General Terms:** Basic things that are used when referring to the AM process as a whole
- **Process Categories:** The different AM processes that are officially recognised by the ISO such as Material Extrusion and Powder Bed Fusion
- **Processing (General):** Common terms used to describe things that are associated with each process category like layers and supports
- **Processing (Data):** Covers data types, software within AM and identifies common nomenclature within each area such as general terms, material and data.

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[55] Harding, X. (2018). Feed your 3D Printer Recycled Plastic. Popsic. [online]. Link

[56] All3dp. (n.d). 3D printer recycled plastic tips for your waste plastic. [online]. Link

[57] Abuzied, H., Senbel, H., Awad, M. and Abbas, A. (2019). A review of advances in design for disassembly with active disassembly applications. Engineering Science and Technology, an International Journal. doi:https://doi.org/10.1016/j.jestch.2019.07.003. Link

The terms have been sorted into specific application fields as the various parties involved in AM will be doing so at various stages along a given value chain.[58] Other sustainability-focussed ISO standards include:

- **ISO/ASTM 52933 titled:** Test method for the hazardous substances emitted from material extrusion type 3D printers in the non-industrial places. ISO/ASTM 52933 sets out test procedures to assess indoor air quality in non-industrial environments as well as pertinent information related to hazardous substances that are emitted such as Volatile Organic Compounds (VOCs) during material extrusion operations.[59]
- **ISO/DIS 59014 titled:** Sustainability and traceability of secondary materials recovery. ISO/DSI 59014 outlines terms and principles and requirements and provides guidance to manage the sustainability and traceability of operations for the recovery of secondary materials.[60]

4.7.3 Ethical Product Disposal and Waste Management

Currently, there is only one company that recycles 3D printed waste filament and sells it – *Recycling Fabrik*. This is a German-based company that mechanically recycles filament. They do this by sorting the waste, shredding it, washing it to remove contaminants and preserve material quality, drying it, then extruding it using filament extrusion to form new filament for sale.[61]

Materialise is another company that specialises in making 3D-printing services for many different industries. They have recently developed a material known as Bluesint PA (Polyamide) 12 which they describe as having similar properties to tradition polyamide, but with the added advantage of being made form 100% re-used PA waste powder.[62] This type of material is a good example of making use of excess material, however, it does not necessarily promote a circular process as this PA still needs to be recycled somehow and there would also always need to be excess powder for the Bluesint PA 12 to be produced.

A better way of tackling this problem would be to come up with a way of creating a circular process, such that waste materials can be easily recovered and used to make new products again, like what *Recycling Fabrik* is currently doing. A potential fair-trade standard was addressed in a 2014 paper by Feeley, Wijnen and Pearce. They noted that there should be opportunities provided for waste pickers to sell their processed waste filament to trading partners who could then make other useful products that would

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[58] ISO. (2022). ISO ASTM 52900. [online]. Link
[59] ISO. (2024). ISO STD 75759. [online]. Link
[60] ISO. (2024). ISO STS 59014. [online]. Link
[61] Recycling Fabrik. (n.d). Link
[62] Materialise. (n.d). 3D Printing Materials. Link

also be sold.[63] This fair-trade standard is broken down into requirements that permit the filament gathered by waste-pickers to be considered as 'ethical filament'. These requirements include:

- **Minimum Pricing -** Workers' wages must meet or exceed minimum wages or wages for jobs with a similar skill set. A minimum price also ensures that the necessary funds to maintain a sustainable business are available.[63]

- **Fair Trade Premium -** A premium price could be put in place for waste-picker recycled filament as the cost between this and commercial filament decreases. The extra revenue would be used to invest in local projects for socio-economic and environmental development.[64]

- **Labour Standards -** Child labour is prohibited. Children are only permitted to work during school holidays and if it does not interfere with their health or personal development. No forced or compulsory labour is permitted.[65]

- **Environmental Standards -** Actions that consider the environment should always be taken when possible. Toxic chemicals should also be dealt with in an environmentally considerate manner.[66]

- **Health and Safety Standards -** Machinery must operate safely and have sufficient accident prevention devices. Waste pickers must be provided with free and adequate PPE (Personal Protective Equipment). The work area should be as hygienic as possible and there must be Medical Staff at hand.[66]

- **Social Standards –** There should be no discrimination based on gender, race, religion, age, disability, sexual orientation etc.[66]

- Finally, introducing Fair Trade to waste pickers is a step in the right direction in the ethical management of AM waste, especially in developing and emerging economies.[67]

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[63] Feeley, S.R., Wijnen, B. and Pearce, J.M. (2014). Evaluation of Potential Fair Trade Standards for an Ethical 3-D Printing Filament. Journal of Sustainable Development, 7(5). doi:https://doi.org/10.5539/jsd.v7n5p1. Link

[64] Fairtrade Foundation. (n.d). [online]. Link

[65] International Labour Organisation. (2020). Link

[66] Fair Labor. (2020). Workplace Code of Conduct and Compliance Benchmarks. Link

[67] EU Monitor (2023). Waste management in the EU: infographic with facts and figures - EU monitor. [online] Link

4.8 Industrial Applications

The applications of AM are always expanding as the technology is evolving rapidly day-by-day – we now have 4D printing research and products emerging. In fact, there could be hardly no industrial sector AM has not touched. Industrial applications in AM are diverse and range from the automotive, to the defence, aerospace and aeronautics' sector, to building construction and architecture, as well as education and research, material development, arts and sculpture, healthcare equipment, manufacturing, maintenance, repair (parts replacement) and recycling, rapid tooling and prototyping, fashion and jewellery, clothing, industrial and consumer goods, sports, movies/theatre, and even not sparing the food sector.[68]

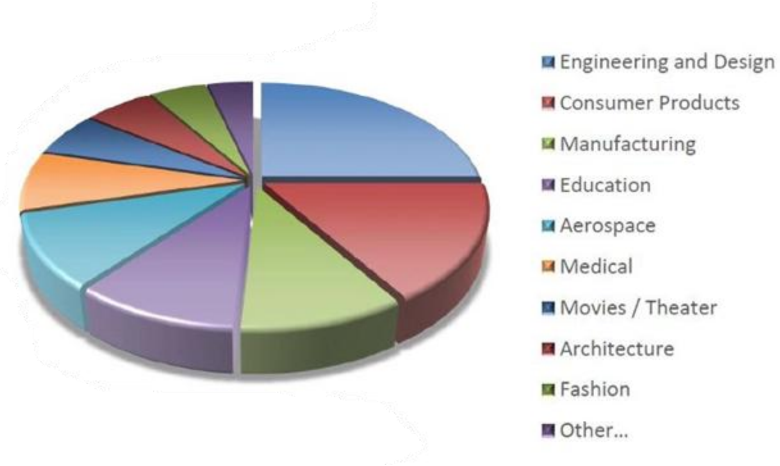

Figure 20: Additive Manufacturing: Industrial Applications and share per sector[68]

Some of the main categories of industrial 3D printing include rapid prototyping, producing functional parts, molds, tooling, spare parts, complex / organic geometrical components, mass customization etc.

4.8.1 Rapid prototyping

Rapid prototyping is a technique in 3D printing used to quickly fabricate a physical part or assembly from a three-dimensional design. With rapid prototyping, engineers and designers can create a better final product in-house, iterating several times incorporating instant changes between digital designs (CAD models) and physical prototypes (transitioning from realistic proofs of concepts to high-fidelity prototypes) with a quick and cost-effective workflow. In rapid prototyping, the near-final-produce parts go under series of real validation tests under actual working environment to pave the way for mass production. This makes it very different than complex, costly, lengthy, generally outsourced traditional prototyping methods, for example, injection moulding

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[68] Autodesk. (2014). Real World Application: 3D Printing. [online]. Link

process which further requires expensive moulds, tools and setup to produce low volume prototypes to test and validate, and thus further hints expensive iterations if the product fails. There are multiple 3D printing processes available, with the ones most commonly used for rapid prototyping being fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS).[69] A simple illustrative workflow of rapid prototyping technique is shown in *Figure 21*.

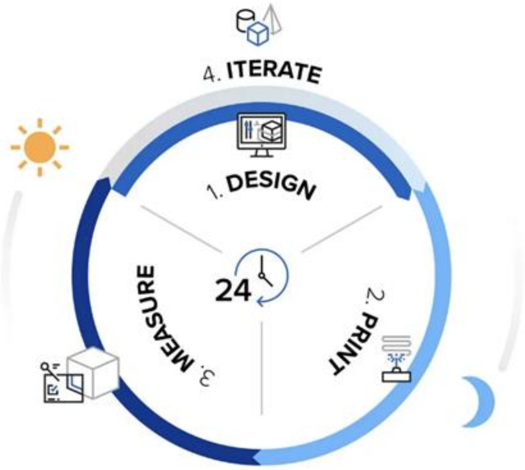

Figure 21: Typical workflow or rapid prototyping[69]

An example of rapid prototyping of an L-bracket for a pick-and-place robot starting from simple metal design to an intricate composites design with just five iterations by University of Sheffield AMRC group[69] is shown in *Figure 22*.

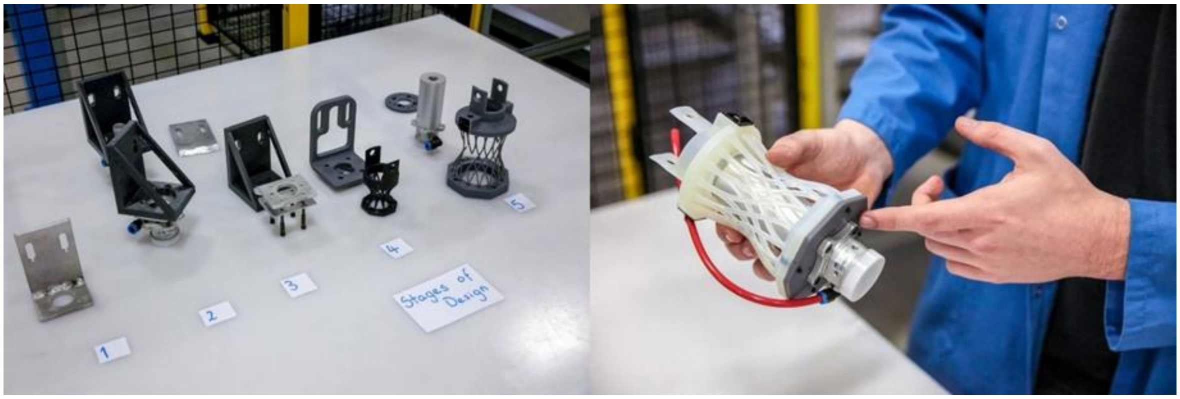

Figure 22: Example of rapid prototyping of L-bracket with five iterations for a robot gripper application[69]

4.8.2 Functional parts

This is an extension of rapid prototyping where industrial parts are specifically designed and produced as final working components as individuals or to be integrated

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[69] Formlabs. (n.d.). Guide to Rapid Prototyping for Product Development. [online]. Link

within assemblies. Rapid prototyping stage stops at the iterative stage while functional prototyping stage involves final manufacturing of the component which could replace any existing machine part and ready to work as replacement. A functional prototyping example of the same pick-and-place robot by AMRC is shown in *Figure 23*.

Figure 23: Example of a functional 3D printed gripper intricate design for a 5-axis pick-and-place robot[70]

Functional parts produced with the 3D printing can be made of any material whether polymers, composites, metals etc. provided these perform well and are fit for application of use.

Another example of functional printing on a heavy-duty scale is of an agriculture harvester 'Oxbo 5170 detasseler' components from PMC Harvesters. The company printed seven printed parts which included 4 suspension sensor holders, angle sensor holder, width indicator and speak holder, shown in *Figure 24*. All parts were prototyped, tested, redesigned to final production and rigorously tested for touch conditions such as impact damage, temperature variations, durability, the very environment in which the machine operates. Furthermore, the company reported 2/3 of cost savings than regular machining processes and has adopted 3D printing for future production.

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[70] Formlabs. (2019). Manufacturing Intricate Gripper Brackets for a Pick and Place Robot. [online]. Link

Figure 24: Functional 3D printed components of a heavy-duty agricultural detasseler machine from PMC Harvesters[71]

4.8.3 Molds / Tooling

Industrial 3D printing has made a tremendous impact on the manufacturing world. 3D printing can produce molds quickly and cost-efficiently up to 90% faster and 70% cheaper[72] especially in low-volume production line than a two-way metal process (first expensive mold creation, and secondly the molded product). The materials can be heat-resistant plastics, metal or ceramic. An example of a 3D printed blow mold developed by PepsiCo is shown in *Figure 25*. These molds are used for prototype runs of about 10,000 bottles.[73]

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[71] Zortrax. (2017). 3D Printing End-use Parts for Heavy-duty Machines of PMC Harvesters. [online]. Link

[72] Protolabs. (2021). 3D-printed molds vs. aluminum tooling. [online]. Link

[73] Nexa3D (2022). CAD to Part in 48 Hours: Ultrafast 3D Printed Tooling Slashes Costs & Lead Times for Bottle Development at PepsiCo. [online]. Link

Figure 25: 3D printed injection mold insert to create a part prototype[74]

With metals, mold 3D printing is worth applicable where the mold designs are un-manufacturable via traditional ways, this is where conformal cooling channels come in (**Erro! A origem da referência não foi encontrada.**). Cooling channels are essential in m etal injection-molding tools so that parts can be cooled faster and uniformly. The cooling stage represents 70% – 80% of the entire cycle time, reducing this time over the lifetime of a mold results in significant savings for manufacturers. Proper cooling also affects the dimensional accuracy, surface quality, and mechanical properties of the final product. Conformal cooling channels feature, which is only available with 3D printed molds, is igniting a revolution of sorts in the mold-making industry.[74]

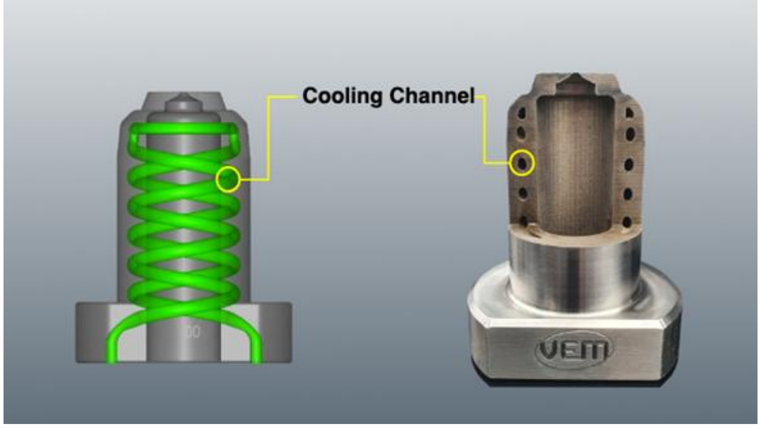

Figure 26: 3D printed mold bushing with internal cooling channels not possible to create with traditional manufacturing[75]

However, despite the advantages of 3D printed molds, there lie a set of associated disadvantages for the parts produced. These include low-volume production

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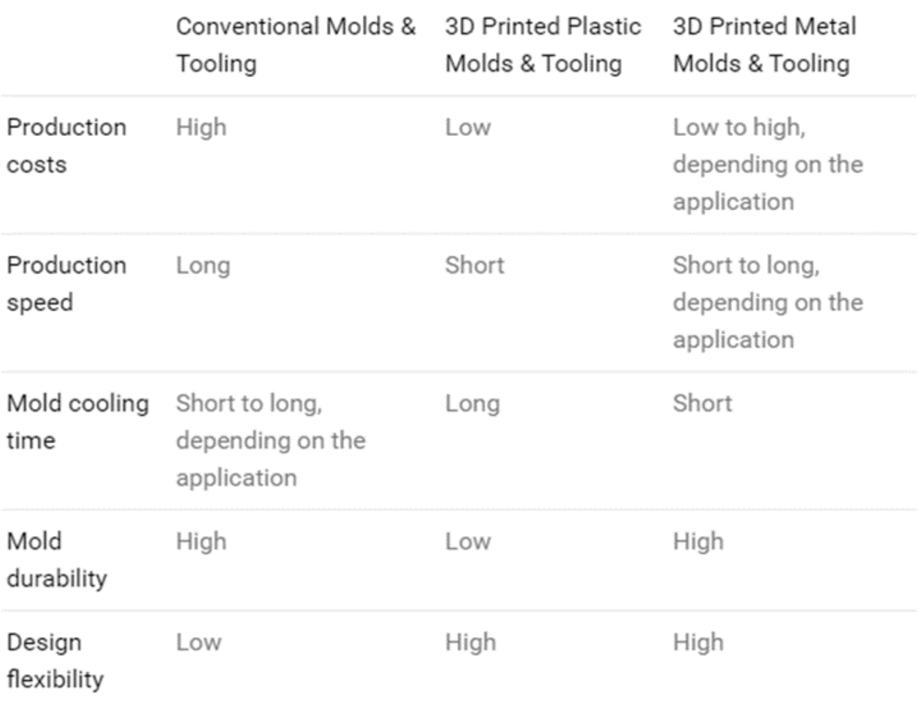
[74] Schwaar, C. (2024). 3D Printing Injection Molds – The Ultimate Guide. [online] All3DP. Link
[75] VEM Tooling. (n.d.). 3D Printed Inserts for Injection Molding. [online]. Link

of simple small size designs normally applicable to prototyping, low temperature process for plastic materials which break down fairly quickly when subjected to the demanding thermal cycles of injection molding (on contrary, aluminium or steel molds face temperatures routinely around 260℃ or greater[72]) and for higher production, frequent printing of new molds as replacement along with testing is required. The durability cycle of 3D printed mold is in 100 to 10,000+ (depending on the material)[74] while the metal counter parts can have a life of unlimited cycles.[72] A comparison of conventional and 3D printed molds in terms of their cost, time, durability and flexibility is summarized in *Table 5*.

Table 5: Comparison of conventional and 3D printed molding processes[74]



	Conventional Molds & Tooling	3D Printed Plastic Molds & Tooling	3D Printed Metal Molds & Tooling
Production costs	High	Low	Low to high, depending on the application
Production speed	Long	Short	Short to long, depending on the application
Mold cooling time	Short to long, depending on the application	Long	Short
Mold durability	High	Low	High
Design flexibility	Low	High	High

4.8.4 Spare Parts

An application of functional prototyping using additive manufacturing is quick and efficient way of replacing and storing spare parts in times of part failure, machine breakdown or as a general preventive maintenance protocol. Long lead times for spare parts can bring production to a standstill if the required parts are not available in inventory. Also, maintaining and storing the spares inventory is costly. With quickly produced 3D printed spares and having a digital virtual inventory (storing blueprints files of spare parts for 3D printing process), the above two bottlenecks are mitigated. Resulting in on-demand, quick, cost-effective localized in-house part replacement without needing to manufacture additional volume of parts and a large physical space to store them, thus smoothening the production via securing supply-chain (especially in case of discontinued or legacy parts) and economizing the inventory storage.[76] [77] Furthermore, original parts can be reverse engineered using 3D scanners, could be further optimized using CAD for longer life-span, and 3D printed for application. The spare parts could be made of polymer or metals depending on the application requirements. Porsche Classic supplies parts for its vintage and out-of-production models and is using 3D printing to produce on-demand, rare, low-volume spare parts for its older vehicles using both polymer and metal (*Figure 27*). Many other automotive industry names such as Mercedes-Benz Trucks, Volkswagen and BMW are embracing 3D printing for this application to shed costing, increase operational efficiency and optimise inventory.[76]

Figure 27: Polymer and metal 3D printed parts from the Porsche Classic division[76]

4.8.5 Complex designs

one of the most significant capability of 3D printing technology is to produce complex challenging geometries normally termed as ‘organic designs’ as it leverages on the design freedom and flexibility. It can produce shapes and features unachievable with conventional manufacturing methods. The geometrical designs are initially developed using typical CAD tools but are optimized for mass reduction and performance improvement using generative or topology optimization techniques backed by inputs from the application of use. Automotive giant Bugatti printed a complex titanium brake calliper with wall thicknesses between 1 to 4 mm using SLS process for its Bugatti Chiron super sports car resulting in 40% weight reduction and higher strength (*Figure 28*).[78]

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[76] AMFG. (2018). How 3D Printing is Transforming the Spare Parts Industry [2021 Update]. [online]. Link
[77] Addinor EU. (n.d.). 3D Printing for Spare Parts. [online]. Link
[78] AMFG. (2019). 7 Complex Designs Achieved With 3D Printing. [online]. Link

Figure 28: An intricately shaped brake calliper with wall thicknesses between 1 mm and 4 mm for Bugatti Chiron[78]

Another example of the complex 3D printing is shown in *Figure 29*, this is about a aerospike rocket engine by a company named Hyperganic. Aerospike rocket engines are 20% efficient than typical bell-design engines, but due to their design complexity and issues with overheating these are less popular. However, by harnessing the power of design flexibility for 3D printing technology, the company was able to produce multiple design iterations including injector heads, advanced heat transfer systems and complex combustion chamber geometries depending on the thrust levels.[79]

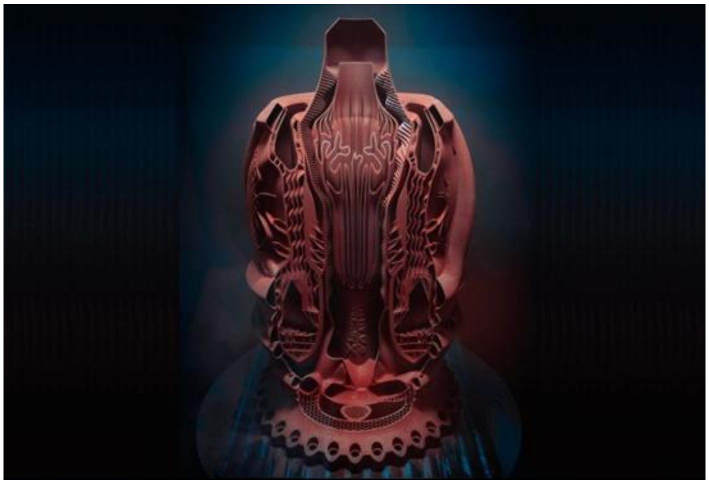

Figure 29: 3D printed aerospike rocket engine by Hyperganic[79]

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[79] Stevenson, K. (2022). The Most Complex 3D Printed Part Ever? [online] Fabbaloo. Link

4.8.6 Mass customization

Mass customization is the production, in series, of personalized goods or services that meet the customers' needs (specific dimensions, added text, color, features etc.). It aims at offering customized products, while maintaining the low price allowed by mass production. It is achieved through computer aided manufacturing (CAM) and an interface linking the CAM with the configuration of a product which is normally done directly online. The objects produced with mass customization are often called "made to order" or "built to order". Mass customization requires three essential elements:[80]

- Capturing consumer's data efficiently (interface can be online or at a sales point or a piece of hardware)
- Transforming this data to use it for the customized design
- Producing the right cost for your market

Traditional way of customization is that customization comes at the end of manufacturing process of a product which include mostly variation in colours, accessories etc. But in bespoke cases, separate specialized molds and tooling is fabricated which is expensive and time consuming. In the past, this way of customization was limited to luxury goods only, however, with the introduction of digital technologies and automated manufacturing processes, mass customization has become more accessible and affordable for a wider range of products. With CAD software and freedom and flexibility offered by 3D printing technology, designers can easily create digital models of products and make modifications to suit individual customer preferences. These digital models can then be used to guide the manufacturing process. Every consumer can have a product tailored specifically to his needs and desires, such as ranging from customized orthopaedic implants, prosthetics, artificial limbs, medical devices (e.g., hearing aids), that are patient specific, to architectural designs, to personalized fashion accessories, to unlimited possibilities in other areas. In transport industry, aerospace or automotive, customers can have their products designed and additively manufactured as per their needs, styling etc., enhancing both performance and comfort. One of the mass customization case studies linked to 3D printing is of a company named 'Normal' which designed and manufactured tailored ear-phones as per the data profiles of its customers resulting in products fit for each individual (*Figure 30*).[80]

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[80] Recrosio, E. (2017). Benefits of 3D Printing: Mass Customization. [online] Sculpteo. Link

Figure 30: 3D printed mass customization example of earphones by Normal[80]

An example of a typical set of steps or workflow in a 3D printed mass customization is illustrated in Figure 31, courtesy of Shapeshift 3D.[81]

Figure 31: Illustration of typical steps in a 3D printed mass customization workflow of a thumb-prosthetic device by Shapeshift[81]

Considering the aforementioned, it is useful to highlight some examples of the industrial use-cases. First, Danish company AirFlight tested titanium 3D printed eight arm-brackets for large scale multi-rotor drones having the capability to lift up to 200kg. Using DfAM optimization, the company was able to have 59% weight reduction of original brackets, 11kg overall drone weight, 80% reduction in material amount and less waste than milling operation.[82] Second, BMW developed advanced automobile technology using 4D printing technology for comfortable seats and airbags which changes under varying circumstance. The silicon material inflates with different air pressures and can adopt bulkiness, increase in size, or stay flat.[83] Third, using ABS-CF reinforced polymer, Prototyp3 3D printed an outdoor event space building facade measuring over 48ft long

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[81] V, C. (2020). Shapeshift 3D on developing AM software for mass customization. [online] 3Dnatives. Link
[82] Dansk AM Hub (n.d.). 3D printed design makes the drone fly longer and lift heavier. [online] Link
[83] Autodesk (n.d.) Real-World Applications of 3D Printing. [online] Link

and 12ft.[84] Finally, not sparing the food sector, people can create 3D printed cakes as in the case of Joshua Lankord, who developed '3D Cake Creator' a 3D printer which prints food with just a push of a button away. The sales share were up to 90% of the 3D cakes.[85]

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[84] www.linkedin.com. (n.d.). PROTOTYP3 on LinkedIn: #3dprinting #3dprinted #3dprintingindustry #exteriordesign #facade. [online]. Link

[85] 3DPrint.com, The Voice of 3D Printing, Additive Manufacturing. (2014). Joshua Lankford's 3D Cake Printer Could Become the New Paradigm for Elaborate Cake Creations. [online] Link

5. Additive Manufacturing Materials

When it comes to classic production means like lathe machining or milling, the quantity of material used, and even most of its properties are predetermined. A block is used, mostly of rectangular or cylindrical shape and the properties of that block correspond to the properties of the final product. However, when it comes to additive manufacturing, the materials used are often of a different shape, size and even aggregate state. There are three different types of materials used in additive manufacturing processes and those are: polymers, metals and ceramics, and the combination of the aforementioned being composites. This chapter will describe all off those materials: their format (shape and aggregate state) and their properties. It will also include a description on how to properly choose a material for a specific need, how to optimise its use in sustainability management, and how certain materials are tested and certified.

