ME-413 : INTRODUCTION TO ADDITIVE MANUFACTURING

Report

Design for additive processes, rules to follow.

Lausanne, autumn 2024

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Abstract

Design for Additive Manufacturing (DfAM) transforms traditional manufacturing approaches, leveraging the unique freedoms and opportunities of 3D printing technologies. Unlike conventional methods, DfAM encourages designs that optimize part geometries, reduce material waste, and allow for complex internal structures and lightweight features that would be impossible or cost-prohibitive in traditional manufacturing.

Central to DfAM is understanding the limitations and possibilities of both the machines and materials involved. Geometric constraints, such as allowable angles, layer thickness, and the impact of support structures, guide designers in achieving precision and functionality while minimizing material use. Additionally, machine parameters like print speed, temperature control, and the ability to handle various materials significantly impact the final output's quality and structural integrity.

DfAM also calls for innovative design strategies, such as topology optimization and generative design, to maximize part performance. These strategies facilitate part consolidation and customization, enhancing functionality and reducing assembly steps. Ultimately, DfAM opens up new applications from rapid prototyping to high-performance industrial production, reshaping manufacturing possibilities and empowering designs that are both efficient and uniquely tailored to additive