5.1 Material types

As it was mentioned before, there are three main types of materials used in additive manufacturing processes and those are polymers metals and ceramics. There are also combinations of two or more constituent materials with different physical or chemical properties and that combination is then called a composite (*Figure 32*). The division of these materials is represented in the figure below. The use of a certain material is directly linked to type of additive manufacturing technology used. Next three subchapters will further explain these materials, starting with polymers.

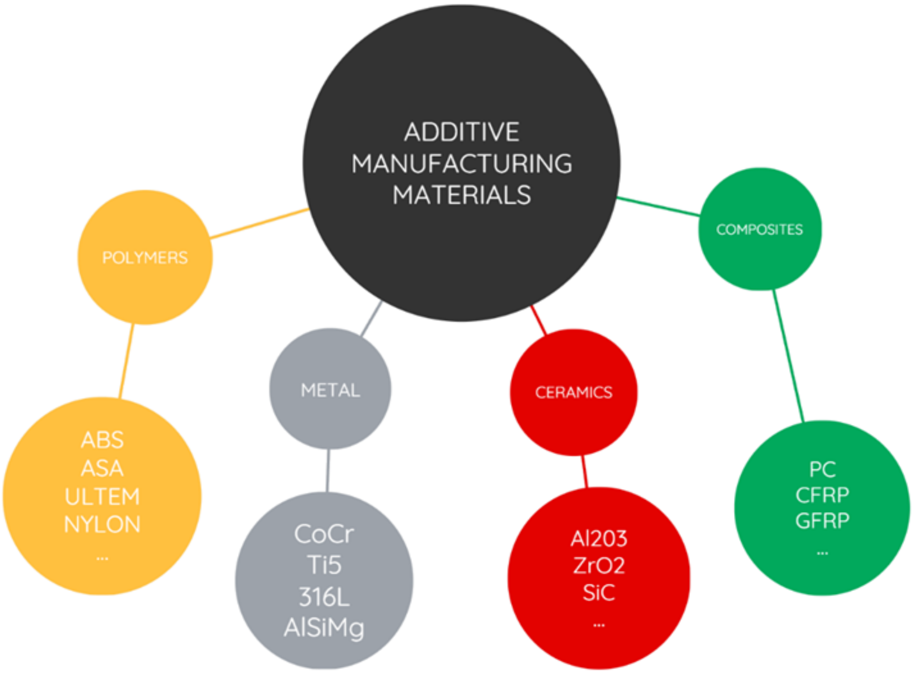

Figure 32: Additive Manufacturing materials

5.1.1 Polymers

Polymers are a group of materials used in additive manufacturing that are composed of repeating structural units called monomers in a process of polymerization in which a chemical reaction bonds monomers into polymers with a covalent bond. Polymers can be classified as natural and synthetic which are further divided into polymers that return to their original shape after being deformed called elastomers and those that don't called plastics. Further classification of polymers for a better understanding of their use and properties is the classification of plastics according to their behaviour at high temperatures. Thermoplastic polymers (plastomers) can be melted and reshaped multiple times without undergoing chemical degradation. In contrast to that duroplasts (duromers), or often called termosets, undergo irreversible chemical reactions when heated and once set they cannot be remelted or reshaped. The classification is shown in *Figure 33*.

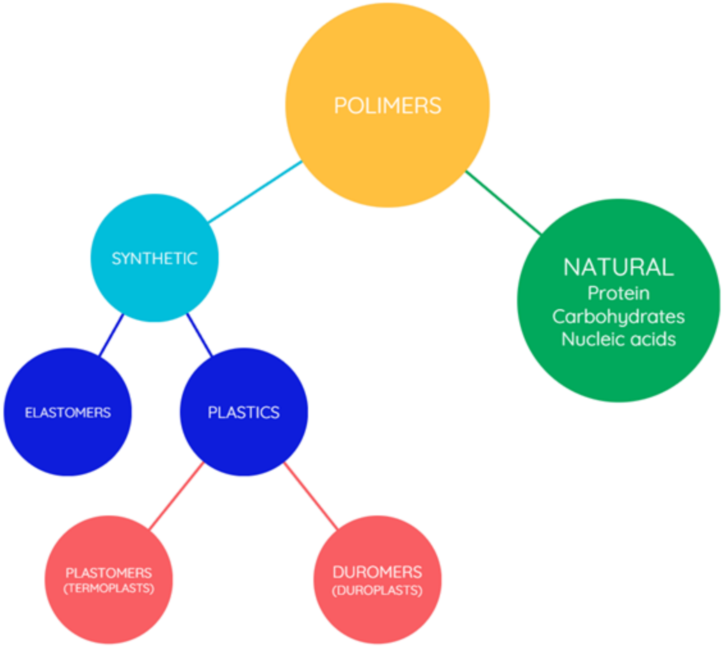

Figure 33: Classification of polymers

In the context of additive manufacturing polymers are classified according to the technology used for the production of a part. As plastomers don't irreversibly change their structure while exposed to heat, they are more often found in filaments used by FDM 3D printers and similar technologies where they are subject to heat, while duromers are epoxy and similar resins, that are set once they are exposed to heat, or in this context a light source of a certain wavelength. The further classification is shown in *Figure 34*.

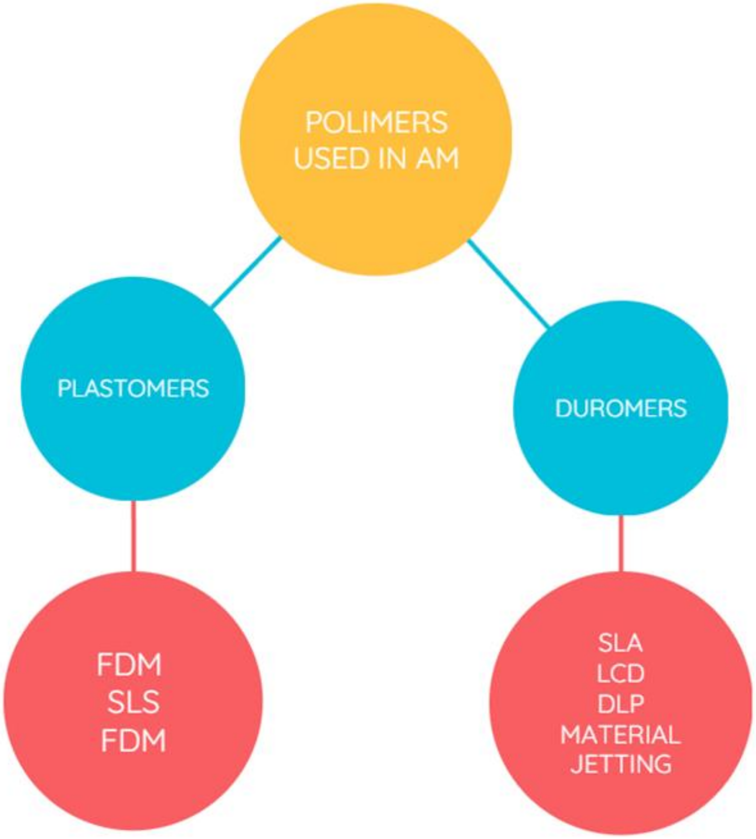

Figure 34: Classification of polymers used in AM

In SLS and MJF technologies some plastomers like PA (polyamide) are used alongside some elastomers more often called TPE/TPR (thermoplastic elastomer/rubber) and a representative of that family of materials is TPU (thermoplastic polyutherane). It is worth mentioning that these materials can also be used by FDM technologies however in a different format.

Plastomers are more often used by FDM technologies and that includes a whole variety of materials like PLA (polyactide), ABS (acrylonitrile-butadiene-styrene), ASA (acrylonitrile- styrene-acrylate), PP (polypropylene), PEEK (polyether-ether-ketone), PEI (Polyetherimide) more often known by the trade name ULTEM and many more.

Durorners are better suited for applications where the aesthetics of the products is one of the key factors, because the technologies that use them are able to create parts with almost smooth surfaces that, in terms of appearance and level of detail, simulate the finishing of products made in the classic way. Duromers that are used in additive manufacturing are different types of resins like epoxy, phenolic or polyutherane.

5.1.2 Metals

A metal material can be defined as a substance composed primarily of metallic elements that exhibit characteristic properties such as high electrical conductivity, thermal conductivity, malleability, ductility, and metallic luster. Metals used in additive manufacturing are mostly alloys, and they can be ferrous, non-ferrous and can even contain precious metals (*Figure 35*). The figure also presents some of the most used materials of every family.

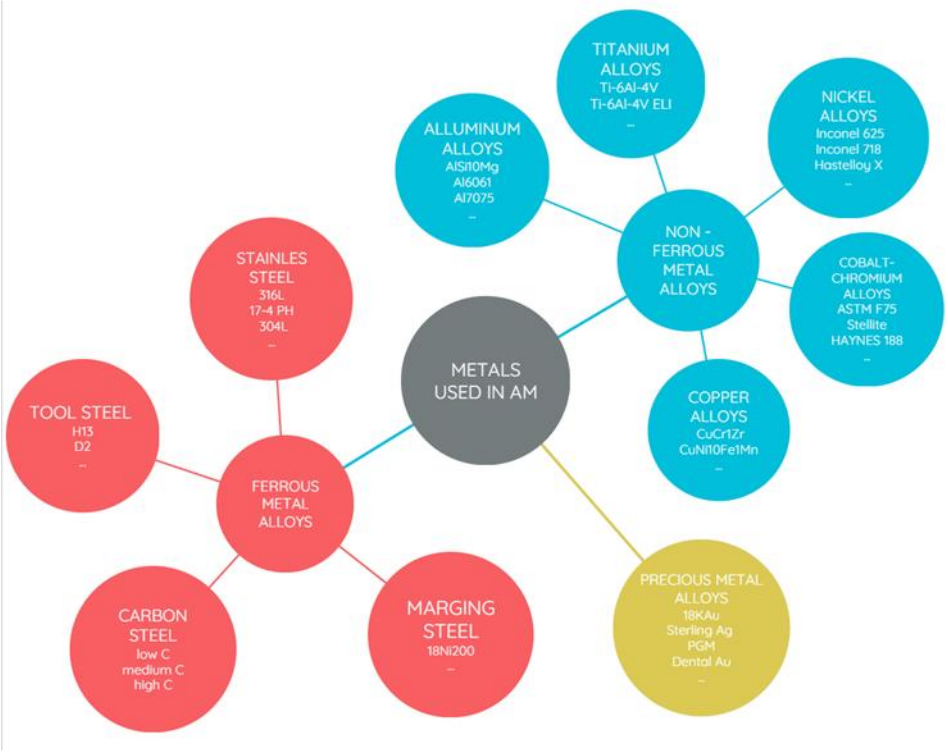

Figure 35: Metals used in AM

It is worth mentioning that, as it is with polymer materials, while there is an overlap in the materials that can be used across different additive manufacturing methods, not all materials are compatible with every technique. The choice of printing method depends on factors such as material properties, part complexity, surface finish requirements, and production volume. It's essential to select the appropriate combination of material and printing technology based on the specific application and desired outcomes. These issues will be explained later in this chapter.

Final products made by additive manufacturing from metal often require heat treatment and postprocessing.

5.1.3 Ceramics

Ceramic materials are inorganic, non-metallic materials that are typically hard, brittle, heat-resistant, and corrosion-resistant. They are composed of metallic and non-metallic elements bonded together through ionic or covalent bonds.

The advantage of using ceramics in additive manufacturing is that it offers a wide range of methods that can be used to make the final product. Binder Jetting, SLS and SLA can all be used in 3D printing of ceramic products from ceramic powder, liquid resin or powder that is joint together by liquid binder.

As it is shown in *Figure 36*, ceramics used in additive manufacturing can be classified in carbides, nitrides, and oxides. As with metal and polymer material, when choosing a convenient method and/or material format it is important to consider material properties, part complexity, surface finish requirements etc.

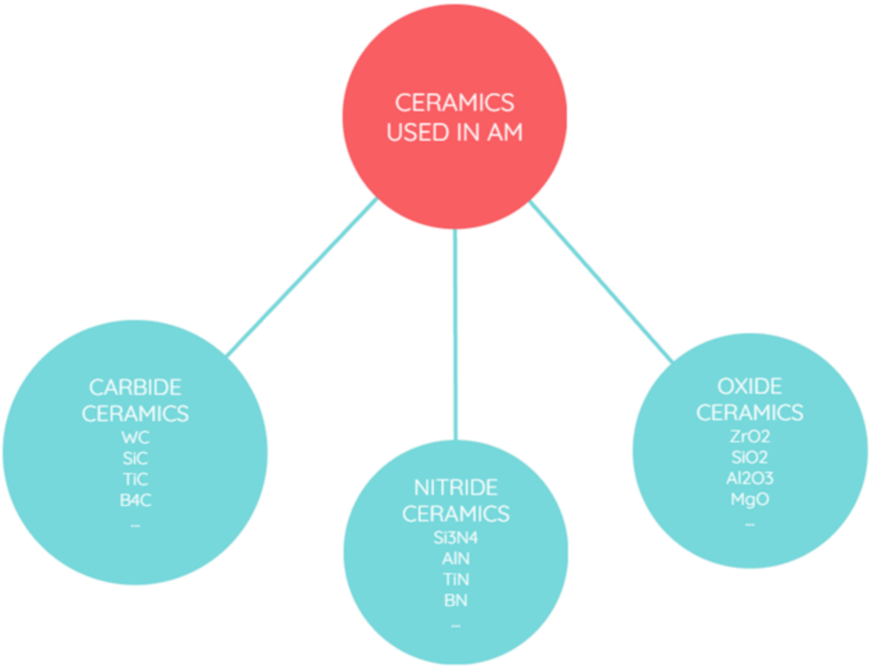

Figure 36: Classification of ceramics used in AM

As it's the case with metals, ceramics often require post-processing steps, such as sintering or firing, to achieve their final properties, which can add time and cost to the manufacturing process. Also achieving consistent material properties, such as strength and porosity, can be challenging.

5.1.4 Composites

A composite material is made by combining two or more constituent materials with significantly different physical or chemical properties to create a new material with enhanced characteristics that cannot be achieved by any of the individual components alone. Composites consist of a matrix material, reinforcement material, and sometimes binder material. They are typically classified by the matrix material as it's shown in *Figure 37*.

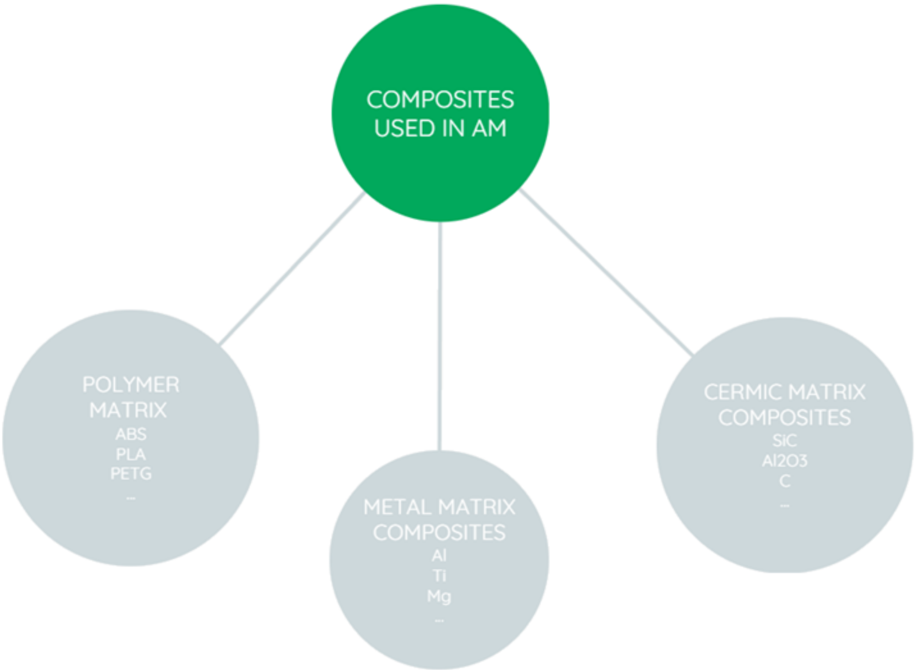

Figure 37: Composites used in AM

Composites are mostly used in automotive and aerospace industries due to their lightweight, high-temperature performance and strength. In additive manufacturing, parts are printed most commonly from CFRPs (Carbon Fiber-Reinforced Polymers) and GFRPs (Glass Fiber-Reinforced Polymers) using special additive methods such as Filament Winding and specialized FDM-like method simply called Continuous Fiber Reinforced Composites (CFRP) Printing.

5.2 Material format

Materials used in additive manufacturing come in different formats meaning they come in different shapes, sizes and even aggregate states. This subchapter will explain the different formats of additive materials and their use in different 3D printing methods.

5.2.1 Filaments

Filaments are one of the most common material formats used in additive manufacturing, particularly in processes like Fused Deposition Modeling (FDM).

Thermoplastic filaments are used in Fused Deposition Modeling (FDM) processes. They come in a variety of materials such as PLA, ABS, PETG, nylon, PC etc. They are typically supplied on spools, as it is shown in *Figure 38* and are fed into the printer's extruder for melting and deposition.

Figure 38: Spools of thermoplastic filaments used in FDM[86]

Metal Filaments are used in processes like Metal Fused Deposition Modelling (Metal FDM) or Composite Fused Filament Fabrication (CFFF). Metal filaments are composed of metal powders mixed with a polymer binder, allowing for the creation of metal or metal matrix composite parts using FFF technology.

5.2.2 Resins

Resins are a format of additive manufacturing material that are in liquified state in standard atmospheric conditions as it is shown in *Figure 39*. They are used in 3D printing methods that use photopolymerization to form a part such as SLA and DLP.

Figure 39: Resin[87]

There are standard resins suitable for a wide range of products but also dental resins that are biocompatible and are often ceramics (ZrO_2), engineering resins of special

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[86] Mantis 3D Printer. (2021). Cheap vs Quality: How Filament Choice Affects Your 3D Prints. Link

[87] P., M. (2023). The Different Types of Resins Available for 3D Printing. Link

material properties and casting resins that are optimized in a way that allows for a creation on highly detailed patterns for metal products.

Compared to filaments, parts made from resins have a higher level of detail and also smoother and more aesthetically attractive surfaces. However more material is used because resins require more supports, hence more postprocessing. In addition to that, resin-based parts can be more fragile and can lose composure when exposed to direct sunlight.

5.2.3 Powders

Mostly used in metal 3D printing technologies such as SLM, DSLM, SLS or EBM, powder format materials offer the ability to produce complex geometries, functional prototypes, and end-use parts with a wide range of materials. *Figure 40* shows a powder being loaded into the 3D printer.

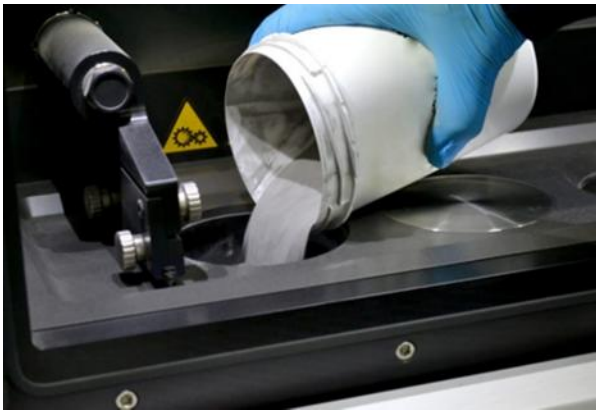

Figure 40: Powder loaded into 3D printer[88]

The most common representatives of this format of additive manufacturing materials are stainless steel, aluminium alloys, titanium, cobalt chrome alloys etc. It is worth mentioning that most of the materials form the previous subchapter can be powder based but metals are mostly used. When it comes to polymers, thermoplastic powders such as nylon, polyamide and polyethylene are used. Representatives of ceramics are alumina, zirconia, and silica while composite powders are CFRPs and GFRPs. Sand powder can be used in a production of casts using binder jetting technology.

Powders used in 3D printing are produced most commonly by gas atomisation. Filaments of metal material are fed into a controlled environment and end of that filament is then melted by a heat coil. Molten metal is then atomized using high-pressure

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[88] Langnau, L. (2020). How metal powder for 3D printing is made. Link

gas streams (typically inert gases like nitrogen or argon) to create droplets that solidify into spherical powder particles. The process is shown in *Figure 41*.

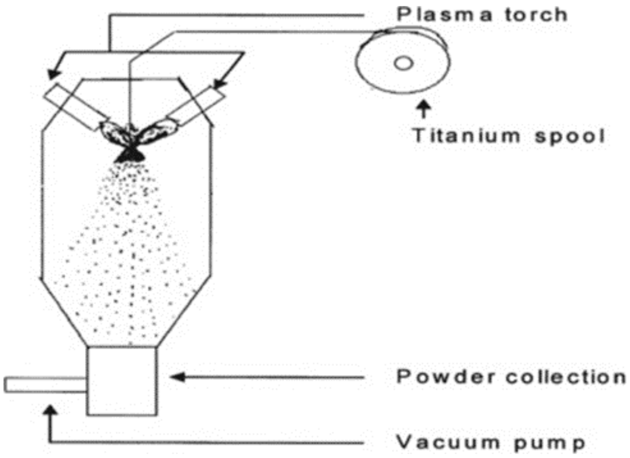

Figure 41: Atomization process[89]

Plasma can also be used to melt the metal filament, and water can be used instead of gas to form the spheres of powder. It is also worth mentioning that powder can be made by electrolysis and metal attrition but much less often.

5.2.4 Pellets

In the context of 3D printing, pellets are small, cylindrical or spherical granules of raw material and are commonly used in a specific type of 3D printing technology known as pellet extrusion or pellet deposition. These 3D printing methods are very similar to FDM.

Pellets used in 3D printing are typically made of thermoplastic materials, such as PLA, ABS, PETG, nylon, and others (*Figure 42*). These materials are widely available and are more cost-effective than purchasing filament spools because they are easier to produce and can easily be recycled from support and other material.

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[89] Kassym, K., Perveen, A. (2020). Atomization processes of metal powders for 3D printing. Link

Figure 42: Pellets used in 3D printing[90]

5.3 Other

This subchapter will further explain properties of certain materials, the optimization of various features in a preparation process for 3D printing and its impact on sustainability issues.

5.3.1 Material properties

Properties of materials can be classified by material format or material itself.

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[90] Indiamart. Colored Plastic Pellets. Link

Table 6: Material properties of AM polymers

Material	Properties	Use
PLA **(Polylactic acid)**	- Biodegradable - Good Strength - Stiff - Heat resistant	- Consumer products - Educational purposes - Food packaging
ABS **(Acrylonitrile butadiene styrene)**	- Impact resistance - Chemical resistance - Toughness - Durability - Heath resistance - Good layer adhesion	- Automotive parts - Electronic housings - Functional prototypes - Consumer products
PETG **(Polyethylene terephthalate)**	- Strength - Flexibility - Impact resistance - Excellent layer adhesion - Chemical resistance	- Functional prototypes - Mechanical parts - Medical devices - Food packaging
Nylon	- Strength - Toughness - Flexibility - Excellent impact resistance - Abrasion resistance	- Gears - Bearings - Mechanical components - Structural parts
TPU **(Thermoplastic polyurethane)**	- Flexible and elastic - Resilience and fatigue resistance - Cyclic load and fatigue resistance - Tear resistance - Chemical resistance - Can withstand repeatable bending	- Seals - Gaskets - Phone cases - Footwear components
PP **(Polypropylene)**	- Lightweight - Chemical resistance - Good impact strength - Moisture resistance - Low friction coefficient	- Automotive components - Packaging - Containers - Hinges

Table 7: Material properties of AM metals

Material	Properties	Use
Titanium	- Highest strength to weight ratio out of every metal - Excellent thermal conductivity - Resistance to corrosion - Biocompatible	- Medical and dental parts - Aerospace - Marine application
Aluminium	- Lightweight - Good strength to weight ratio - Excellent thermal conductivity - Resistance to corrosion	- Aerospace - Automotive industry - Heat exchangers - Electronics
Stainless steel alloys (316L, 17-4 PH, 15-5 PH, 304…)	- Resistance to corrosion - Strength - Customization according to need	- Automotive - Aerospace - Consumer goods
Tool Steels (H13, D2, A2, M2, S7…)	- High hardness - Wear resistance - Toughness - Thermal stability	- Tooling and cutting application - Molding and forming
Cobalt chrome alloys (CoCrW, CoCrW…)	- Biocompatible - Resistance to corrosion - Wear resistance - High melting point	- Medical and dental parts - Applications involving friction and abrasion

Table 8: Material properties of AM ceramics

Material	Properties	Use
Alumina **(Al_2O_3Aluminium Oxide)**	- High hardness - Chemical resistance - Thermal stability	- Wear resistant applications - Suitable for corrosive environments - Applications involving thermal stress
Zirconia **(ZrO_2 Zirconium Oxide)**	- High toughness - Impact resistance - Biocompatibility - Low thermal conductivity	- Medical implants - Dental prosthetics - Barrier coatings - Insulating applications
Silicon carbide **(SiC)**	- High strength - Stiffness - High thermal conductivity - Chemical resistance	- Heat exchangers - Thermal management applications - Application in harsh environments
CFRPs **(Carbon Fibre Reinforced Polymers)**	- Excellent strength to weight ratio - High stiffness - Fatigue resistance - Rigidity and dimensional stability	- Lightweight structural components - Applications subjected to cycling loading - Automotive and aerospace
GFRPs **(Glass Fibre Reinforced Polymers**	- Good strength - Good impact resistance - Resistance to corrosion - Electric insulation properties	- Structural applications - Electric and electronical applications

Table 9: Properties of AM material format

FILEMENT	PELLETS
- Ready for direct extrusion - Requires extra steps in production - Vacuum-sealed packaging	- Requires additional processing steps before extrusion - Cheaper and more recyclable - Bulk packaging (bags or containers) - Susceptible to moisture absorption and degradation

5.3.2 Selection and optimization – printing best practices – Stratasys GrabCAD

As it is with any production method, in additive manufacturing it is of key importance to analyse the product, think about its use and optimize it. The selection and optimization are closely related to material properties.

Part orientation can have a huge effect on the amount of time it takes to build your part. Generally, the shorter your part is in the Z axis the faster it will build. The part on the left in *Figure 43* would take much longer to build than the same part laid down on the right.[91]

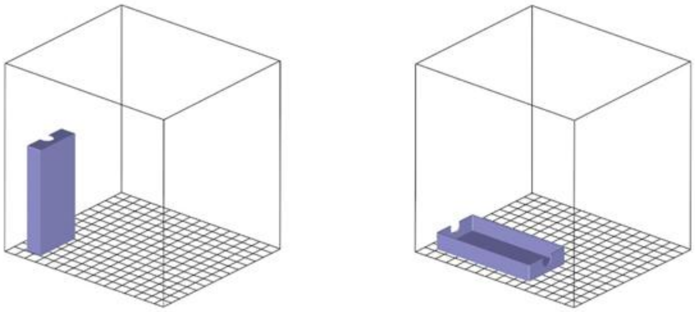

Figure 43: Speed/build time[91]

Support usage is also dependent on part orientation. Any overhangs must be held up by support material. For example, in *Figure 44* the stand on the left would have a very large amount of support under it whereas the stand on the right would use a very minimal amount of support. Less support material will also shorten your build times.[91]

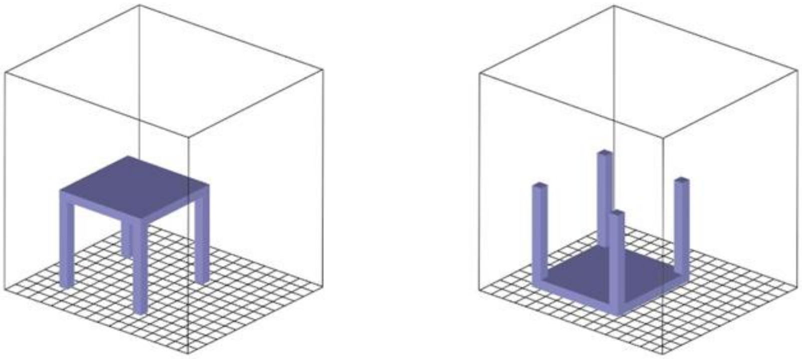

Figure 44: Support usage[91]

It is important to understand that surface quality is directly associated with part orientation. When there are curved surfaces on the top or bottom of the part they will

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[91] GrabCAD. (2020). 3D printing best practices. Link

appear “stair stepped” after being built. By orienting the part with curved surfaces positioned in the Z axis (to the sides) the surfaces will appear much smoother. For example, in *Figure 45* below the wings and fuselage of the jet on the left will have a stepped appearance, the jet on the right will take longer to build, but the finished appearance will be much better.[91]

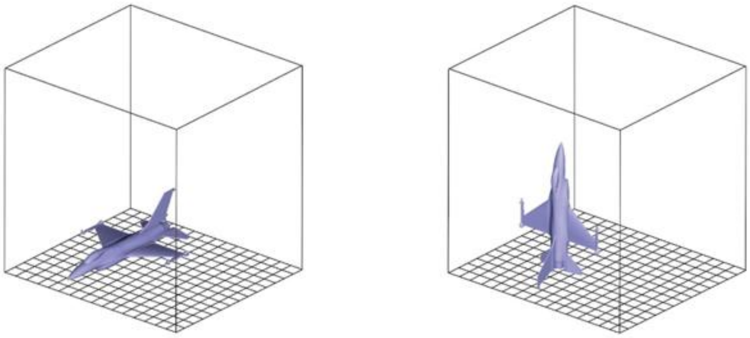

Figure 45: Surface quality[91]

Support removal is a concern especially when using breakaway supports. In *Figure 46* below, the supports filling the longer hole on the left part will be difficult to remove since they are deep inside the part. The same part on the right will not need supports in the longer hole since it is vertical and the supports in the shallower holes will be relatively easy to remove.[91]

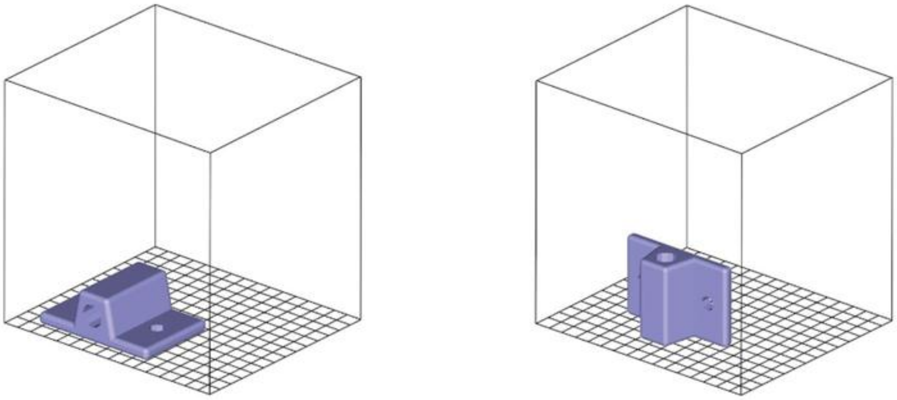

Figure 46: Support removal[91]

Part orientation has a large effect on part strength. When stress will be applied to a part such as the broom holder in *Figure 47*, it is better for the tabs to be in the same layer as the body of the part (part on the right). The adhesion of one layer to another is weaker than the adhesion of the layer within itself. The part on the left would be much weaker when used as a functional model. You can think of it like splitting wood. It is easy to split with the grain but very hard across the grain.[91]

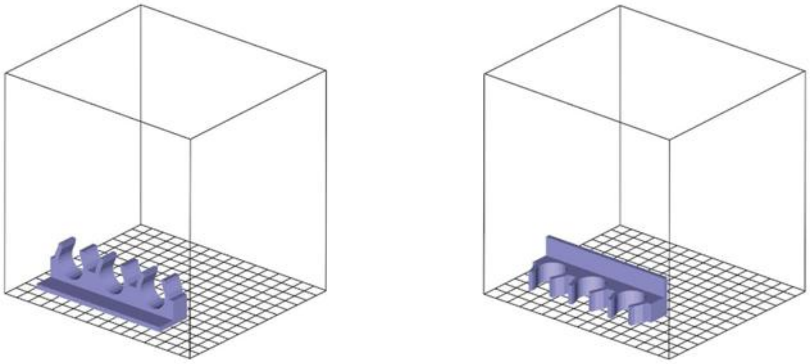

Figure 47: Part strength[91]

Interior fill styles will have a direct effect on most of the properties of the part. The style used will depend on the intended use of the part. Most commonly used infill styles for polymers are shown in Figure 48 from left to right: solid, spars and double dense.[91]

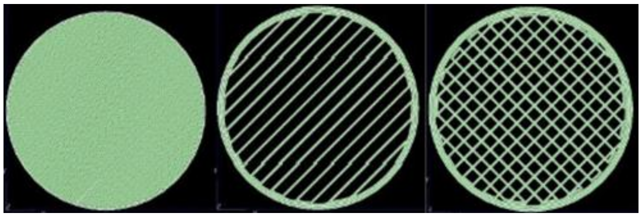

Figure 48: Most commonly used infill style: solid, spars and dense[91]

5.3.3 Sustainability of AM materials

Additive manufacturing techniques can contribute to sustainability in forms of material efficiency, recycling and reuse with bio-based and recyclable materials, material optimization etc.

When it comes to material efficiency SLM or FDM methods build objects layer by layer, often requiring less raw material compared to traditional subtractive manufacturing methods. This reduction in material waste contributes to overall sustainability.

Many additive manufacturing materials, such as thermoplastics used in FDM or metal powders used in powder bed fusion techniques, can be recycled and reused.

Biodegradable polymers or sustainable biomaterials are also being developed. These materials reduce dependence on fossil fuels and minimize environmental impact throughout the product lifecycle.

Additive manufacturing enables the production of lightweight, complex, and optimized designs that use less material while maintaining structural integrity and performance. Lightweighting reduces energy consumption during transportation and operation, contributing to sustainability efforts.

Localized production and on demand manufacturing using additive technologies means less energy and time wasted on transport leading to lower carbon emissions associated with shipping and logistics.

Additive manufacturing enables the production of customized parts on-demand, reducing the need for large inventories of standardized parts. This inventory reduction lowers excess production and material waste associated with overstocking and obsolescence.

5.3.4 Material Innovation and Emerging Trends

The field of additive manufacturing is undergoing significant transformations, driven by innovative material developments and emerging trends that promise to redefine its capabilities and applications. This section explores four key areas of material innovation that are paving the way for new possibilities in 3D printing technology. From the ability to print with multiple materials simultaneously to the advent of bioprinting, the evolution of advanced polymers, and the shift towards recycled and sustainable materials, these advancements are shaping the future of manufacturing.

5.3.4.1 Multi-material Printing

Traditional 3D printing techniques typically involve printing with a single material at a time. However, advancements in multi-material printing allow for the simultaneous deposition of multiple materials, enabling the fabrication of complex, functional parts with diverse properties. One nozzle that is similar to a classical FDM printers can change 2-8 materials quickly and in high resolution. This capability opens up opportunities for creating products with integrated electronics, sensors, and even biological components.

5.3.4.2 Bioprinting

Bioprinting involves the precise deposition of biological materials, such as living cells and biomaterials, to fabricate tissues and organ-like structures. This technology holds immense promise for regenerative medicine, drug testing, and personalized healthcare. Recent developments in bioprinting include the use of bioinks with improved biocompatibility and the integration of vascular networks to support tissue viability.

5.3.4.3 Advanced Polymers

Polymer-based additive manufacturing continues to evolve with the introduction of advanced materials exhibiting enhanced mechanical properties, chemical resistance, and temperature stability. Innovations in polymer composites, including carbon fibre-reinforced plastics and graphene-enhanced materials, enable the production of lightweight, high-performance components for aerospace, automotive, and sporting goods industries.

5.3.4.4 Recycled and Sustainable Materials

With growing environmental concerns, there's a trend toward using recycled and sustainable materials in additive manufacturing. Companies are exploring alternative feedstocks derived from recycled plastics, biodegradable polymers, and even waste materials like recycled metals and wood-based filaments. These eco-friendly materials not only reduce environmental impact but also offer cost savings and new design opportunities.

6. Advanced designing tools

In the evolving landscape of manufacturing, the integration of additive manufacturing technologies has revolutionized the design and production processes of complex components. Traditional manufacturing methods often impose limitations due to their reliance on outdated knowledge, processes, and capabilities. These constraints result in designs that are compromises, balancing functional requirements with the realities of manufacturing technology, operating costs, waste management, and other lifecycle factors.

Additive manufacturing, commonly known as 3D printing, breaks these barriers, allowing for the creation of intricate geometries and optimized structures that were previously unachievable. This chapter delves into various innovative design methods that have emerged in tandem with additive manufacturing technologies. These methods include Topology Optimization, Generative Design, Multiscale Structure Design, Multimaterial Design, Parts Consolidation, and Lattice Structures, each offering unique advantages and capabilities.

With additive manufacturing, designers can prioritize the application-specific requirements and creative aspirations for components, rather than being constrained by traditional manufacturing limitations. This shift enables the production of highly efficient, lightweight, and structurally sound components for industries such as automotive, aerospace, and biomedicine.

In the sections that follow, we will explore each design method in detail, highlighting their principles, advantages, disadvantages, and real-world applications. By understanding these methods, designers and engineers can harness the full potential of additive manufacturing to innovate and optimize their product designs, leading to enhanced performance, reduced costs, and minimized environmental impact.

6.1 Design for Additive Manufacturing *(DfAM)*

Manufacturing technology, operating costs, waste management, etc. are limiting factors that influence the component design process, even if they are not directly related to its functionality. Currently, the resulting design is a compromise that takes into account all the specific factors of the product life cycle.

Manufacturing technology is one of the limiting factors that has a significant impact on product design. The working principle of traditional manufacturing technologies is based on relatively old knowledge, know-how and available capabilities. The conventional design approach does not achieve the optimum part properties for its application.

Modern additive manufacturing technologies enable innovative component design processes to be implemented. The design of the structure is determined only by the application and the specific requirements of the designer for the component. The complex geometry of an optimized part for the specified conditions is often difficult or impossible to produce with traditional manufacturing technologies.

Based on the new knowledge and understanding of the capabilities of additive manufacturing technologies, the following design methods have been introduced:

- Topology Optimization
- Generative Design
- Multiscale structure design
- Multimaterial design
- Parts Consolidation
- Design for mass customization
- Lattice structures
- Thermal issues in design

In the following subsections, each innovative design method is described in more detail.

6.1.1 Topology Optimization

Topology Optimization is a mathematical iterative method that works on the principle of removing and distributing material in a defined space of the original shape of the part. The optimization is based on predefined conditions - load, functional elements of the part that must be preserved (contact surfaces, holes, etc.), constraints, limiting space (original shape of the part).

Often Topology Optimization is confused with the Generative Design method. The main difference is that topological optimization improves the design of an existing component, and the Generative Design method creates a new component with an optimal design.

The optimization itself is preceded by a strength simulation of the part using the finite element method. The results are stress and strain maps that serve as input to the optimization process (*Figure 49*).

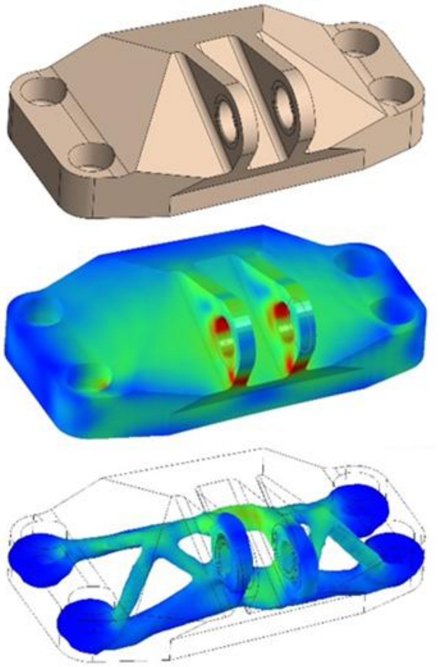

Figure 49: Optimized shape of component after Topology Optimization[92]

The optimization process can be based on different strategies. The most widely used topological optimization strategies are:

1. Maximize stiffness for a given mass
2. Minimize mass while respecting constraints
3. Maximize lowest frequencies for a given mass

For the strategies *Maximize stiffness for a given mass* and *Maximize lowest frequencies for a given mass*, it is necessary to define the desired weight of the optimized part.

Optimization strategy *Minimizing mass while respecting constraints* requires setting a limiting factor, such as:

- maximum permissible stress
- maximum permissible deformation
- maximum/minimum wall thickness
- manufacturing technology

In this strategy, material is being removed and distributed as long as the topological optimization conditions are satisfied. A schematic representation of the entire topological optimization process is shown in Figure 50.

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[92] FE Training. (2018) Topology Optimization (Part 1). Link

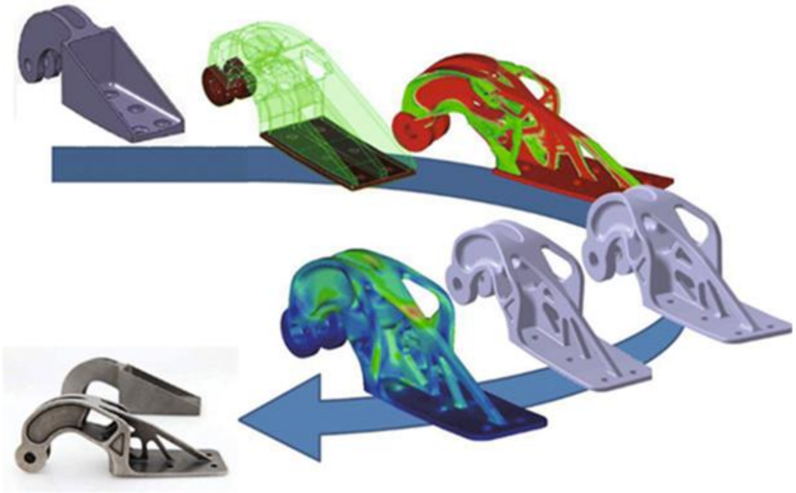

Figure 50: Steps of Topology Optimization process[93]

The principles of Topology Optimization have been known for several decades. The method provides optimal designs for components that are very complex in terms of geometry and are unmanufacturable or difficult to manufacture by traditional manufacturing methods (chip machining, casting). It is with the advent of additive manufacturing technologies that it has become more widely applied to the component design process.

Currently, Topology Optimization is being implemented in the development of components for the automotive, aerospace, space and medical industries. These are highly efficient components with optimal strength, mass and dynamic parameters for a specific function. The resulting design is characterized by organic shapes that are only manufacturable by 3D printing. Advantages of topology optimizations are:

- design optimization
- saving money
- saving time
- reducing environmental impact
- eliminating errors

Design optimisation

This is a rather obvious fact, but it is the major advantage that also brings smaller added benefits to the design. An optimised design balances every quality as a product of the best solution (the best here meaning the most efficient or appropriate). It is made

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[93] Meng, L., Zhang, W., Quan, D. et al. From Topology Optimization Design to Additive Manufacturing: Today's Success and Tomorrow's Roadmap. Arch Computat Methods Eng 27, 805–830 (2020). https://doi.org/10.1007/s11831-019-09331-1. Link

to have a smaller size and weight without sacrificing the structural or component quality.[94]

Saving money

Manufacturing 3D printed parts can still be more expensive to produce than their non-optimized, traditionally manufactured counterparts, but these lightweight designs can offer larger cost savings to manufacturers in other ways:[94]

- Better fuel efficiency as there is less energy required to put parts in motion thanks to the lower friction (airplanes, automotives)
- Lower packaging and transportation costs
- Less heavy machinery necessary for assembly lines

Saving time

While working with topology optimization software still requires significant expertise, TO tools can rapidly produce high-performance designs that an engineer could not create manually. This means less time and energy spent in CAD design and reliable end results with fewer iterations of the design.[94]

When it comes to the manufacturing of the parts, additive manufacturing processes can also turn around final parts quickly as they don't require tooling, which can take weeks or months to be delivered for traditional manufacturing methods.[94]

Reducing Environmental Impact

Creating smaller, lightweight products reduces a manufacturer's overall carbon footprint by requiring less building material in the first place. When compared to traditional subtractive manufacturing tools, parts produced through additive processes also generally require less raw material and produce less waste.[94]

Oftentimes, the most significant savings occur throughout the lifetime of the parts. For example, lightweight parts for airplanes reduce their environmental impact by requiring less fuel.[94]

Eliminating errors

At its foundation, topology optimization is about eliminating errors. By conducting stress testing, the process accounts for a wide range of variables and avoids risky assumptions that could lead to faulty products.[94]

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[94] Formlabs. (n.d.). Topology Optimization 101: How to Use Algorithmic Models to Create Lightweight Design. Link

6.1.2 Generative Design

Generative Design is an innovative method of designing. It is a program that iteratively generates the design of a component by considering the predefined conditions and requirements of the designer. The input parameters determining the iterative shape generation process are:

- functional elements and nodes (contact surfaces, holes)
- limiting volume (space determined by the distribution of surrounding components)
- load
- constrains
- material
- allowable stress (or safety factor)
- target weight
- manufacturing technology
- price

Unlike the Topology Optimization method, where an existing part shape is optimized, the Generative Design method creates a set of entirely new and unique geometries (*Figure 51*).

Figure 51: Set of generated geometries[95]

The effect of manufacturing technology on the geometry of the generated motorcycle triple clamp shape is presented in *Figure 52*.

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[95] Danon, B. (2018). How GM and Autodesk are using generative design for vehicles of the future. Link

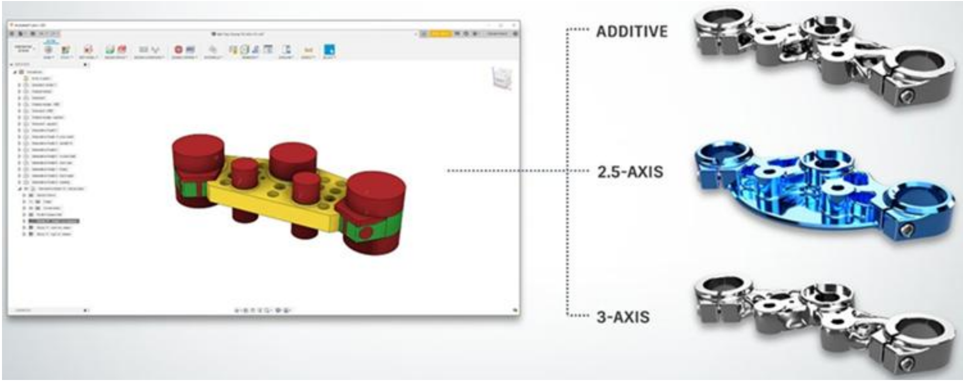

Figure 52: Impact of manufacturing technology on the generated shape[96]

The software also provides the user with an output that compares the individual generated geometries against the specified conditions (Figure 53).

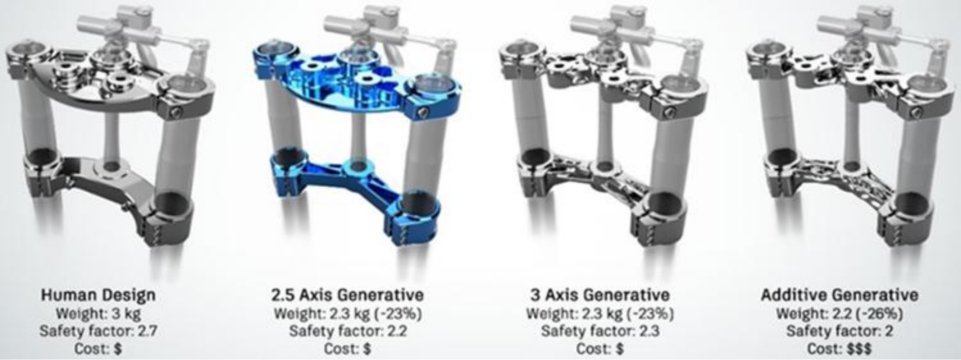

Figure 53: Comparison of generated shapes[96]

Advantages of Generative Design are:

- simultaneous exploration
- accelerated design timeline
- leverage advanced manufacturing processes
- expert results
- optimized product costs

Simultaneous exploration

A notable benefit of generative design is that it allows the simultaneous exploration, validation, and comparison of hundreds or thousands of design options. The software can display and compare design options in a way that enables engineers to quickly and efficiently find the ones that best meet a project's parameters and needs.[97]

Accelerated design timeline

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[96] Willis, K.D.D. (2024). Generative Design 2.5 Axis Milling Constraints. Link

[97] Generative Design 101. Link

When engineers leverage AI to discover and test new complex design iterations quickly, efficiently, and at scale, they can drastically shorten research and development timelines for new products. As a result, companies utilizing generative design can gain a competitive edge in accelerating products' time to market.[97]

__Leverage advanced manufacturing processes__

Generative design can create complex designs like organic features and internal lattices to leverage the unique design freedom offered by additive manufacturing technologies. It also offers the ability to consolidate parts, so a single complex geometry created by a generative algorithm and 3D printed can often replace assemblies of dozens of separate parts.[97]

__Expert results__

Concerned about the skills gap? An entry-level mechanical engineer can now create a part using generative design without extensive knowledge. And when the system returns hundreds of suitable solutions, artificial intelligence, included with generative design technology, can quickly help filter myriad design options.[98]

__Optimized product costs__

Generative design can save money by rooting out over-designed parts. These are designs that, while reliable, may use more materials or complex manufacturing methods than necessary.[98]

6.1.3 Multiscale structure design

The Multiscale structure design method is used to create components with a multilevel structure, which is characterized by a system of cells and grids at the micro or macro level. Such a textured structure has excellent mechanical properties and reduces the weight of the part. Parts designed by this method are mainly used in aerospace applications (*Figure 54*).

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[98] McClintock, C. (2023). A Beginner's Guide to Generative Design. Link

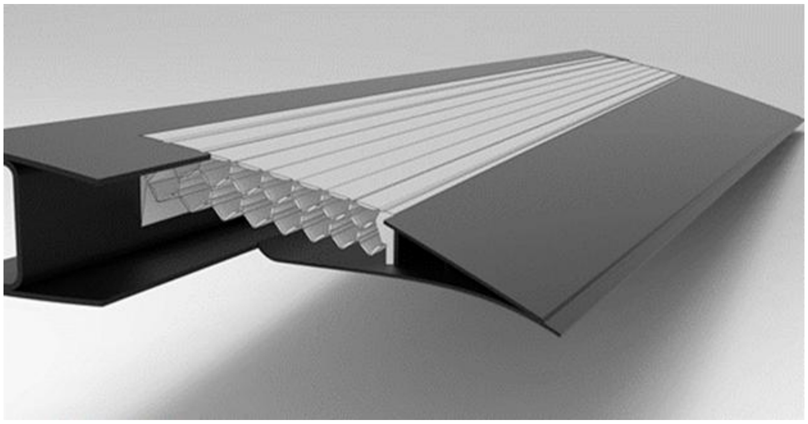

Figure 54: The concept of a multiscale structure design of wing

Bio-implants with a structure consisting of a system of cells and grids, produced by additive manufacturing technology, are now beginning to be used in the field of biomedicine (*Figure 55*).

Figure 55: Multiscale structure of bio-implants – osseointegration

6.1.4 Multimaterial design

One way to achieve the desired mechanical, physical and chemical properties is to produce a multi-material component - composites. Recent additive manufacturing technologies already make it possible to produce parts from composite materials.

To fully exploit the potential of such materials, new methods of both design and simulation have been developed. Modern optimization and simulation software can also cope with the inhomogeneous properties of designs made of multiple materials that form a composite material or are functionally graded in structure.

The production of parts from composite materials by additive Material Extrusion, common knowns as FDM technology, is very widespread. The carrier component of the filament consists of carbon or glass fibres and the binder is polymer (*Figure 56*).

Figure 56: Carbon fiber PETG filament

The design of a part, which consists of a number of functionally graded materials, is shown in *Figure 57*.

Figure 57: Nickel-copper combustion chamber demonstrator parts on the build platform[99]

Multi-material 3D printing allows for the use of different materials within the same object, each selected for specific properties like rigidity, elasticity, or temperature resistance.[100]

The core benefit lies in its ability to integrate different materials into a single print job. This significantly expands the design possibilities and functional capabilities of printed objects. By using this technology, designers can achieve a level of complexity and utility that was previously unattainable with traditional single-material 3D printing methods.[100]

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[99] Seidel, Ch. (2022). Multi-material metal parts by Powder Bed Fusion: New application opportunities. Link

[100] McGarry, S. (2023). The Benefits of Multi-Material 3D Printing. Link

The integration of multiple materials in a single print also allows for the optimization of individual parts of an object when adhering to specific requirements. For example, an item can be designed with rigid internal structures for strength and stability while having flexible external surfaces for enhanced grip or comfort. This marriage of diverse material properties in a single object is especially crucial in industries like biomedical, automotive, and consumer electronics. Here the combination of strength and flexibility is often required.[100]

Additionally, multi-material 3D printing is a step forward in manufacturing efficiency. This technology reduces the need for multiple-part assembly, as an object with varied materials can be produced in one go. This not only decreases production time but also minimizes potential assembly errors, leading to higher quality and more reliable products.[100]

6.1.5 Parts Consolidation

Due to the limited capabilities of traditional manufacturing methods, components with complex geometries are broken down into several, more easily manufacturable, parts. Joined together by either dismountable or non- dismountable joints, they subsequently form the whole of the component. Additive manufacturing allows the individual parts of the original component design to be merged into a single complex unit. This method is called parts consolidation.

Designing a part using the Parts Consolidation method not only results in a reduction in the number of parts, but also a reduction in component weight, easier assembly, and improved performance (*Figure 58* and *Figure 59*).

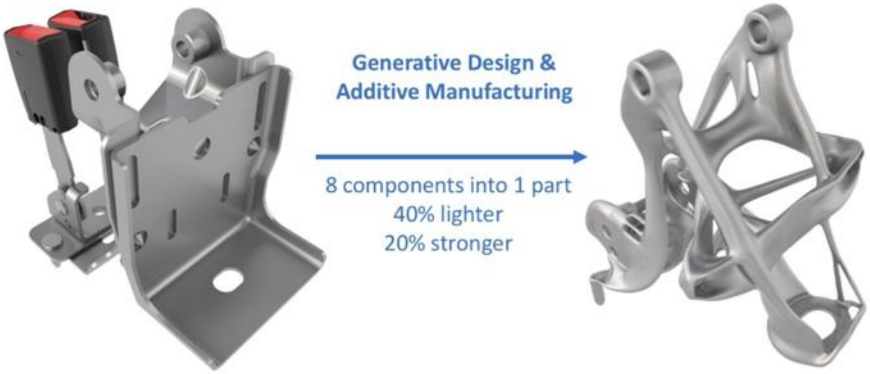

Figure 58: Reduction in the number of components of the safety-belt anchorage mechanism[95]

Figure 59: Piping system designed by the Parts Consolidation method[101]

Advantages of Part Consolidation method are:

- elimination of assembly
- fewer points of failure
- lower operation costs
- reduction in the supply chain
- low risk of failure
- cost saving
- easy assembling

Elimination of assembly

This includes reduced labor, inventory, fixturing/tooling, and manufacturing floor space dedicated to your final product. Assembly inspection is also reduced, no opportunities for assembly errors.[102]

Fewer points of failure

Maintenance costs are reduced long term, and you can stock fewer replacement parts. If needed, low-volume replacements can be made quickly and cost effectively.[102]

Reduction in the supply chain

As parts consolidation results in a smaller number of components to be used, it effectively reduces the supply chain as the demand decreases. The reduction in supply chain can help your business profits increase as you save on the supply costs.[103]

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[101] Schwaar, C., Newton, E. (2022). 3D Printing for Part Consolidation – The Ultimate Guide. Link

[102] Proto Labs. Part Consolidation for Additive Manufacturing. Link

[103] Parts Consolidation with Additive Manufacturing- From Multiple to Singular. Link

Low risk of failure

Part consolidation reduces or eliminates number of risks. For example, you can circumvent the risk that your supplier can no longer supply the part in question. This supplier risk is multiplied by the number of parts in the assembly. If you're able to print multiple parts as a single unit using AM, the chance of encountering this issue greatly decreases. There are other risks that are reduced as well. The instances of part failure decrease when the part has been manufactured as a single unit rather than assembled separately. Another risk is obsolescence; when the part reaches the end of its life you will not have remaining inventory that must be disposed.[103]

Cost saving

This is one of the best and most obvious benefit of consolidating your parts with AM. If you are needing fewer parts to assemble means you are spending less money on assembly costs. If the assembly is taken out of the equation that means you will reduce potential cost-driving factors such as quality control or inventory management. Through parts consolidation, you are also lessening the risk of hidden costs and project delays. It even benefits in supply chain optimization which further helps in cost reduction.[103]

Easy assembling

Due to a smaller number of parts, it gets easy to assemble them which reduces the labour. Faster the assembly takes place, faster the products get ready to dispatch.[103]

6.1.6 Lattice Structure

Lattice Structure is a system of open cells and grids. This type of structures (difficult to produce with traditional manufacturing technologies) is widely applied to the design of components intended for 3D printing production (*Figure 60*).

Figure 60: Component with Lattice structures[104]

The Lattice Structures (*Figure 61*) are characterized by mechanical properties as low weight and density, and multifunctionality (sieve function, heat dissipation). Thanks to these properties, they are used in parts for the automotive, aerospace and medical industries.

Figure 61: Different types of Lattice structures[105]

Advantages of Lattice Structure are:

- lightweighting
- cost Effectiveness
- high strength-to-weight ratio
- energy absorption

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[104] Materialise. (2020). Titanium Inserts for Spacecraft: 66% Lighter with Metal 3D Printing. Link

[105] Altair. (2022). Types of Lattices for Additive Manufacturing – Terms Engineers Need to Know. Link

- thermal management

Lightweighting

Design engineers often leverage lattice structures for lightweighting aerospace or automotive components, industrial machinery, orthotics, and prosthetics to reduce part weight while retaining structural integrity.[106]

Latticing enables you to reduce solid mass without compromising on performance. Using a shell and lattice infill approach, 50% or higher weight reductions are not uncommon. Less material also reduces manufacturing costs, making production with additive manufacturing economically viable.[106]

Another benefit of lattice structures in lightweighting applications is that they can be highly resilient to damage. This property makes them suitable even for critical components where the part must endure significant loads.[106]

Cost Effective

With less material than parts produced by conventional manufacturing methods, lattice structures are far less expensive than solid structures, making them an ideal option for 3D printing.[107]

High strength-to-weight ratio

If designed according to accepted principles, parts with lattice structures can have unparalleled strength-to-weight ratios. This advantage makes them ideal in automotive and aerospace applications (among others), where it's critical to minimize mass.[107]

Energy absorption

Lattice structures are very efficient at dissipating impact and shock loads because the cell configuration helps the whole structure flex and distribute energy. Complex lattice types can redirect and better distribute energy in multiple directions to absorb impact force.[106]

Thermal management

Heat transfer rate is proportional to the available heat transfer area, and lattice structures naturally provide a large surface area. Specifically, gyroids, a type of TMPS lattice, are especially useful for thermal management and heat exchanger applications.[106]

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[106] nTopology. (2022). Guide to lattice structures in additive manufacturing. Link

[107] Dassault Systèmes. What is a Lattice Structure in 3D Printing. Link

Gyroids have a high strength-to-weight ratio and naturally separate the flow into multiple interweaving channels or domains while providing a substantial surface-to-volume ratio. This makes gyroids effective for creating more compact heat exchangers that offer higher efficiency.[106]

Lattice cores are the heart of many 3D printed high-performance heat exchangers that find applications in aircraft and road vehicles, industrial facilities, electronics cooling, and precision manufacturing.[106]

6.1.7 Design for Mass Customization

Thanks to the fact that in additive manufacturing a part is printed directly on the basis of the generated map of the digital CAD model, it is possible to modify the part very quickly and inexpensively.

This design method is characterised by parametric modelling. The individual dimensions of the part are defined in the CAD software using a parameter. The parameter values can be changed, for example, via Excel. This design method enables the rapid generation of parts similar in design, shape, dimensions or appearance to customer requirements - part personification (*Figure 62* and *Figure 63*).

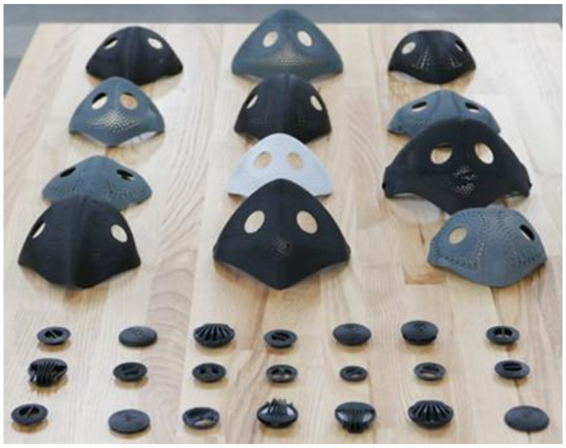

Figure 62: Personified masks

Figure 63: Customized glasses[108]

Advantages of Mass Customization are:

- automated customization from scan to print
- revolutionize your product strategy
- lean manufacture: series of one
- tailor-made designs
- improved inventory management

Automated customization from scan to print

With a digital workflow that includes design automation and optimized printing processes, you can take advantage of seamless, automated mass customization from start to finish. By digitalizing manual processes, you'll break down barriers to entry, lower the cost of innovation, and make your production reliable, repeatable, and faster than ever.[109]

Revolutionize your product strategy

Thanks to unmatched design freedom, innovation is the backbone of 3D printing. With the benefits of this technology, you can diversify your product line, reach into untapped markets, and bolster your market share by creating complex, innovative products that cater to the individual consumer.[109]

Lean manufacture: series of one

With 3D printing, mass customization becomes an entirely digital process - you can print on demand or in short production runs with no minimum order quantity or set-up costs. While too costly through traditional manufacturing methods, 3D printing makes mass customization lean and affordable.[109]

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[108] AMFG. (2020). 3D Printing and Mass Customisation: Where Are We Today? Link
[109] Materialise. Mass Customization. Link

Tailor-made designs

One-size-fits-all really fits no one. With the design freedom of 3D printing, you can design and create products that offer your customers what they want and need - personalized to their tastes, current trends, and even their anatomy.[109]

Improved inventory management

Improved inventory management can reduce overhead costs and waste, contributing to sustainability, which is increasingly valued by the customer base.[110]

6.2 Thermal issues in design

In 3D printing, the quality of a part is greatly affected by the thermal processes involved in the manufacturing process. The effect of heat is particularly significant in metal additive manufacturing. A typical problem is the deformation of parts printed by Binder Jetting technology, during the sintering process (*Figure 64*).

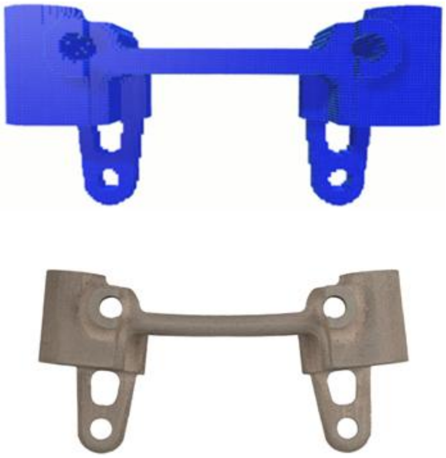

Figure 64: Part printed straight, sintered warped[111]

Simulation software that models heat generation and transfer is used to optimize part design and process parameters for production. The optimization software pre-deforms the part design and defines the optimum printing and sintering parameters, thereby reducing or eliminating the negative effects of thermal processes during the manufacturing process (*Figure 65*).

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[110] Formlabs. Guide to Mass Customization. Link

[111] Desktop Metal. Live Sinter™. Link

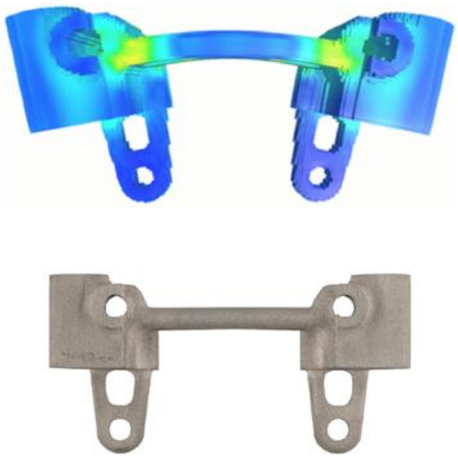

Figure 65: Live Sinter™ geometry printed, sintered straight[111]

7. Designers - Sustainable Design

7.1 Sustainable Design (Eco-design)[112]

One of the main characteristics of the world we live in, is that the requirements and demand on the products and services we consume are continuously growing. Not only due to the fact that more people become active consumers, but also the demand of each consumer have been increasing, both from technical (product features, high value-added services, etc.) and economic (competitive prices) perspectives. This phenomenon puts significant pressure on production systems, which face the challenge of satisfying demand without increasing production and maintenance costs. From the producer's and consumer's point of view, the cost of a product is typically perceived as the financial transaction of the purchase, linked to producing and selling it. However, it is important to consider the entire value chain of a product, from end-to-end (e.g.: production, delivery and usage), including the environmental impact of each stage that is dependent on the associated inputs and outputs. The diagram below (*Figure 66*) is intended to present a simplified schematic of these inputs and outputs:

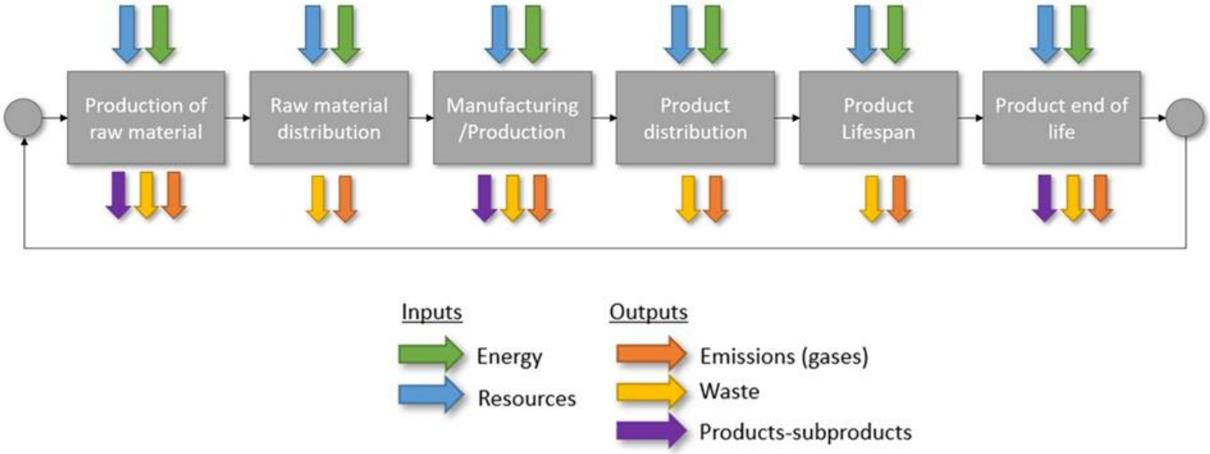

Figure 66: Value chain of a product

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[112] The foundation for developing the contents included in this section comes from previous work by project members in the addressed areas. This topic has already been partially addressed, for example, in the "Sector Skills Strategies for Additive Manufacturing" (SAM) project, in which several organizations participating in the SINGforGREEN project were involved. Link

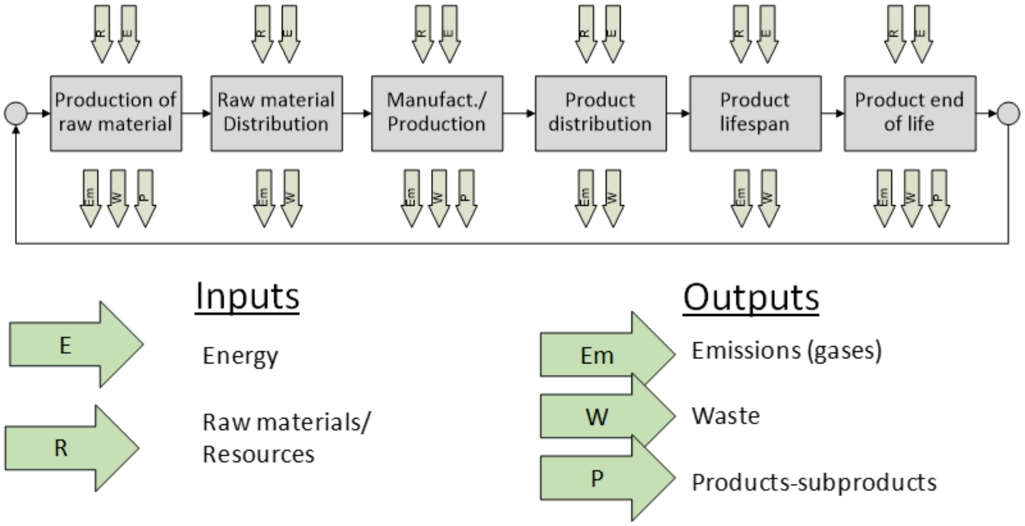

Figure 67: Product Lifecycle Inputs and Outputs[113]

The diagram above (*Figure 67*) shows the generic life cycle of a product, in which the stages associated with the extraction and transformation of the raw materials, the manufacturing process itself, the use and withdrawal of the products, and all the intermediate transportation stages (both to get the raw materials to the products and to get the products to the consumers) are presented.

On this basis, it is easy to identify that, from an environmental point of view, the sustainability of a product depends on the impact that the associated processes generate, which can generically be measured through the following two terms:

- The impact of inputs: associated to the materials and energy consumed throughout the life cycle
- The impact of the outputs: the sum of the harmful emissions to the environment and the non-reusable and potentially harmful waste generated throughout the process.

Based on the above considerations, the sustainability of a product is inherently linked to the sum of the environmental impacts of the processes associated with its manufacturing, maintenance and disposal. Thus, working to increase the sustainability of a product requires a broader vision, in which, all stages in the value chain are relevant to understand the extent to which a product's impact can be reduced.

There are different alternatives to reduce the environmental impact of a product. Companies can optimise the manufacturing processes already implemented such as the recovery of waste from production, reduction of the percentage of non-compliant products, substitution of fossil fuels for renewable energies, optimisation of supply chains and electrification of fleets, etc. However, these alone do not involve

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[113] IDONIAL. SAM / IAMQS Training: Sustainability in AM, 24th to 31st March 2022. Link

modifications to the product itself, presenting serious limitations in the environmental impact reduction, since usage and disposal stages are disregarded from the optimisation process.

To reverse the trend, there is an area of study and implementation capable of approaching the entire value chain in a more global perspective, Design.

Design has the capacity to act on several layers of the product, since it not only determines the product geometry, main characteristics and quality but has a direct impact on the:

- materials and manufacturing processes necessary for the production
- utilization models, useful life, consumption, and maintenance of the product during its life
- business models around the product
- associated transport and supply networks
- recoverability of the product or its components after the end of their useful life

Thus, and going back to the title of this section, it is now possible to provide a definition for ***Sustainable Design***, as the "*design process that seeks to incorporate the minimisation or reduction of environmental impact as a requirement of a product throughout its life cycle, considering the product in terms of impact not only as a physical entity, but as the sum of all the environmental impacts incurred in generating, transporting, using and disposing it*".

Now, that the above definition was provided, another concept frequently used in these fields of study can be introduced, the concept of ***Ecodesign***. This concept is relevant, and an aspect that will appear later on. It is central in some complementary fields, and more specifically in that of ***Ecodesign*** standardisation. From the point of view of the present document, both **"*Sustainable Design*"** and **"*Ecodesign*"** share the same purpose enunciated and will be indistinctly use from now on. As a mean to explore these concepts further, in the following section they will be elaborated in more detail showcasing how design is potentially linked to the impact of each stage of the product life cycle.

7.2 Influence of design on the sustainability of a product. Full life cycle point of view[112]

In this subchapter, the diagram from *Figure 67* is being used as reference to explain how design can have an effective impact on each of the stages included in this generic product life cycle schematic. The direct relationship of each stage to design, and its modification potential to act at the environmental impact is presented hereafter.

7.2.1 Production of raw materials

Raw materials usually have to be extracted and processed for the respective manufacturing technologies. Taking metals as an example. Metals can be required in several forms, blocks, wires, powders... From this point of view, the raw material can be considered as a product itself, so actually, depending on where we position ourselves in the value chain, our perspective can change … Thus, this very first stage will present its own inputs and outputs, so its impact could be modified, depending on the amount of material required for the product's production process, and on the number and nature of the processes concerning its extraction and transformation (for actually becoming a valid raw material for our process).

Another good example is the transformation process to achieve powders for fusion or sintered based additive manufacturing since powders are not found in nature in the required form in order to be the input materials for these manufacturing processes.

Answering the question ***"Does design have potential to modify the impact of this stage?"*** *Absolutely! Product design is directly responsible for the variety and quantity of raw materials needed to manufacture the product, as well as indirectly for the format in which these raw materials are to be presented.*

7.2.2 Raw material distribution

Related to the previous stage, if the product has the potential to determine the nature and quantity of raw materials needed, distribution has the potential to influence the impact of the logistics processes linked to the supply of the raw materials. It is difficult to generalise from this fact, however, as the location of raw material precursors and processing facilities may be varied and may even respond to strategic criteria, it would only be possible to establish a general association of the potential impacts of this stage with the quantity of raw materials required to manufacture a product. In any case, this association should also be viewed with caution from this general perspective, since it is not possible to generalise about such relevant aspects as, for example, the size and volume of the batches transported affect the impact generated per unit of mass or volume of raw material.

So... ***"Does design have potential to modify the impact of this stage?"*** *In principle, reducing the quantity and variety of materials needed to manufacture a product should have a positive impact at this stage (impact reduction), but it is not possible to make further statements without taking into account the specific nature of the raw materials and their logistics processes.*

7.2.3 Manufacturing/production

This is one of the life cycle stages where changes of the design of a product can bring the greatest impact. As seen previously, Design has a great potential to generate impacts, since it directly connects to resource consumption, energy consumption, waste and emissions from production. The environmental impact of each technology is linked to the number of units produced, the associated energy consumed, the resources needed, and the emissions and waste generated in the process. In this sense, and as a very crude example of the potential differences, if, for the same metal product (considering for the hypothesis a product that fulfils the same function operating for the same amount of time in exactly the same way, with two different designs) we had the option to manufacture it by subtractive or additive processes, although the latter may be more costly in terms of energy per unit of time than the former, the speed of the latter process would certainly result in a considerably lower impacts.

*So… **"Does design have potential to modify the impact of this stage?"** Absolutely. The design of the product totally conditions and even limits the manufacturing processes and technologies that can be selected. This stage will have the greatest environmental impact of all those seen so far, a designing in a way that minimises material consumption and manufacturing times, will bring advantages in the impact profile at this stage.*

7.2.4 Product distribution

At this stage, it is again difficult to generalise about how the design of a product can influence its structure and distribution networks, as these are linked in particular to the location of production centres and the location of intermediate and final customers. Two general strategies commonly used to reduce the impact in distribution are: reducing the volume and packaging of the product and bringing the means of production closer to the final customers. The former depends on aspects that may be closely linked to design, while the latter may be more closely linked to the manufacturing technologies themselves. For instance additive manufacturing technologies are more susceptible to greater decentralisation than most of traditional ones, which can lead to shorter and more advantageous distribution chains.

*So… **"Does design have potential to modify the impact of this stage?"** In principle, reducing the volume of product and reducing the distances to consumers should have a positive impact in terms of reducing the impact of this stage, but it is not possible to make further statements without taking into account the specific nature of the finished product and its logistics.*

7.2.5 Product Lifespan

From a sustainability point of view, the product is not "done" once it is produced and reaches the customer. The use of the product can have a greater sustainability impact than all the remaining stages. Thus, although in domestic consumption we are surrounded by "single use" products, we also rely on products that remain with us for a long time, and which are directly responsible for consuming considerable amounts of resources and energy, either directly (e.g.: a mobile phone, a fridge, a printer, a hob, a

3D desktop printer, an air conditioner or heater, a vehicle, etc.) or even indirectly (e.g.: clothes and kitchen utensils, which require water and electricity for cleaning).

Generically speaking, the potential for generating or reducing impact will be greater for:

- long life products
- high levels of optimisation of material, weight, and volume of the product, especially if the product is to be transported during its lifetime
- high levels of functionality, that minimise the need for additional products
- low levels of consumption of consumables, energy, and maintenance over their lifetime

*So... **"Does design have potential to modify the impact of this stage?"** Absolutely! Design is obviously directly responsible for each and every one of the above impact-generating aspects.*

7.2.6 Product End of Life

Within a circularity concept, this stage involves not only the removal of a product that has reached the end of its life, but also implies either a second life under less demanding conditions, or the recycling of as many elements and materials as possible. This stage is therefore highly relevant to the overall impact of a product, as it has an impact on its overall life span, on the amount of net waste it generates, and on how recycling can reduce the consumption of raw materials in the same or other product generation processes.

*So... **"Does design have potential to modify the impact of this stage?"** Absolutely! Design has a fundamental role to play at this stage, as it is directly responsible for such important aspects as the typology and variety of materials, as well as the modularity and ease of separation of a product into its constituent elements and materials, both of which completely determine whether or not the product can be recycled.*

7.3 Main action areas of additive manufacturing as a tool for more sustainable design

Although in a simple way, the previous section was dedicated to show how the different stages of a product's life cycle are relevant to determine its sustainability impact. One of the most relevant aspects retrieved is that sustainability assessments are a function of more than just the manufacturing process and consumption of raw materials. It extends to the upstream and downstream of the value chain, and require a specific analysis to understand which are the stages mostly contributing, and which are the ones negligible.

Generalisations about additive manufacturing sometimes contain simplistic messages about the potential of these technologies: *"reduction on the resource consumption based on the principle of "layer-by-layer" manufacturing", "only the material needed to make each part is used",* ... A more in-depth analysis inevitably leads to the conclusion that such claims miss many of the steps responsible for environmental impact generation, and the reality is that a case-by-case analysis is required (a subject to be addressed in subsequent sections).

In this sense, one of the objectives of this document is to identify the cases in which additive manufacturing have a demonstrable potential to reduce the impact of a product. Thus, from the experience of the partners of the SINGforGREEN project, there are three main scenarios where additive manufacturing can lead to a potential improvement in sustainability from this global perspective of the life cycle.

7.3.1 Highly complex products

The term "high complexity" can have several meanings, ranging from products incorporating a high number of parts, to products that are difficult to manufacture using conventional technologies. In either case, this high complexity gives rise to a number of possible implications:

- High number of manufacturing, transfer, and processing operations.
- Need for specific tooling for several of the manufacturing operations.
- Difficulties and quality defects arising from joining operations and/or systems.
- Maintenance during the lifespan of the product subject to the occasional failure of some parts.
- High need for spare parts, assembly, and disassembly operations for replacement.
- Difficulty in disassembly and recycling at end of life/recycling.

From a general perspective, and from a sustainability point of view, a product that requires a high number of manufacturing operations and subject to regular maintenances will be costly, as well as its potential expenditure of raw materials, energy, spare parts, etc. In these cases, additive manufacturing has a high power to simplify the design, reducing the number of product components, and reducing all the operations and needs present in a more conventional manufacturing system.

7.3.2 Products with a high influence on the consumption of other resources during their life cycle

There are many products that generate consumption throughout their life cycle, whether they are commodities, raw materials, energy, spare parts, etc. Examples, in this case, are the products or parts from vehicles or transport systems, in which weight is directly linked to energy or fuel consumption. In these cases, additive manufacturing is often applied to produce lighter products with a long-life, which results in a decrease in their responsibility for energy or fuel consumption over their entire life cycle, which in these sectors is represents several years.

7.3.3 Tooling/Spare parts/short series products/highly customisable products

One of the best-known aspects of additive manufacturing technology is its ability to produce a physical product without requiring tooling, which is a key aspect when dealing with the manufacture of high uniqueness or low target number of units. Manufacture low volume products is, typically, high costly. Large quantities of material are needed, and the development and manufacturing of additional tooling end up not being diluted as in high volume production … In all cases, additive manufacturing is potentially advantageous, as it can dispense with a considerable volume of materials and operations, and its potential for a more beneficial balance of sustainability impact, is considerable.

These three scenarios are not necessarily representative of each and every one of the cases where additive manufacturing can have a net impact on increasing the sustainability of a product, but they are illustrative of the most common situations in which this positive effect can occur. It is feasible to think of cases where several of these scenarios could converge at the same time. In any case, it is possible to make a statement in the light of the above, the potential of additive manufacturing to increase the sustainability of a product will be greater as:

- higher the simplification level of the previous production processes
- higher the lifespan of the product
- higher the potential for modification of the design to improve its efficiency in the use of other resources or to reduce the product's maintenance needs

Some graphical representation of design modifications in line with the above-described scenarios, are presented hereafter.

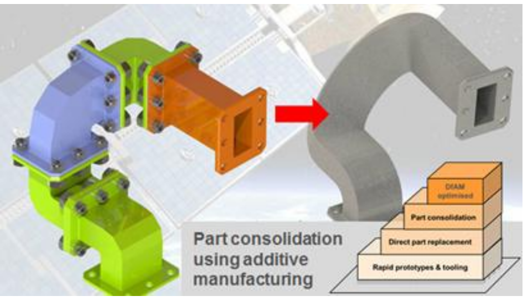

Figure 68: Part consolidation example[114]

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[114] Saunders, M. (2015). Simplify your design and save weight using AM. Link

Figure 69: Part consolidation example[115]

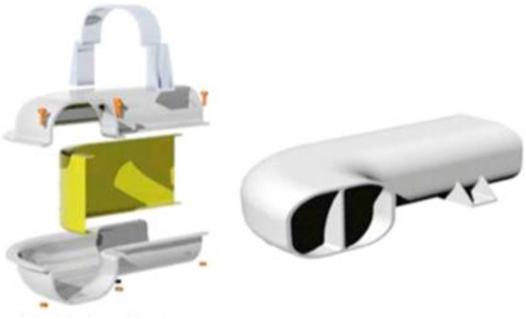

Figure 70: Part consolidation example[116]

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[115] Fournier, S. (2016). Use Case: The redesign of a metal industrial flow manifold. Link

[116] Yang, S., Tang, Y., Zhao, Y. (2015). A new part consolidation method to embrace the design freedom of additive manufacturing. Link

Figure 71: Part consolidation example[117]

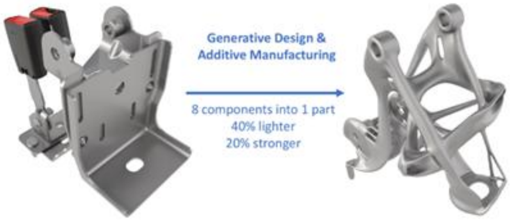

Figure 72: Part consolidation example[95]

Figure 73: Part consolidation example[118]

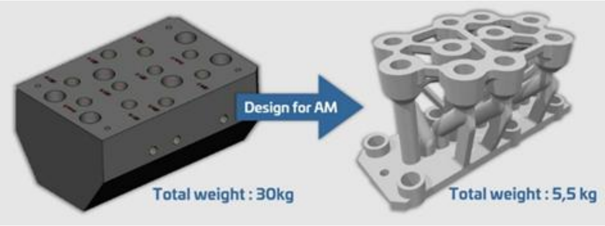

Figure 74: Weight reduction example[119]

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[117] HP. Design for Additive Manufacturing. Part consolidation case study. Link

[118] Carter, C. (2018). Additive Manufacturing Takes Flight – GE Aviation's Integration of 3D Printing to Enable Innovation. Link

[119] Sertoglu, K. (2020). GKN Additive achieves 80% weight reduction with hydraulic block redesign. Link

Figure 75: Weight reduction example[120]

Figure 76: Weight reduction example[121]

Figure 77: Weight reduction example[122]

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[120] Samant, R. (2018). Designing for Additive Manufacturing Brings with It Design Freedom. Link

[121] J., M. (2020). Topology optimization for 3D printing. Link

[122] Goehrke, S. (2017). Topology Optimization Eases Additive Manufacturing Design — A Few Questions For: Frustum. Link

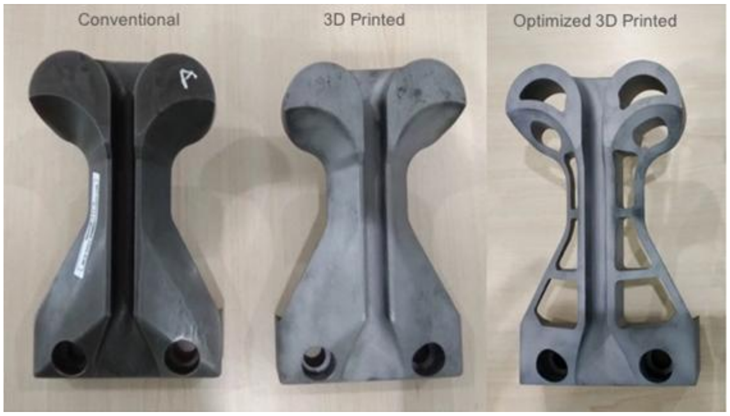

Figure 78: Weight reduction example[123]

7.4 Estimating and assessing the sustainability of a product. Main types of impact assessment tools

Designing in a sustainable way, or, in other words, using eco-design principles, is done to ensure that the organisational structures, operational and guiding elements of the organisation (policies and strategies, objectives) are defined in an effective way to ensure a correct integration of eco-design.

It is not the intention of this document to provide a detailed presentation of all of the available tools, nor for the reader to learn how to implement them (these techniques themselves require specific skills and knowledge), but to convey that designing in a sustainable way requires going beyond the "intention" to design more sustainable. It requires considering and measuring design alternatives, to assess and compare them, from the sustainability perspective. In this sense, there are multiple qualitative and quantitative tools for analysing the environmental profile of the product and setting environmental priorities, each of them being more suitable for specific applications and circumstances as they differ in complexity and cost. The following *Table 10* summarizes some of the main groups of tools, briefly described and ordered by complexity level.

Table 10: Types of typical cited tools for assessing the sustainability of a product or process[124]

Tool	Type	Description
Check-List	Descriptive	Checklist, based on asking and answering a series of questions, the answers to which can provide guidance on the main impact points of the product.
MET Matrix	Semi-quantitative	Materials, Energy, Toxic Emissions Matrix. It correlates the different stages of the product life cycle with the generation of impacts in each of them.

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[123] Immensa. (2019). 3D Printing Cost Reduction Using Weight Optimization. Link

[124] Pihkola, H., Pajula, T., Tapia, C., Ritthoff, M., Saurat, M. (2016). Sustainability Assessment Methods and Tools for Cross-sectorial Assessment. Link

Tool	Type	Description
Web/polar diagrams	Semi-quantitative	It is a graphical tool, which subjectively evaluates the degree of implementation or benefit of the environmental improvement ideas proposed for the product at each stage of its life cycle.
Carbon footprint	Quantitative	It consists of calculating the total amount of greenhouse gases (GHG) emitted directly or indirectly by an activity, product, or process over its entire life cycle. This includes all stages, from the extraction of raw materials, production, transport, use and end-of-life of the product or service.
MIPS	Quantitative	Material Input per Service Unit (MIPS) is based on measuring the total amount of materials needed to provide a unit of service or product throughout its life cycle, including the extraction, manufacture, use and final disposal of the materials.
CED	Quantitative	Cumulative Energy Demand (CED) concept refers to the total amount of energy required to produce a product or service throughout its life cycle, taking into account all stages from the extraction of raw materials to their final disposal.
LCA	Quantitative	Life Cycle Assessment (LCA), which consists of quantifying the natural resources consumed and emissions generated at each stage of the life cycle, in order to identify areas for environmental improvement and make informed decisions to reduce the overall environmental impact of the product or process.

Table 10 includes both qualitative and quantitative tools. From an objective perspective, the assessment of the potential impact of a product and the comparison of various alternatives will require the use of quantitative methods, but this does not imply that the capacity of qualitative or semi-quantitative methods to develop analyses and considerations in the initial stages of product development or redesign should be underestimated.

In addition, the application of quantitative methods often involves the use of specific methods, databases, and software. Combining different methods can be useful to discard design alternatives that are already far from sustainable in their concept.

7.4.1 A benchmark for a quantitative and comprehensive sustainability measurement tool: LCA[125]

Life Cycle Assessment (LCA) is the most frequently mentioned tool for measuring the potential impact of a product or process, as it is multi-sectoral and consists of an

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[125] The content of this section is developed based on the previous experience of the members of the SIGNforGREEN project regarding the application of eco-design tools. The literature in this field is extensive; however, there are suitable contents for broader audiences that can serve as a good introduction to the subject, such as "Life Cycle Assessment (LCA) – Everything you need to know", Ecochain. Link

objective process for assessing the environmental burdens associated with the life cycle of a product, process or activity. LCA capabilities can be summarised as follows:

- compile an inventory of relevant inputs and outputs
- evaluate the potential environmental impacts associated with those inputs and outputs
- interpret the results of the inventory and impact phases in relation to the objectives of the study

Thus, the LCA has the capacity to provide information on the environmental performance of the product or process from the procurement of raw materials to the end of its useful life, including manufacturing processes, transport, distribution, use and maintenance. From the methodologies listed in Table 10, this is the most complete, as it has the potential to consider all process stages, as well as all consumption and emissions. LCA generally comprises five major stages, detailed in the following scheme and explained hereafter.

7.4.1.1 Goal and scope definition

Every LCA application has to clearly define what the expected achievements and desired goals are. The general purpose of LCA is to do an environmental assessment of a product/process/activity, focusing on quantifying its impacts.

For every case, particular goals have to be defined, as well as a suitable Functional Unit. The functional unit is a measure of the function of the studied and it provides a reference to which the inputs and outputs can be related. In the context of a given product, it is possible to assume that the functional unit can be a unit of that product (it is assumed that it is not sold per unit of mass or volume, but as a single, indivisible product).

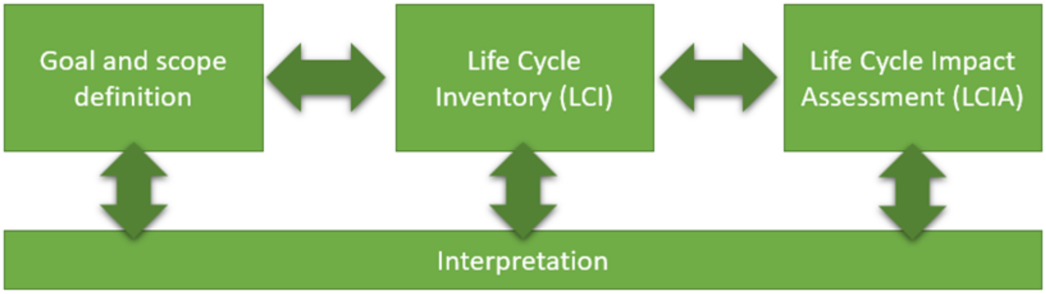


Figure 79: LCA major stages

Apart from the definition of goals, that are adequate and consequent with a defined project, the definition of a proper scope is key to obtain quality results. The step for defining the scope is where all the different possibilities for carrying out an LCA are observed and analysed. This leads to the definition of the assumptions and selection of the boundary conditions. To support the definition of the goals and the scope, there is a general question that needs to be answered: *"From where to where is LCA going to be applied?"*. *Table 11* presents several options.

Table 11: Different LCA scope alternatives

General Approach	Basic Description
Cradle-to-Grave	Full Life Cycle Assessment from resource extraction ("cradle") to use phase and disposal phase ("grave")
Cradle-to-Gate	Assessment of a *partial* product life cycle from resource extraction (*cradle*) to the factory gate (i.e., before it is transported to the consumer)
Cradle-to-Cradle	Specific kind of cradle-to-grave assessment, where the end-of-life disposal step for the product is a recycling process. It is a method used to minimize the environmental impact of products by employing sustainable production, operation, and disposal practices and aims to incorporate social responsibility into product development.
Gate-to-Gate	Partial LCA looking at only one value-added process in the entire production chain.
Wheel-to-Wheel	Specific LCA used for transport fuels and vehicles. The first stage, which incorporates the feedstock or fuel production and processing and fuel delivery or energy transmission, and is called the "upstream" stage, while the stage that deals with vehicle operation itself is sometimes called the "downstream" stage.
Ecology-based	Quantitatively takes into account regulating and supporting services during the life cycle of economic goods and products. It was designed to provide a guide to wise management of human activities by understanding the direct and indirect impacts on ecological resources and surrounding ecosystems.

It should be noted that the choice of a general approach may be subject to the context of the product and the resources available for the analysis work, but ideally a Cradle-to-Grave analysis is desired, unless previous experience allows its exclusion, that concludes little relevance to the process as a whole.

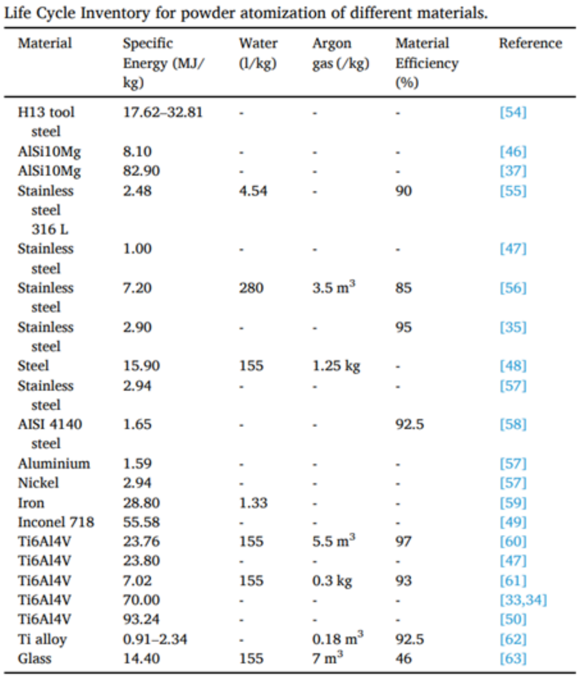
7.4.1.2 Life Cycle Inventory (LCI)

Life Cycle Inventory (LCI) corresponds to the data collection portion of the LCA. LCI is the straight-forward accounting of everything involved in the studied system. It consists of detailed tracking of all the flows in and out of the process system, including raw resources or materials, energy by type, water, and emissions to air, water and land by specific substance. This kind of analysis can be extremely complex and may involve dozens of individual sub-processes in a supply chain (e.g., the extraction of raw resources, various primary and secondary production processes, transportation, etc.) as well as hundreds of tracked substances.

It is unlikely to "model" all the sub-processes and substances involved in a studied system, but since they constitute significant process consumptions, they end up having significant environmental impacts, and can't just be left out the scope of the LCA.

Fortunately, the LCA tools allow the quantification of these upstream processes impacts, thanks to the incorporation of its impact to recognizable databases[126]. One of the best known and most widely used is ECOINVENT, a widely used database containing detailed information on the environmental impacts of a wide range of industrial products and processes. It provides data on material and energy flows, as well as associated emissions and waste throughout a product's life cycle, from raw material extraction to final disposal. This data is used by life cycle assessment (LCA) professionals to analyze and compare the environmental performance of products and processes. An example is provided in Table 12, where data about the impact associated with the production of different powder metal materials is presented.

Table 12: Partial view of the emissions and consumption of the production of MEA[127]



Life Cycle Inventory for powder atomization of different materials.

Material	Specific Energy (MJ/kg)	Water (l/kg)	Argon gas (/kg)	Material Efficiency (%)	Reference
H13 tool steel	17.62–32.81	-	-	-	[54]
AlSi10Mg	8.10	-	-	-	[46]
AlSi10Mg	82.90	-	-	-	[37]
Stainless steel 316 L	2.48	4.54	-	90	[55]
Stainless steel	1.00	-	-	-	[47]
Stainless steel	7.20	280	3.5 m^3	85	[56]
Stainless steel	2.90	-	-	95	[35]
Steel	15.90	155	1.25 kg	-	[48]
Stainless steel	2.94	-	-	-	[57]
AISI 4140 steel	1.65	-	-	92.5	[58]
Aluminium	1.59	-	-	-	[57]
Nickel	2.94	-	-	-	[57]
Iron	28.80	1.33	-	-	[59]
Inconel 718	55.58	-	-	-	[49]
Ti6Al4V	23.76	155	5.5 m^3	97	[60]
Ti6Al4V	23.80	-	-	-	[47]
Ti6Al4V	7.02	155	0.3 kg	93	[61]
Ti6Al4V	70.00	-	-	-	[33,34]
Ti6Al4V	93.24	-	-	-	[50]
Ti alloy	0.91–2.34	-	0.18 m^3	92.5	[62]
Glass	14.40	155	7 m^3	46	[63]

7.4.1.3 Life Cycle Impact Assessment (LCIA)

The LCI result is usually a very long list of emissions, consumed resources and sometimes other items. The interpretation of this list is difficult. LCIA is defined as the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a system. The LCIA can contain hundreds of "elementary flows" that represent emissions or extractions to and from the environment. In order to understand what this mean, ISO prescribes a step known as classification. The elementary

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[126] openLCA Nexus. Your source for LCA and sustainability data. Link

[127] Kokare, S., Oliveira, J.P., Godina, R. (2023). Life cycle assessment of additive manufacturing processes: A review. Link

flows from the inventory are assigned to the impact categories according to the substances' ability to contribute to different environmental problems.

The severity of the impacts of each elementary flow for a defined impact methodology is defined by its characterization factor. Those characterization factors are based on well documented science literature and are internationally accepted. Two different impact categories approach can be used:

- Midpoint impact category, or problem-oriented approach, that translates impacts into environmental themes such as climate change, acidification, human toxicity, etc.
- Endpoint impact category, also known as the damage-oriented approach, that translates environmental impacts into issues of concern such as human health, natural environment, and natural resources.

Endpoint results have a higher level of uncertainty compared to midpoint results but are easier to understand by decision makers.

In order to be able to convey to the reader what the final translation of this process is, we show below a diagram in *Figure 80*, that comes from the field of concrete 3D printing. Here, 4 scenarios are put against 5 different factors related to sustainability:

- Global Warming Potential (GWP), measured in kilograms of CO2 equivalents
- Acidification Potential (AP), measured in kilograms of SO2 equivalents
- Eutrophication potential (EP), measured in kilograms of N equivalents
- Smog Formation Potential (SMP), measured in kilograms of O3 equivalents
- Fossil Fuel Depletion (FFD), measured in MJ

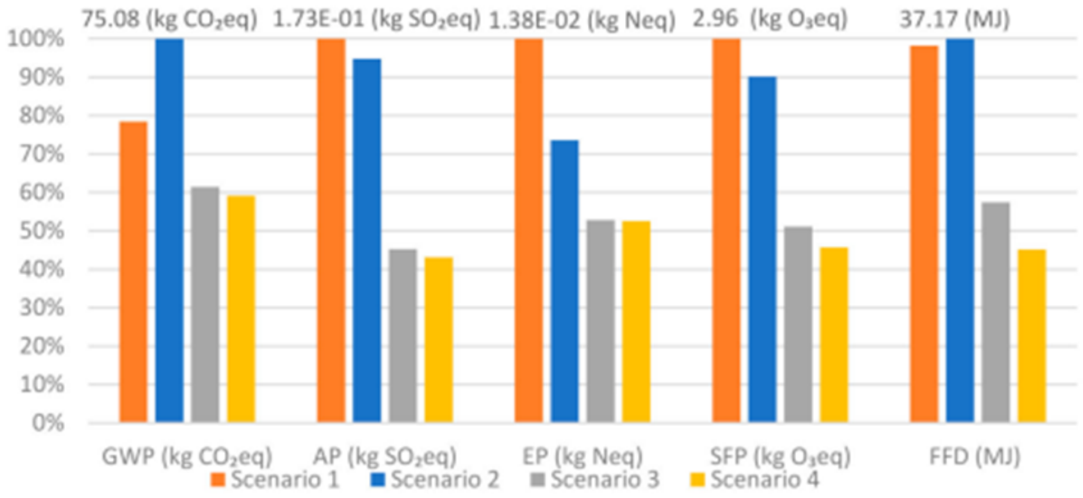

Figure 80: Example of comparison between different manufacturing alternatives for printed cement[128]

Figure 80 shows a very partial view of the information and comparisons that can be made with such tools, but it is a clear indication that they allow for the establishment and application of comparative frameworks with which to make decisions affecting the sustainability of a product.

7.5 Elements to support the implementation of eco-design

Implementing Eco-design goes beyond using the right tools, as in any area of the organisation, it is not simply a question of tools or resources, but the management of the organisation's activity so that it actively incorporates Eco-design in the product development processes.

In this sense, there is an international standard that provides the basis for what can be commonly understood as a management system that ensures the incorporation of Eco-design in an organisation, ISO 14006 (currently in its 2020 edition)[129]: "Environmental management systems - Guidelines for incorporating eco-design".

The standard specifies the requirements for the design and development process of an organisation's products and/or services, which enable the organisation to establish a system of continual improvement of its products and/or services from design and development, through an environmental management system. The general areas of knowledge required to incorporate Eco-design into a Management System are also identified and consist of the following:

- assessment of the impacts of products on the environment

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[128] Mohammad, M., Masad, E., Al-Ghamdi, S.G. (2020) 3D Concrete Printing Sustainability: A Comparative Life Cycle Assessment of Four Construction Method Scenarios. Link

[129] ISO 14006:2020(en): Environmental management systems — Guidelines for incorporating ecodesign. Link

- identification of appropriate eco-design measures to reduce the adverse effects of these environmental impacts
- design and development process and how the eco-design process is integrated and managed within a Management System

In the same way, ISO 14006 analyses the 3 main aspects that will guide the incorporation of Eco-design in organisations and in the management systems:

- benefits of Eco-design and involvement of top management
- the incorporation and management of the Eco-design process within an Environmental Management System
- the Eco-design process from the product life cycle approach

As a consequence of all of the above, ISO 14006 standard is a tool that help companies to:

- minimise the environmental impacts generated by products or services from their design, promoting a preventive approach
- raise market awareness of the importance of the environmental impact generated by products or services, promoting active information by the producing companies, both to users and to other key agents throughout the life cycle, such as recyclers
- encourage a shift in perspective from an approach based on the environmental aspects associated with product manufacturing to a broader identification including those generated at other stages of the life cycle
- establish a systematic approach to ensure continuous environmental improvement in the design of products and services, i.e., that all products designed or redesigned incorporate some environmental improvement

7.5.1 ISO 14006 standard as a basis for the implementation of Eco-design

The fact that legislation related to the environmental impact of products is being implemented at an increasing pace around the world is encouraging many organisations to improve the environmental performance of their products. These organisations need guidance on how to apply their efforts in a systematic way to achieve their environmental objectives and maintain continuous improvement in the environmental performance of their products as well as their processes, i.e., they need guidance on Eco-design.

In order to carry out Eco-design in a systematic and reasonable way, organisations need to implement an appropriate process and, in addition, have or be able to access the necessary competence to carry out and manage it s.

The ISO 14006 standard provides the necessary methodology to systematise the Ecodesign management processes within organisations, as well as the necessary competence for its implementation. The incorporation of environmental management practices into the design of products and services offers multiple opportunities and internal benefits for companies:

- it helps to identify and comply with the environmental legal requirements applicable to the product that are currently in force and also considers future requirements contained in drafts and Directives that have not yet been transposed
- it constitutes a preference for companies as a supplier of green purchasing products or services
- ensures that the organisation complies with applicable environmental legislation, including legal environmental requirements concerning its products and/or services
- it ensures that it manages the design and development of its products and/or services in such a way that all of them will continuously improve environmentally over time
- reduction of production and energy costs by optimising the resources used (consumption of materials, improvements in packaging, etc.)

This allows organisations to minimise the environmental impact of products and services by designing them in such a way that they are minimised at every stage of their life cycle, from production to end of use, while at the same time facilitating compliance with legislative requirements.

In addition, the implementation of a system according to the standard can provide the following benefits to potential customers:

- environmental product innovation and therefore market differentiation
- responding to customer needs and expectations, e.g., in green public procurement tenders
- improving the image of the product and of the organisation itself
- material savings and lower energy consumption for the user in electrical and electronic products

This is why for an organisation, one of the best ways to ensure the effective implementation of eco-design in its organisational processes is precisely the implementation of a Management System based on the requirements set by the ISO 14006 standard.

8. Sustainable production

8.1 Sustainable methods of Production for Additive Manufacturing

As described above, additive manufacturing is a group of manufacturing technologies with innumerable advantages from the perspective of designers and engineers, who see it as a means to overcome limitations imposed by other technologies, as well as a fast track for testing new alternatives. If we now look at these technologies from a sustainability perspective, two different but complementary approaches are possible.

8.1.1 Individual approach: how to make the most efficient use of technology, once technology is a central aspect of manufacturing

First of all, we have to consider that the group of additive manufacturing processes is considerably broad, with currently 7 different processes (*Figure 81*), which realise the same concept through different means, each of them with their pros and cons.

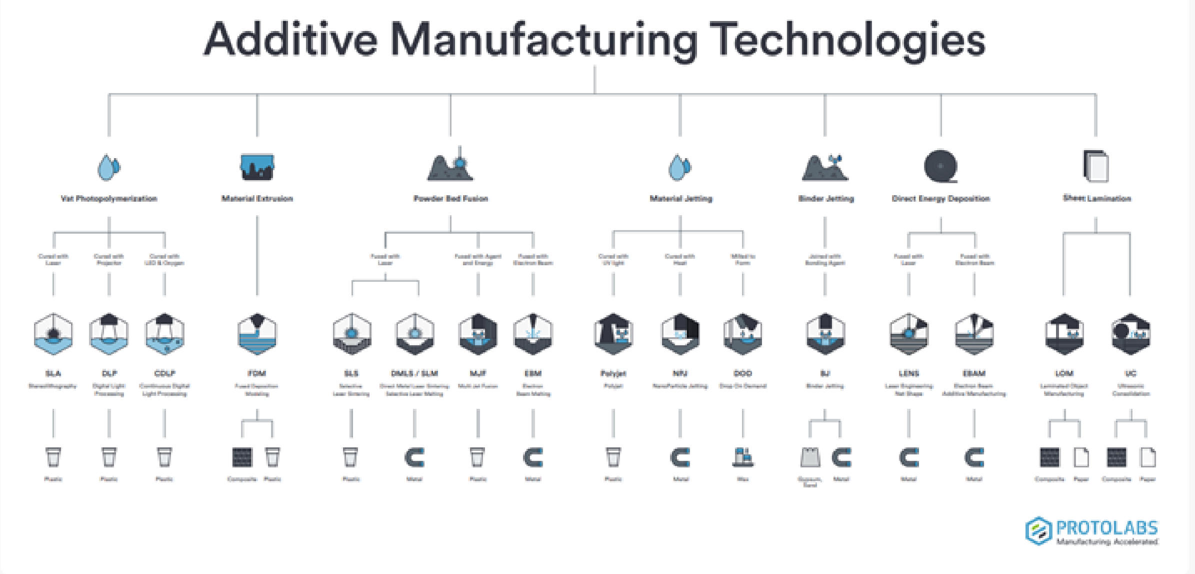

Figure 81: Different AM technologies[130]

In this sense, it is difficult to make statements that are likely to be true for each and every case, but it is possible to carry out a qualitative analysis by looking at the following factors:

- raw materials
- additive manufacturing process

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[130] Protolabs Network. Additive Manufacturing Technologies. Link

- additional post-processing, hybrid manufacturing

8.1.1.1 Raw materials

As a general rule, all these technologies make use of raw materials with a high degree of prior transformation, i.e. most of the raw materials are the result of processes involving several mechanical and thermal operations that finally result in the raw material of the process, be it very finely particulate powder, filaments, pellets, mixtures of materials with binders, etc.

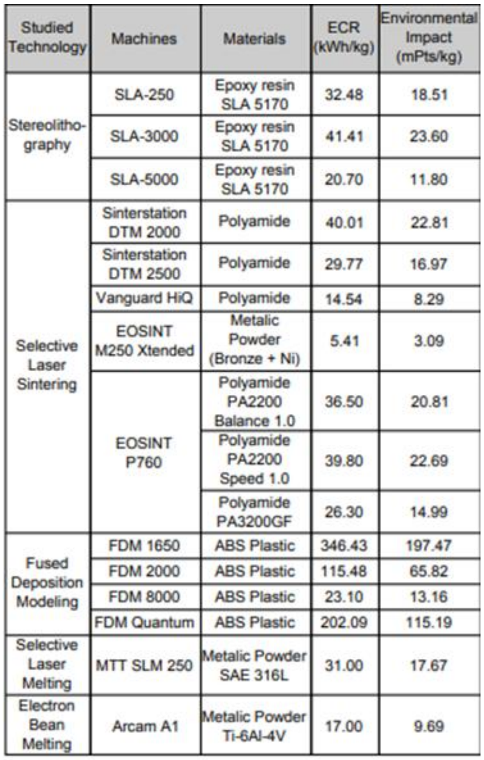
Based on the above, it could be argued that the impact associated with the production of each unit of raw material is in principle not negligible.

Different processes can provide very different profiles in this respect, and for example, while a process that fuses/sintered metal powders implies a high energy cost per kg of metal to be atomised, the materials needed for the process but not fused/sintered often offer high recyclability through screening processes (recycling with low energy/resource costs). In contrast, recycling a plastic that has already been already melted but is not part of the build may not make sense, as the material properties have been greatly altered during the process, and if not, it may require several forming steps until the material is once again in a filament form. It is also necessary to take into account that many of the processes require the use of support materials (to avoid the sagging of a geometry due to the action of gravity).

This leads in any case to the same conclusion that we could draw for any other manufacturing process, namely that savings, minimisation of consumption and the use of recycled materials is a highly important element in minimising the impact of applying these technologies.

8.1.1.2 Additive manufacturing process

If the differences in terms of raw materials are large in terms of the potential impact profile of the different additive manufacturing processes, the differences are even more relevant from this point of view. Again using the same example as in the previous case, while fusing/sintering metal powder may require the use of high power lasers (e.g. lasers between 200 and 400 W, operating for the whole duration of the manufacturing process), as well as the creation of a drag and/or inert atmosphere (consumption of noble gases, use of compressed air, etc.), other processes of powder metal deposition may require the use of high power lasers (e.g. lasers between 200 and 400 W, operating for the whole duration of the manufacturing process), as well as the creation of a drag and/or inert atmosphere (consumption of noble gases, use of compressed air, etc.), and other processes of molten plastic filament deposition, although they require heating the filament to around 200 or 300 °C, can be carried out in process conditions close to ambient conditions.



Studied Technology	Machines	Materials	ECR (kWh/kg)	Environmental Impact (mPts/kg)
Stereolitho-graphy	SLA-250	Epoxy resin SLA 5170	32.48	18.51
	SLA-3000	Epoxy resin SLA 5170	41.41	23.60
	SLA-5000	Epoxy resin SLA 5170	20.70	11.80
Selective Laser Sintering	Sinterstation DTM 2000	Polyamide	40.01	22.81
	Sinterstation DTM 2500	Polyamide	29.77	16.97
	Vanguard HiQ	Polyamide	14.54	8.29
	EOSINT M250 Xtended	Metalic Powder (Bronze + Ni)	5.41	3.09
	EOSINT P760	Polyamide PA2200 Balance 1.0	36.50	20.81
		Polyamide PA2200 Speed 1.0	39.80	22.69
		Polyamide PA3200GF	26.30	14.99
Fused Deposition Modeling	FDM 1650	ABS Plastic	346.43	197.47
	FDM 2000	ABS Plastic	115.48	65.82
	FDM 8000	ABS Plastic	23.10	13.16
	FDM Quantum	ABS Plastic	202.09	115.19
Selective Laser Melting	MTT SLM 250	Metalic Powder SAE 316L	31.00	17.67
Electron Bean Melting	Arcam A1	Metalic Powder Ti-6Al-4V	17.00	9.69

Figure 82: Electric consumption and environmental impact of different AM Technologies[131]

With all of the above, and as for any other manufacturing technology, it would be possible to establish a well-defined impact profile for each combination of technology and material per unit of time, as based on these combinations it is possible to determine both the energy consumption and the consumption of additional consumables, as well as correlating it with the amount of raw material processed and its recyclability. By virtue of the above in *Figure 82*, and bearing in mind that on many occasions the selection of one manufacturing technology or another will be determined by the material selected, the variable to work with in order to minimise the impacts of this stage is fundamentally time.

8.1.1.3 Additional post-processing, hybrid manufacturing

While on (few) occasions an additive manufacturing technology may result in a fully finished product ready to be shipped, it is common for most parts manufactured using these technologies to require further processing or finishing. This is for two reasons: the first is that the process itself may require the removal of excess material, the separation of parts from a build plate or the removal of supports; the second reason is that additive manufacturing is likely to be an intermediate stage in a wider

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[131] Le Bourhis, F., Kerbrat, O., Hascoet, J., Mognol, P. (2013). Sustainable manufacturing: Evaluation and modeling of environmental impacts in additive manufacturing. Link

manufacturing process, for example starting with one technology to produce a pre-form and then one or more other technologies to provide the final features and finish.

Again, in this, additive manufacturing technologies are no different from other technologies, in the sense that every technology must be put in the context of its own capabilities, as well as in the context of its optimal use. For example, it should always be borne in mind that additive manufacturing is not generally intended to manufacture what is already being manufactured with technologically and economically mature processes/technologies (in general, if a part can already be manufactured with another technology very competitively on time and cost, it is unlikely that additive manufacturing can offer any improvement in those terms, unless those technologies demand high batch volumes), but at providing what other technologies are unable to provide. In essence, for additive manufacturing to be used efficiently in terms of its potential environmental impact, it is necessary to think about both the effort/benefit ratio involved, and the "place" that such a technology should occupy in a specific manufacturing process.

8.1.2 Global approach: additive manufacturing and environmental sustainability as part of a business case approach and analysis process

It should always be borne in mind that a product that finally reaches a consumer is the result of a path in which the producer has previously had to carry out a highly complex sequence of operations, in which cost and the perpetuity of the business are undoubtedly the key decision elements. With this in mind, it is necessary to consider how additive manufacturing and sustainable design can "carve a niche" in the decision-making processes, which as the diagram below (*Figure 83*) shows involves several aspects.

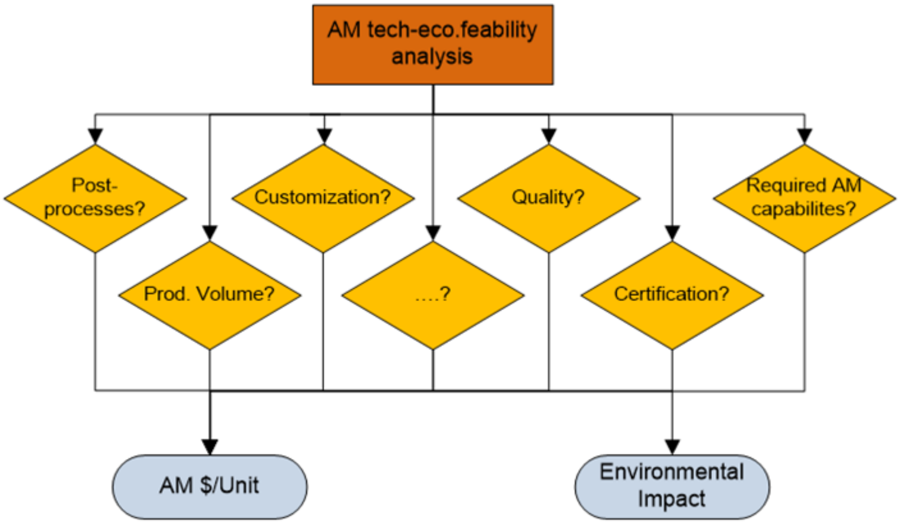

Figure 83: Elements for comprehensive business case analysis[132]

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[132] IDONIAL. Link

This intention may face several hurdles:

- As far as additive manufacturing is concerned, although it is a technology that many stakeholders treat as "new" in its various variants, the truth is that a look at the last two decades shows a large number of use cases and success stories, which prove a technical maturity more than sufficient to be able to produce fully reliable products, and proof of this is precisely the high penetration of these technologies in the aerospace sector, by far the most demanding of all existing sectors.

  In this sense, the reality about its current technical capability is the same as for any other technology outside this spectrum, and that is that harnessing it only requires the means, and people who are aware of what they can (and cannot) do, to integrate it in a way that makes sense for a given industrial activity.

- Based on the above, organisations in the industrial sphere would need to incorporate resources and professionals with a high level of knowledge in these technologies, since considering them as something external or at an early stage of evolution, apart from being an erroneous approach, makes it very difficult to achieve objectivity when assessing how it is possible to achieve the desired cost minimisation through one or another technology.

- As far as environmental sustainability is concerned, and again, when the main driver is economic, it is easy to understand that for industrial agents sustainability may be a desirable, but not the main requirement when creating new products or revising existing ones. In the search for reasons for this, one might think that, although in some sectors the effect that working on sustainability can have in reducing the total cost of ownership of a product has been unequivocally demonstrated (there are paradigmatic examples in the aerospace sector, where, due to the long life span of a product, it is possible to reduce the total cost of ownership of a product), where, due to the long life span of the products, weight reductions imply great environmental and economic savings), perhaps there is still a lack of exemplary cases in more reticent sectors, where it is still necessary not only to have an impact at the level of awareness and culture, but also from the perspective of working on specific cases that have an illustrative effect.

The above aspects are indicative of areas where efforts will be needed in the coming years, both for the "standardisation" of additive manufacturing technologies as technologies at the full disposal of industry, and for the natural integration (and not as an additional element) of sustainability as an aspect that can lead to more environmentally friendly products, but also to lower production or usage costs.

9. Learning Techniques

9.1 Evolution of Learning: Traditional to Digital in Additive Manufacturing Training

Learning techniques are an extensive set of tools and methods which are employed to secure knowledge and skills acquisition. Modern learning techniques have undergone a strong transformation from traditional to digital. This transformation was driven by the aspiration to enhance efficiency and accessibility and improve the quality of education and training. In this chapter, we will present the transformation path from traditional learning to digital learning, the basics of such transformation, and the development of the requirement for the establishment of training standards for educational and learning purposes, such as ISO 21001, will be presented.

9.1.1 Traditional Learning and Tools

The process of teaching-learning involves three relevant dimensions: The teacher, the classroom (or place where the process happens) and the methodology and tools used by the teacher to deliver the contents. These dimensions are intimately connected. The teacher explores his/her own style of teaching according to the group of learners' characteristics, the limitations of the place where the class will take place and the type of content to be delivered, which can go from traditional resources to other innovative resources.

In traditional learning, learners attend the class for a fixed time duration and learn about a specific topic. Although many teachers can make use of technology, they still run the class in a traditional learning set-up, which includes hand-written notes, assignments, and tests. Usually, a textbook that is standardised for that course is adopted by the teacher as the main tool. In the traditional learning process, the class depends on the teacher to acquire the knowledge and skills.[133]

Traditional resources, or tools, includes, also, the exploitation of materials which are designed either in written or printed form. Examples include magazines or books. When using traditional tools, teachers are also making efforts to address the student's needs and meet the learning outcomes.

The advantages and disadvantages of using traditional learning are presented in *Table 13*.

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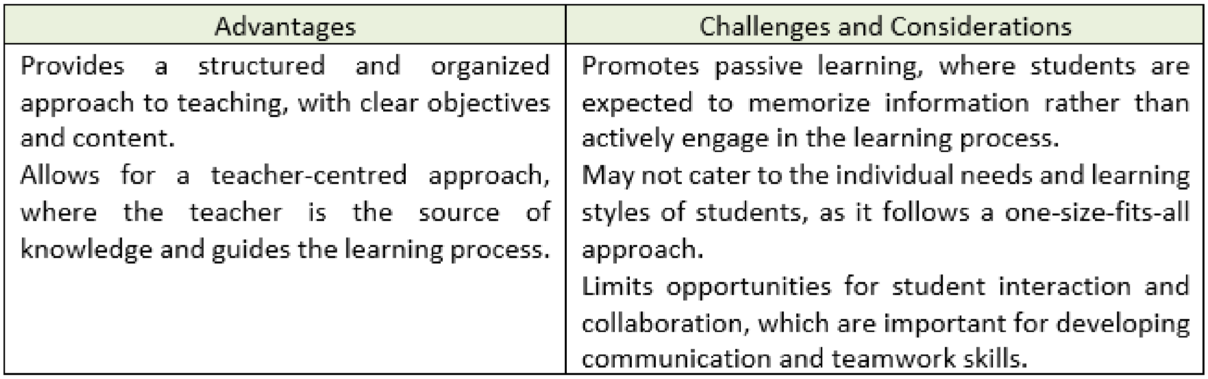
[133] Ansary, N. (2022). Traditional and Digital Resources in the Teaching Learning Process: Advantages and Limitations. Link

Table 13: Advantages and disadvantages of using traditional learning[134]



Advantages	Challenges and Considerations
Provides a structured and organized approach to teaching, with clear objectives and content. Allows for a teacher-centred approach, where the teacher is the source of knowledge and guides the learning process.	Promotes passive learning, where students are expected to memorize information rather than actively engage in the learning process. May not cater to the individual needs and learning styles of students, as it follows a one-size-fits-all approach. Limits opportunities for student interaction and collaboration, which are important for developing communication and teamwork skills.

In the traditional approach, homework, tests, and quizzes are more common. Grades and/or numerical evaluation methods are used in traditional schools. Teachers provide lesson plans and projects for students to work on in traditional schools.[135]

In traditional classrooms, the pedagogical methods commonly employed are lecture-based teaching, Socratic method, and cooperative learning.

The lecture-based approach refers to a traditional classroom teaching model, where the instructor delivers the lecture verbally in combination with a projector, visual display surface and writing surface (e.g. a blackboard or dry-erase whiteboard). This is generally considered a teacher-centred and content-oriented approach. In other words, traditional lecture-based instruction is designed to promote learning through practice questions and exercises that typically stimulate less classroom interaction between the instructor and students, and between students themselves.

The Socratic Method, named after the Greek philosopher Socrates, is a teaching dialogue between teacher and students that enables the participants to centralise their shared values and beliefs. In the Socratic method, the teacher is not supposed to share his/her beliefs and values but enable their exploration and challenge. It aims to enact thoughts and convince people to reevaluate their frames of reference.[136]

Cooperative learning is a pedagogical practice that fosters socialization and learning among learners from pre-school to tertiary levels. It involves students working together to achieve common goals or complete group tasks.[137]

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[134] Hadžimehmedagić, M., Akbarov, A. (2013). Traditional vs Modern Teaching Methods. Advantages and Disadvantages. Link

[135] Shi, Y., Peng, Ch., Yang, H.H., MacLeod, J. (2018). Examining interactive whiteboard-based instruction on the academic self-efficacy, academic press and achievement of college students. Link

[136] Delic, H., Bećirović, S. (2016). Socratic Method as an Approach to Teaching. European Researcher. Link

[137] Gillies, R. (2016). Cooperative Learning: Review of Research and Practice. Australian Journal of Teacher Education. Link

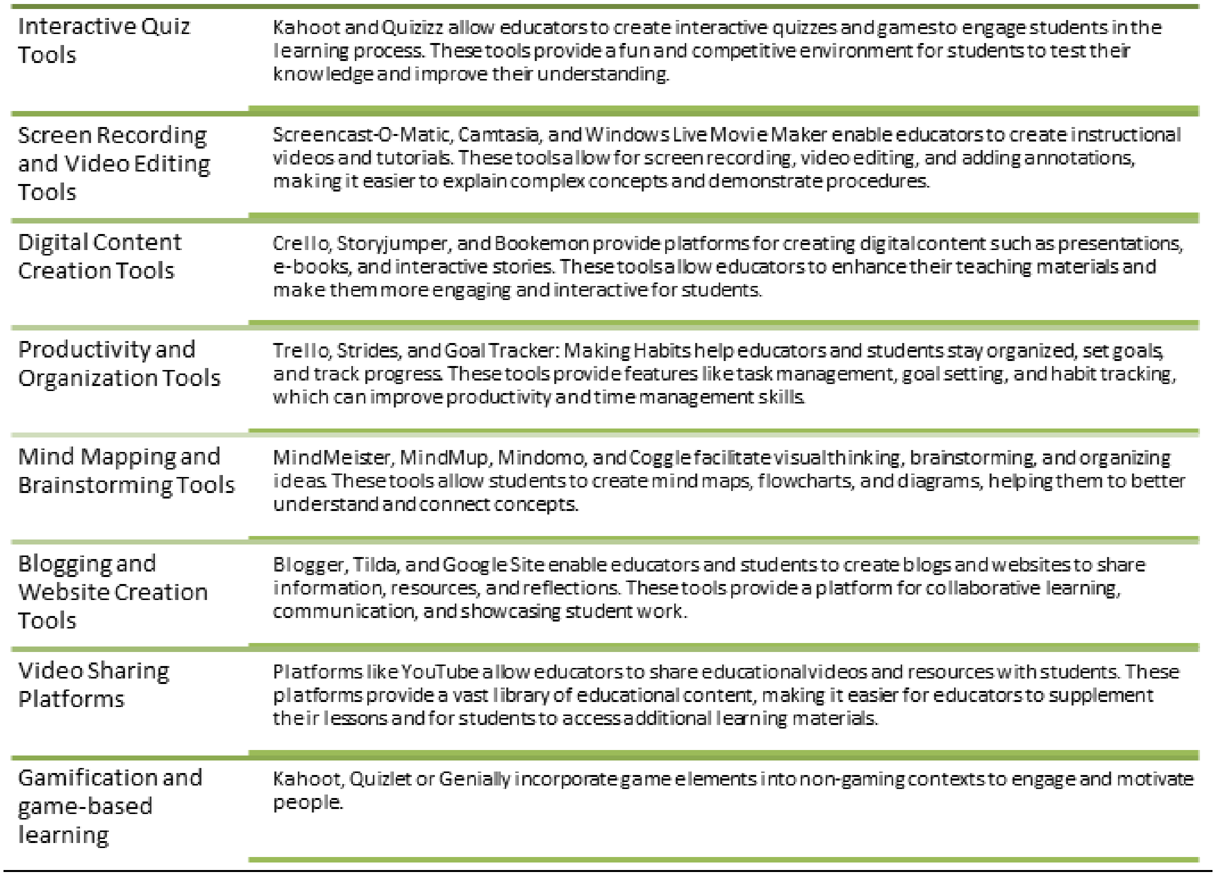
9.1.2 Digital learning and tools

Digital learning, unlike traditional learning approaches that depend on physical material and interaction, leverages technology to boost educational quality. Due to the increase of digital devices and access to the internet, such tools have become common in the contemporary learning environment.

Digital learning, which may also be referred to as online learning or e-learning, is the use of digital technologies to enable and improve teaching and learning. Digital learning is the term used to describe a wide range of educational activities and resources that are electronically accessible, often over the Internet or on digital equipment. It is accessible in a variety of ways including multimedia displays, internet-based classes, virtual classrooms, electronic games, and simulations.

Some of the categories of Digital training tools are presented in the following table (*Table 14*).

Table 14: Digital training tools



Interactive Quiz Tools	Kahoot and Quizizz allow educators to create interactive quizzes and games to engage students in the learning process. These tools provide a fun and competitive environment for students to test their knowledge and improve their understanding.
Screen Recording and Video Editing Tools	Screencast-O-Matic, Camtasia, and Windows Live Movie Maker enable educators to create instructional videos and tutorials. These tools allow for screen recording, video editing, and adding annotations, making it easier to explain complex concepts and demonstrate procedures.
Digital Content Creation Tools	Crello, Storyjumper, and Bookemon provide platforms for creating digital content such as presentations, e-books, and interactive stories. These tools allow educators to enhance their teaching materials and make them more engaging and interactive for students.
Productivity and Organization Tools	Trello, Strides, and Goal Tracker: Making Habits help educators and students stay organized, set goals, and track progress. These tools provide features like task management, goal setting, and habit tracking, which can improve productivity and time management skills.
Mind Mapping and Brainstorming Tools	MindMeister, MindMup, Mindomo, and Coggle facilitate visual thinking, brainstorming, and organizing ideas. These tools allow students to create mind maps, flowcharts, and diagrams, helping them to better understand and connect concepts.
Blogging and Website Creation Tools	Blogger, Tilda, and Google Site enable educators and students to create blogs and websites to share information, resources, and reflections. These tools provide a platform for collaborative learning, communication, and showcasing student work.
Video Sharing Platforms	Platforms like YouTube allow educators to share educational videos and resources with students. These platforms provide a vast library of educational content, making it easier for educators to supplement their lessons and for students to access additional learning materials.
Gamification and game-based learning	Kahoot, Quizlet or Genially incorporate game elements into non-gaming contexts to engage and motivate people.

The table below (*Table 15*) summarizes the advantages, challenges, and considerations regarding digital training tools.

Table 15: Advantages, challenges, and considerations of digital training tools

Advantages	Challenges and Considerations
Accessibility: Digital tools provide anytime, anywhere access to educational resources, overcoming geographical barriers and time constraints. Interactivity: Interactive features such as quizzes, simulations, and multimedia content engage learners and promote active participation. Personalization: Digital tools can adapt content to individual learning styles and preferences, catering to diverse student needs. Engagement: Gamified elements and immersive experiences captivate learners' attention and foster motivation to learn. Data-driven insights: Digital tools generate data on student performance and engagement, enabling instructors to track progress and customize instruction.	Digital divide: Disparities in access to technology and internet connectivity may limit the effectiveness of digital tools for some learners. Technological barriers: Technical issues and learning curves associated with using digital tools can hinder adoption and implementation. Pedagogical integration: Effective use of digital tools requires careful planning and integration into instructional practices to maximize their impact on learning outcomes. Privacy and security: Safeguarding sensitive student data and ensuring privacy protection are essential considerations when using digital tools.

To improve how classes are being delivered, most teachers take the initiative of introducing a set of attractive and engaging teaching learning materials or resources which have the potential to make the learners experience real joy in learning various concepts. Those teachers who are acquainted with the process of using both traditional and digital resources perfectly in the classroom achieve a new height of success, distinction, fame and popularity in the educational world.[133]

9.2 Training Tools in Additive Manufacturing

This section discusses the use of various training tools in additive manufacturing education, including innovative teaching methods and immersive technologies like AR and VR. These tools enhance traditional learning methods and provide hands-on experiences, preparing students and professionals for the industry's challenges. The research shows that when using these tools, educators can create a dynamic learning environment that promotes creativity, critical thinking, and practical skills development in additive manufacturing.

9.2.1 Teaching Factory Model

The Teaching Factory model integrates real-world manufacturing practices into educational settings to provide learners with practical experience and industry-relevant skills. The Teaching Factory aims to bridge the gap between academia and industry by simulating a factory environment within educational institutions. Through hands-on projects, collaborative learning, and industry partnerships, students gain valuable insights into manufacturing processes and develop problem-solving abilities. The concept of the Teaching Factory model in preparing students for careers in manufacturing and fostering innovation in the field is presented in the schemes below (*Figure 84*).[138]

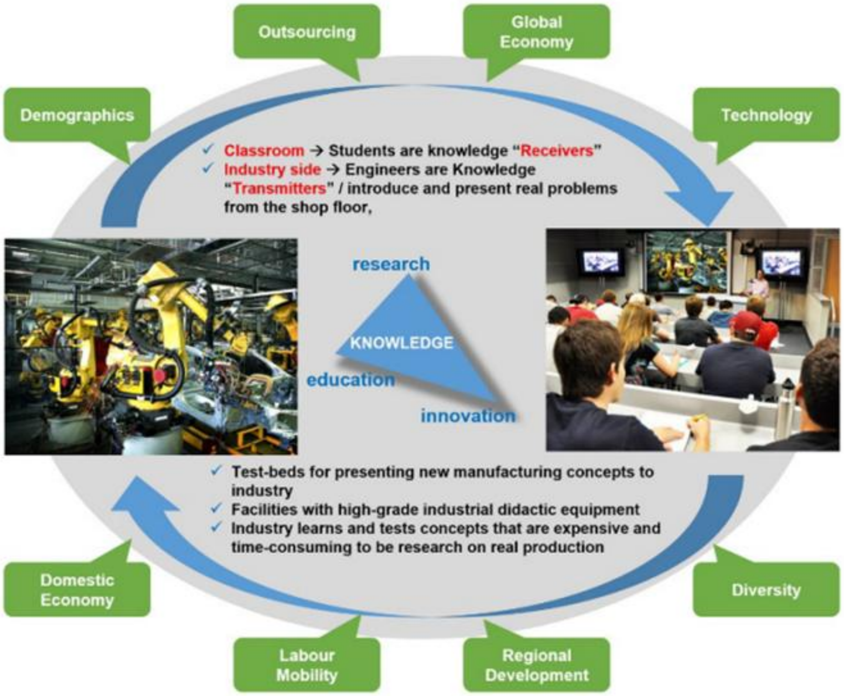


Figure 84: The teaching Factory concept[138]

The Teaching Factory is a two-way knowledge transfer channel that focuses on manufacturing topics as the foundation for new synergy models between academia and industry. The technological topics are independent of the Teaching Factory's operation and can be updated to provide the necessary knowledge foundation for manufacturing needs. The channel aims to exchange novel ideas and solutions, balancing the time and cost required for learning and testing. Two operational schemes

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[138] Chryssolouris, G., Mavrikios, D., Rentzos, L. (2016). The Teaching Factory: A Manufacturing Education Paradigm. Link

are "factory-to-classroom" and "academia-to-industry." The "factory-to-classroom" concept aims to transfer the real production/manufacturing environment to the classroom, enhancing teaching activities with existing knowledge in daily industrial practice. Delivery mechanisms must be defined and developed to enable classroom students to fully understand the production environment. The concept focuses on virtual enterprise operations with training services delivered on a virtual basis. The configuration layout of the factory-to-classroom concept should follow a modular approach for flexibility and accommodate multiple knowledge receivers. The sessions can follow either a "one-to-one" approach or a "one-to-many" approach.

9.2.2 Augmented and Virtual Reality (AR/VR)

Augmented Reality (AR) is a technology that combines virtual elements with our perception of reality, allowing teachers to provide virtual examples and gaming elements to enhance learning and memory. This technology can enhance the learning experience for students and enhance their understanding of the material.

Virtual Reality (VR) is a technology that allows users to experience a simulated environment, separate from the physical world, through a headset. This technology can be used in education to create immersive learning experiences, allowing students to visualize complex concepts, conduct experiments, and engage in hands-on activities. VR technology has the potential to revolutionize education by offering experiential learning opportunities that transcend traditional classroom boundaries, fostering curiosity, creativity, and critical thinking skills.

The Fraunhofer Institute for Additive Production Technology (IAPT) offers research and development programs that integrate AR and VR technologies into additive manufacturing processes. These programs focus on enhancing process visualization, training, and optimization using immersive AR/VR simulations.[139]

3D Bear has developed a learning resource for augmented reality and 3D printing, combining immersive technologies with pedagogical content for optimal learning outcomes. The company offers professional development, implementation, and workshops for these immersive learning tools.[140]

9.2.3 Project-based Learning

Project-based learning (PBL) is a powerful method that helps students apply theoretical knowledge in practical situations. It involves students designing new models

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[139] Fraunhofer Institute for Mechatronic Systems Design IEM. AR/VR Lab. Link

[140] 3DBear. Link

and acquiring problem-solving skills. PBL helps students acquire practical and technical knowledge, as industries demand graduates with multidisciplinary education.[141]

The Problem-Based Learning (PBL) approach focuses on students solving open-ended problems rather than deductive information presentation. The problem is authentic and reflective of professional practice, motivating students to learn content. Students work in small groups to identify their knowledge, needs, and access to information. PBL enables students to acquire desired knowledge, enhance problem-solving skills, and self-directed learning competency. However, providing an open-ended problem is not enough; instructors must guide the learning process and lead students through reflection and debriefing after the experience.

The Additive Manufacturing for Space and Aerospace course at Politecnico di Milano involved students redesigning the support for the ION Cubesat Carrier, a small spacecraft designed by Italian start-up D-Orbit. The team was asked to minimize the weight of the redesigned support, comply with the structure's mechanical requirements, and optimize its manufacturability. The winning team, composed of four students, achieved the highest weight reduction (-65%) while meeting all mechanical and "printability" requirements. D-Orbit is working with ESA for this version of the spacecraft, and their technology will also be used for ESA's Clean Space initiative. The project concluded with a final presentation day for the participants.[142]

The MSc Additive Manufacturing course at Politecnico di Milano involves students working on team projects to design and print parts for additive manufacturing (AM) using Fused Deposition Modeling. Examples include producing toy cars and bridges for competitions.

These projects allow students to learn new software tools, such as topological optimization, build preparation, processes, simulation, and 3D printers. They also experience the potentials and limitations of AM methods in practice. The competition strengthens students' commitment and fosters interest in training topics, allowing them to apply their knowledge in practice and experience the potential of AM methods.[143]

9.2.4 Case Studies and Critical Thinking

The use of case studies can be a teaching strategy to promote critical thinking. Critical thinking and case studies are defined as teaching methods. They can facilitate and promote active learning, help clinical problem-solving, and encourage the development of critical thinking skills. A case study is a real or hypothetical scenario that demonstrates the complexities of real-life situations, helping students understand how

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[141] Sharma, A., Dutt, H., Sai, Ch.N.V., Naik, S.M. (2020). Impact of Project Based Learning Methodology in Engineering. Link

[142] D-Orbit. Link

[143] SAM. (2018). Operational Guideline on Context and Training Tools. Link

these complexities influence decisions. It involves applying knowledge and thinking skills to a real-life situation, enhancing students' understanding and application of real-life situations.[144]

The Additive Manufacturing for Space and Aerospace course at Politecnico di Milano emphasizes the importance of incorporating real-life case studies in training for both university-level and professional courses. The course aims to provide students with a current industrial implementation approach of additive manufacturing (AM) on high-quality products, covering end-to-end design/manufacturing processes of real spacecraft, satellites, rockets, or aircraft parts. This includes design/topology optimization, selection of ideal AM technology, optimization of process parameters, mechanical characterisation, and production of a breadboard for full-scale testing and orbital flight. The course also provides case studies and examples of failure investigations on real components.[144]

9.2.5 Lectures by AM experts

Multi-disciplinary approaches in additive manufacturing (AM) involve inviting experts from different fields to lectures on specific topics. This approach is common in both MSc courses and professional courses. For example, the MSc Additive Manufacturing course at Politecnico di Milano includes lectures from faculty experts in various fields, such as manufacturing processes, quality engineering, data analytics, metrology, and measurements, along with seminars from industry experts or research groups. These seminars provide students with real-world experience, challenges, and opportunities to understand the current state-of-the-art adoption of AM technologies in the industry and their impact on societal and economic growth.

After mapping different training tools that can be used in additive manufacturing training, the five training tools or methodologies described above have advantages and constraints. Also, they can have recommendations for being delivered in AM training context. The SAM project identified the recommendations in applying learning tools in AM training (*Table 16*).

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[144] UNSW Sydney. Writing a Case Study Report in Engineering. Link

Table 16: Recommendations in applying learning tools in AM training[143]

Type of Training tool	Advantages	Constraints	Recommendations for being applied in AM training	Assessment
Teaching Factory	Hands-on learning experiences. Brings industry closer to academia. Hands-on teaching	Depends heavily on the infrastructure.	Should be used in conjunction with other "traditional" learning activities.	Problem-based; group work;
Augmented reality (and Virtual reality	In-line process learning;	Currently only available for a few processes and variables. No hands-on experience. Virtual.	Should be used in conjunction with other "traditional" learning activities or teaching factory.	Practical, interview
Project (Project-based learning (PBL))	Can be carried out along with the training. Students get to see the whole process chain. Equally valuable for all people. Easily adjustable project sizes.	Will have to be developed for the whole course.	Strongly advised as people can learn from learning by doing and applying the 3D printing process chain.	Individual; interview
Case study	Allows to implement the obtained knowledge.	Depending on case study – hands-on experience might be missing.		Essay: problem based.
Lecturing	Easy to get an overview of knowledge from all students. Face-to-face. Easier approachable.	No hands-on experience. Targets mostly students or pupils.	The documentation of the working materials is out there.	Multiple choice, Essay, interview.

9.3 Training Standards for Education

The relevance of having training standards in education relies on the possibility of having a framework for maintaining quality, credibility and reputation for the education institutions and educational programmes. The standards promote harmonization across different institutions or regions, regardless the location or socioeconomic background. This contributes to equality and fairness in education and training.

Standards also promote transparency by providing clear recommendations which will contribute to levelling the expectations in education outcomes and processes.

ISO 21001 Educational Organizations — Management Systems for Education is a comprehensive document developed by the International Organization for Standardization (ISO) that provides guidelines and requirements for implementing management systems in educational organizations. The primary objective of ISO 21001 is to improve the quality and effectiveness of educational processes by establishing a framework for systematic management practices.

The document begins by defining the scope and applicability of ISO 21001, which includes all types of educational organizations, including schools, universities, training centres, and vocational institutions. It highlights the importance of meeting the diverse needs and expectations of learners, instructors, administrators, and other stakeholders.

ISO 21001 sets the requirements and recommendations for educational organizations to follow to achieve their educational objectives. These requirements include:

- **Leadership and Governance:** Educational organizations are required to establish clear leadership structures and governance mechanisms to ensure effective decision-making and accountability.
- **Planning and Implementation:** The document outlines the process of planning and delivering educational programs, including defining learning objectives, selecting teaching methods, and allocating resources.
- **Support Services:** ISO 21001 emphasizes the importance of providing support services to learners, such as counselling, mentoring, and career guidance, to increase their learning experience.
- **Assessment and Evaluation:** Educational organizations are required to implement clear assessment and evaluation processes to monitor learner progress, measure learning outcomes, and ensure continuous improvement.
- **Documentation and Record-Keeping:** ISO 21001 specifies the documentation requirements for educational organizations, including policies, procedures, and records related to educational activities.
- **Continuous Improvement:** The document approaches the need for educational organizations to continually monitor and evaluate their performance, identify areas for improvement, and take corrective actions as necessary.

Overall, the relevance of introducing training standards in education when approaching learning techniques is fundamental if we seek to provide effective and quality training.

Finally, when addressing sustainability and innovation in the context of design activities for additive manufacturing technologies, teaching and learning techniques are also elements to consider, as innovation also involves the methodologies used in the teaching-learning process. The main aim of this chapter was to bridge the gap between learning methods and tools (traditional and digital) and AM training tools, always bearing in mind education standards as a way of contributing to quality assurance in training.

10. Sustainability integration into AM designers training programs

The importance of sustainability in industry, particularly in additive manufacturing (AM), has become increasingly important. The role of AM designers in the scope of sustainability has potential. Integrating sustainability into AM designers' training programs is an important step toward influencing a new generation of professionals with the necessary knowledge and skills to face sustainable design and manufacturing. This chapter explores the current scenario of AM designers' training programs, identifies opportunities for integrating sustainability, and examines best practices for effectively incorporating green topics into curricula.

10.1 Current training schemes for AM professionals

EWF manages two Qualification Systems for Personnel in Manufacturing, ensuring skills development aligned with industrial requirements and quality standards, regardless of the context in which training takes place ensuring that the industry has access to the right set of skills. One of the qualification systems is in the field of AM, namely the International Additive Manufacturing Qualification System.

The International Additive Manufacturing Qualification System (IAMQS) is a set of qualifications for different proficiency levels in additive manufacturing technologies, based on industry requirements and validated by experts. The IAMQS provides a common framework for the qualification of professionals in additive manufacturing, also known as 3D printing. The system offers 12 qualifications in Additive Manufacturing, implemented in 7 countries.

The IAMQS covers different AM professional profiles, including Operator, Supervisor, **Designer**, Process Engineer, and Coordinator. Each qualification is made up of different Competence Units (CUs) according to the specific AM professional profile.

The system has also developed three transversal CUs that can be flexibly included in tailored training: Certification, qualification, and standardization in AM, Business in AM, **Sustainability for AM, Metal AM Sustainability and Circularity, Polymer AM Sustainability and Circularity**, Aerospace and Part Quality Control, and Outlook of Professional Careers in Additive Manufacturing.

The IAMQS qualification list includes International Metal AM Operator for DED-ARC Process, International Metal AM Operator for DED- LB Process, International Metal AM Process Engineer for DED- ARC, International Metal AM Process Engineer for PBF- LB, International Metal AM Designer for DED Processes, International Polymers AM Designers, International Metal AM Coordinator, and International Metal AM Supervisor.

10.1.1 International Metal AM Designer for DED Processes (I MAM DED)

Metal AM Designers for DED Processes are the professionals with the specific knowledge, skills, autonomy and responsibility to design metal AM solutions for DED Processes. His/her main tasks are to:

- Design Metal AM solutions for DED Processes ensuring and validating that parts can be made cost-effective and efficiently.
- Close DED Processes design projects by verifying requirements for production with engineer as well as process requirements, ensuring liaison with other technical areas to sign of drawings.
- Contribute to projects in a teaming environment cooperation with AM Team.

Students completing examinations will be expected to be capable of applying the achieved learning outcomes at a level consistent with the qualification diploma level.

The modular course contents are given in the following structure (overview) in *Table 17*.

Table 17: International Metal AM Designer for DED Processes Course content

COMPETENCE UNITS	I MAM D-DED	
	Recommended Contact Hours*	Expected Workload**
CU 00: Additive manufacturing Process Overview	7	14
CU 25: Post Processing	14	28
CU 57: Relevant principles of DED Processes for Design	14	28
CU 58: Design Metal AM parts for DED Processes	35	70
CU 61: Simulation Analysis	21	42
Subtotal (without optional CUs)	**91**	**182**
CU 62: Simulation Execution	14	28
Total	**105**	**210**

* Contact Hours are the minimum recommended teaching hours for the Standard Routes. A contact hour shall contain at least 50 minutes of direct teaching time.

** Workload is calculated in hours, corresponds to an estimation of the time students typically need to complete all learning activities required to achieve the defined learning outcomes in formal learning environment

10.1.2 Metal Additive Manufacturing Designer for PBF Processes (I MAM D-PBF)

The Metal AM Designers for PBF Processes are the professionals with the specific knowledge, skills, autonomy and responsibility to design metal AM solutions for PBF Processes. His/her main tasks are to:

- Design Metal AM solutions for PBF Processes ensuring and validating that parts can be made cost-effective and efficiently.
- Close PBF Processes design projects by verifying requirements for production with engineer as well as process requirements, ensuring liaison with other technical areas to sign of drawings.
- Contribute to projects in a teaming environment cooperation with AM Team. Students successfully completing examinations will be expected to be capable of applying the achieved learning outcomes at a level consistent with the qualification diploma level.

The modular course contents are given in the following structure (overview) in *Table 18*.

Table 18: Metal Additive Manufacturing Designer for PBF Processes course content

COMPETENCE UNITS	E/I D-PBF	
	Recommended Contact Hours*	Expected Workload**
CU 00: Additive manufacturing Process Overview	3.5	7
CU 25: Post Processing	14	28
CU 59: Relevant principles of PBF Processes for Design	21	42
CU 60: Design Metal AM parts for PBF Processes	28	56
CU 61: Simulation Analysis	21	42
Subtotal (without optional CUs)	**91**	**182**
CU 62: Simulation Execution	14	28
Total	**105**	**210**

* Recommended Contact Hours are the minimum recommended teaching hours for the Standard Routes. A contact hour shall contain at least 50 minutes of direct teaching time.

** Workload is calculated in hours, corresponds to an estimation of the time students typically need to complete all learning activities required to achieve the defined learning outcomes in formal learning environments plus the necessary time for individual study.

10.1.3 AM Designer for Polymers

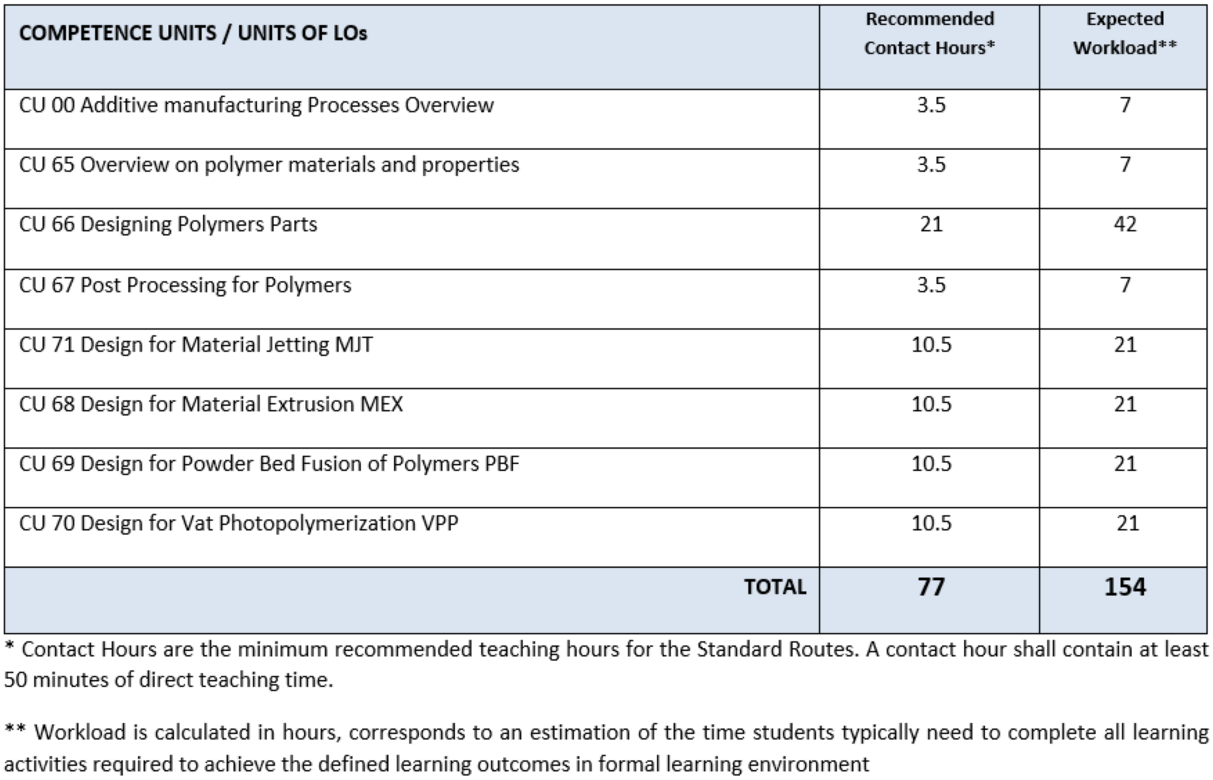
AM Designers for Polymers are the professionals with the specific knowledge, skills, autonomy and responsibility to design AM solutions for the main Polymers Processes. His/her main tasks are:

- Create part design solutions for AM polymer processes ensuring that:
    - the design considers AM benefits
    - the part can be manufactured in a cost-effective and efficient way

  - post-processing can be applied.
- Close polymer design proposals by verifying requirements for production, post-processing, quality control and process requirements with the project responsible, ensuring liaison with other technical areas to sign the drawings.
- Contribute to projects in cooperation with AM Team and costumers.

The Qualification structure is presented in the following table (*Table 19*).

Table 19: Qualification Structure AM Designer for Polymers



COMPETENCE UNITS / UNITS OF LOs	Recommended Contact Hours*	Expected Workload**
CU 00 Additive manufacturing Processes Overview	3.5	7
CU 65 Overview on polymer materials and properties	3.5	7
CU 66 Designing Polymers Parts	21	42
CU 67 Post Processing for Polymers	3.5	7
CU 71 Design for Material Jetting MJT	10.5	21
CU 68 Design for Material Extrusion MEX	10.5	21
CU 69 Design for Powder Bed Fusion of Polymers PBF	10.5	21
CU 70 Design for Vat Photopolymerization VPP	10.5	21
TOTAL	**77**	**154**

* Contact Hours are the minimum recommended teaching hours for the Standard Routes. A contact hour shall contain at least 50 minutes of direct teaching time.

** Workload is calculated in hours, corresponds to an estimation of the time students typically need to complete all learning activities required to achieve the defined learning outcomes in formal learning environment

In the last few years, the European project Sector Skills Strategy in Additive Manufacturing -SAM (January 2019-June 2023), provided a strategic approach for skills development in AM. SAM project provided a dynamic forecast methodology focused on skills gaps, shortages and mismatches identification, anticipation, and validation were developed to design and/or revise qualifications and profiles in AM with the engagement of relevant stakeholders within the European and National landscapes.

The forecast methodology addressed within SAM, consisted of continuous market research to determine skills mismatches and gaps by implementing a set of online surveys with representatives from industry/employers, workers in AM and recruitment agencies.

The surveys covered a range of subjects, which included, for example, general information and background, AM skills and professional profile needs, relevance of various skills categories, and AM employability data. SAM project, classified skills into four different categories, which we highlight the Green Skills:

- Technological skills defined as "Ability to apply knowledge and use know-how to compete tasks and solve problems" [within specific activities]" (Adapted from CEDEFOP 2008)
- Digital skills defined as "range of abilities to use digital devices, communication applications, and networks to access and manage information. They enable people to create and share digital content, communicate and collaborate, and solve problems for effective and creative self-fulfillment in life, learning, work, and social activities at large" (UNESCO, 2022)
- Entrepreneurship or entrepreneurial skills defined as "transversal key competence applicable by individuals and groups, including existing organizations, across all spheres of life" or "when you act upon opportunities and ideas and transform them into value for others." The value that is created can be financial, cultural, or social." (ENTRECOMP, 2016)
- **Green skills are defined as "knowledge, abilities, values and attitudes needed to live in, develop and support a sustainable and resource-efficient society (CEDEFOP, 2015)**

The SAM project has led to the development of a competence unit on Sustainability for Additive Manufacturing (AM), covering green awareness, circular economy, and Life Cycle Assessment for all AM professionals (*Table 20*, *Table 21*, *Table 22*). The unit aims to raise awareness of the importance of sustainability applied to AM. The competence unit (CU) is designed to be basic level, aligning with the European Qualifications Level (EQF) level 3. Students will gain basic knowledge in understanding the economic and social contexts of sustainability policies, incorporating sustainability into the product's life cycle, and understanding the limitations and routes in sustainability implementation. The course will also teach participants to spot ideas for alternative, more sustainable solutions, identify advantages and disadvantages of AM sustainability topics, identify cases where AM can lead to more sustainable products, and take the initiative to make sustainable choices throughout the product life cycle.

Table 20: SAM Project CU – Sustainability for Additive Manufacturing

COMPETENCE UNIT – Sustainability for Additive Manufacturing	**Recommended Contact Hours***
Economic and social context for sustainability policies	1
Sustainability along the product life cycle	1.5
AM within a sustainable production scheme	3.5
Case studies	1
Total	7
Workload	14

Table 21: SAM Project CU - Metal AM Sustainability and Circularity

COMPETENCE UNIT – Metal AM Sustainability and Circularity	**Recommended Contact Hours***
Overview of Sustainability	0.5
Concept & Practice of Circularity	0.5
Potential sustainability benefits of AM	0.5
Measuring, predicting, and justifying sustainability	0.5
Overview of metal AM process chains and their impact on sustainability	0.5
Impact of AM feedstock on sustainability	0.5
Impact of part design and material selection	1
Impact of AM process selection and build set-up on sustainability	1
Impact of Part post processing on sustainability	0.5
Impact of Metal AM facility design and operation	0.5
Repair, reuse & recycling approaches in metal AM	0.5
Recap on all topics covered, assessment and complete post-CU survey	0.5
Total	7
Workload	14

Table 22: SAM Project CU - Polymer AM sustainability and circularity

COMPETENCE UNIT – Polymer AM sustainability and circularity	**Recommended Contact Hours***
Overview of polymer AM process chains and their impact on sustainability	0.5
Impact of AM feedstock on sustainability	1
Impact of part design and material selection	1
Impact of AM process selection and build set-up on sustainability	1
Impact of Part post-processing on sustainability	0.5
Impact of Polymer AM facility design and operation	0.5
Repair, reuse & recycling approaches in polymer AM	0.5
Measuring, predicting, and justifying sustainability	1.5
Recap on all topics covered	0.5
Total	7
Workload	14

10.2 Best practices in integrating green topics in AM

The integration of green topics into additive manufacturing (AM) practices has become increasingly important in recent years. AM offers a promising solution for industries to reduce their carbon footprint and minimize waste, as it can produce customized, on-demand parts using fewer resources. Following, there are some examples of case studies that demonstrate the transformative potential of AM in achieving sustainability goals, from reducing material waste and energy consumption to optimizing product designs for enhanced performance and durability. Through collaborative projects and partnerships, organizations have leveraged AM technologies to revolutionize their manufacturing processes, create eco-friendly products, and contribute to a circular economy. Case studies from hypercar manufacturers to sustainable housing startups demonstrate the diverse applications of AM in addressing environmental challenges and driving positive change.

The Dansk AM Hub is a Danish business foundation that aims to become a global leader in additive manufacturing (AM) technologies, specifically 3D printing. It serves as Denmark's national hub for AM, promoting collaboration, knowledge sharing, and technological advancement. Through initiatives like the AM Summit, annual reports, and strategic project development, it encourages the adoption of AM technologies among Danish businesses, enhancing their international competitiveness and driving innovation and sustainability. Based on Dansk AM Hub, there are examples of successful integration of green in AM.

10.2.1 AM made hypercars greener, faster and better looking

"Zenvo is a Danish manufacturer of exclusive sports cars, of which they build quite a few each year. The low number means both that all the components for the cars must only be used in small numbers and that Zenvo takes more than usual care to ensure that every single part of the car is as optimized as possible: Light, strong, beautiful. 3D printing as a form of production was therefore straightforward with the wheel suspension design."[145]

10.2.2 With AM technology, Wohn will build cheap and more sustainable Tiny Houses

"In addition to the clear potential in rethinking the way we build, WOHN has chosen to use AM technology as a form of production for three primary reasons. Firstly, because of the great design freedom it provides in terms of design and strength. With AM, it is possible to rotate the fiber direction, which increases the strength across the layers. Secondly, AM is a suitable form of production in relation to using waste material in the right fractions (specific types of recycled material). And thirdly, AM allows for on-demand and fast production, where a module of 20 m2 can be produced and fully adapted in four days."[146]

10.2.3 Redesigned cooling system makes hot water for district heating

"Heatflow produces solutions for transferring heat from servers to the district heating network. They are constantly working to reduce the heat loss so that they can transfer the energy as efficiently as possible. The structure of their components, especially the geometry, is absolutely crucial in this connection, and therefore 3D printing was an obvious way forward, because it precisely allows geometric structures, which are otherwise not possible or very wasteful."[147]

"We wanted to optimize our systems so that we could cool the electronics even better and transfer the excess energy with as little loss as possible. This gives our customers the opportunity to use more of the excess heat themselves or transfer it to the district heating network, says Dennis Nadal Jensen, who is VP of technology at Heatflow."[147]

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[145] AM Hub. AM made hypercars greener, faster and better looking. Link

[146] AM Hub. With AM technology, Wohn will build cheap and more sustainable Tiny Houses. Link

[147] AM Hub. Redesigned cooling system makes hot water for district heating. Link

10.2.4 Can you design a wall with less material and the same load-bearing capacity?

“Apex Wall was designed and 3D printed in collaboration with MDT Flexible Products from Kolding and is a remarkable example of how topology optimization can revolutionize the construction of 3D printed load-bearing elements. By utilizing modern 3D software and technology, it has been possible to significantly reduce material consumption without compromising the construction's strength and load-bearing capacity.”[148]

10.3 Current Gaps

Introducing the topic of *Current Gaps* in the context of additive manufacturing (AM) and green skills involves highlighting the existing challenges and areas for improvement within the industry. These gaps represent further development and innovation opportunities to address the growing demand for sustainability in additive manufacturing practices.

The manufacturing industry has historically had a very high influence on environmental impact[149] making it urgent to identify how the industry and its employees can contribute to change towards a sustainable society. There is a growing skill gap among employees in manufacturing industries causing a lack of capability to match skill needs for fast technological development and requirements on sustainability. The resulting mismatch of technical and managerial knowledge and experience will critically impact companies in competitive markets. A smart matching process to strategically support employees in their learning paths, by matching them to new relevant skills and matching those skills to learning activities, could bridge the widespread skill gap and address challenges e.g., motivation to learn.

The paper "Skills Matching for a Greener Industry 4.0 – A Literature Review" identifies the skill gap in manufacturing industries and its impact on companies in competitive markets. The study focuses on job profiles and the skills required for green jobs. It found that people in green jobs need higher abstraction levels, more work experience, on-the-job training, and higher education than those in nongreen jobs. To increase green skills, the authors propose learning-by-doing activities. The transition towards green growth is similar to the industrial revolution, and there is a need to close the skill gap. Governments should partner with industry and employers to address this issue. Green jobs are more diverse in their skill requirements, with sophistication and novelty being key factors. The skill gap may be due to failings in education and training, as well as a lack of incentives for employers to invest in developing transferable skills. The

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[148] AM Hub. Can you design a wall with less material and the same load-bearing capacity? Link

[149] Braun, G., Stahre, J., Hämäläinen, R. (2022). Skills Matching for a Greener Industry 4.0 – A Literature Review. Link

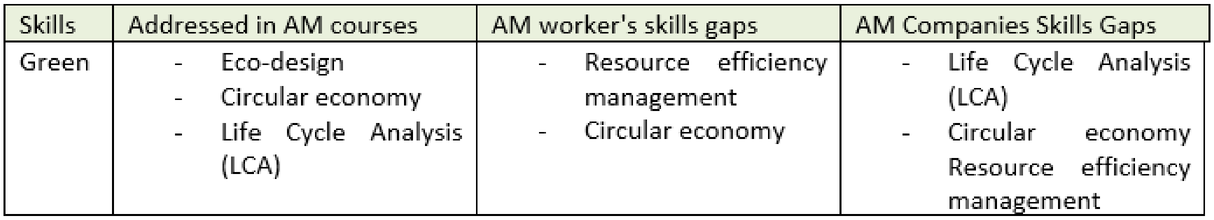
International Labour Office suggests that the green transformation will not only change existing jobs but also create new ones.[150]

Some of the solutions to address the skill gap and promote green growth:

- "Social dialogue among all stakeholders to define skills and education policies; a combination of top-down and bottom-up approaches to better reflect training provision needs; and public-private partnerships for skills and capacity development."[150]
- The "match of demand and supply of skills"[151], lifelong learning, reskilling of workers, and enhancing policies to develop skills are mentioned as parts of reaching the goal of staying productive and creating green skills.[152]

Having the AM Observatory of SAM project as a starting point, namely the Skills Gaps and demands by target group provided by the auscultation using surveys and interviews on key target groups (June 2020-April 2021), namely Additive Manufacturing (AM) companies/employers' skills gaps and AM workers skills gaps, in what it is related with the green skills, the main findings are presented in the following *Table 23*.

Table 23: Skills Gaps and Demands by Target Group[153]



Skills	Addressed in AM courses	AM worker's skills gaps	AM Companies Skills Gaps
Green	- Eco-design - Circular economy - Life Cycle Analysis (LCA)	- Resource efficiency management - Circular economy	- Life Cycle Analysis (LCA) - Circular economy Resource efficiency management

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[150] International Labour Office. (2015). Skills for green jobs. ILO package of publications and tools. Link

[151] CEDEFOP. (2009) Future skill needs for the green economy. Publications Office of the European Union. Link

[152] CEDEFOP. (2021). The green employment and skills transformation: insights from a European Green Deal skills forecast scenario. Luxembourg: Publications Office. Link

[153] SAM. AM Market World. Link

11. Final Thought – Conclusion

Through this document it has been possible to analyse in some detail the topics identified at the beginning of the document. The purpose of this work has been to structure and analyse all the potential contents that could form part of a training curriculum around the themes of design, additive manufacturing and sustainability. In order to make it possible an assessment on the interest on translating the different identified topics to a future curriculum addressing the subject matter, the next table () is aimed at making some reflections that can be useful.

Table 24: Reflections

Thematic	Conclusions	Curricular relevance
Relationship in the selection of an additive manufacturing technology and the modification of "upstream" and "downstream" processes	The relevance of the choice of additive manufacturing technology and how this can change not only manufacturing, but all upstream and downstream processes, including logistics, has been highlighted. Its potential relevance for inclusion in a curriculum is high. It should be part of the designer's body of knowledge, even if starting from the general principle of additive manufacturing (layer by layer), without taking a specific technology as a reference.	High: should be developed in some detail
Overall concept of the product life cycle	Closely linked to the previous theme, it has also become evident how the concept of the product life cycle is very important for the designer to acquire a point of view that is not only limited to his or her work or its connotations in terms of subsequent manufacturing. It is perhaps a more global domain than the previous one, so it is considered that it could encompass the same, and would therefore be rated higher.	Very High: should be addressed in great detail
Specific knowledge of the development cycle associated with additive manufacturing.	The cycle associated with additive manufacturing has been set out simply but clearly. It is extremely important for the designer to be aware of it, in order to understand how the different stages modify what can be a traditional product design and development process.	Medium: can be approached from a conceptual point of view, examples in specific technologies

Thematic	Conclusions	Curricular relevance
	It is understood in any case that the concept can be basic for anyone minimally familiar with additive manufacturing, so assuming that this knowledge will already exist in the designer, or that it will be accessible through non-specific training, its valuation is lower than in previous cases.	are employable.
Differentiation between additive manufacturing technologies	Even though they share a basic concept, additive manufacturing technologies differ greatly from each other, with differences that do not only cover the materials or the nature of the processes themselves, but also the associated design "rules". These aspects are key in each technology, or at least in the most widespread ones, when it comes to increasing the potential of each one of them to minimise material consumption, manufacturing times, post-processes, etc., and are therefore very relevant from the point of view of sustainability. It is therefore highly relevant for a curriculum that aims to illustrate the possibilities of combining design methodologies, additive manufacturing technology and the potential improvements in sustainability of the different alternatives.	High: should be developed in some detail, taking at least into account the most important technologies from an industrial point of view (PBF, FDM, SLA, WAAM, etc.).
Knowledge on raw materials for additive manufacturing	As in any other field related to design, a thorough knowledge of the materials that can be used is a basic aspect in order to propose a design capable of responding to the requirements in the most efficient way possible. In this sense, the choice of some materials over others can be a key aspect of the sustainability of a product, which is why its importance cannot be overlooked in a future curriculum. It is also a complementary theme to the previous one, as different technologies and post-processes are often linked to different materials.	High: should be developed in some detail, in line with the technologies covered in some depth in the previous theme.
Knowledge of design techniques particularly suited for use in conjunction with additive manufacturing technologies.	The combination between advanced design methodologies and additive manufacturing is perhaps one of the "strong points" among all the above, since only additive manufacturing has the capacity to take maximum advantage of techniques and tools such as topological optimisation, generative design, lattice structure	Very High: should be addressed in great detail, providing illustrative examples of at least a couple

Thematic	Conclusions	Curricular relevance
	design, minimisation of the number of components in a product, etc... It is therefore obvious that this set of issues is of critical importance for a future curriculum in the fields of interest.	of optimised design technicians.
Knowledge of techniques for identifying and accounting for impacts	Concepts such as Life Cycle assessment are not easy to approach, as they require a body of knowledge that, depending on the scope, may require a complete knowledge of the process upstream and downstream of the design process. It is therefore complicated for a non-specific training in the subject to create a complete capacity in a potential student, but techniques such as the one mentioned above are tools that allow the identification, accounting and comparison of impacts between different alternatives, and so to speak, "not measuring" implies not knowing whether the measures implemented with the awareness that they reduce the impact of a product are effective or not. Thus, while perhaps in full detail, a future curriculum around design, additive manufacturing and sustainability cannot avoid addressing these issues in as much detail as possible.	High: should be developed in some detail, with a thorough approach to the full methodology, and if possible, a simple case study as an example.
More general sustainability knowledge	It is necessary to bear in mind that sustainability is, before being a set of tools or knowledge, a "philosophy", which is based on the awareness that it is possible to maintain or improve the well-being of individuals based on the application of a series of fundamental precepts. Although this is not technical knowledge, it should be included in a curriculum in the areas to be addressed, perhaps as a necessary introduction to other knowledge.	Medium: it can be approached from a conceptual point of view.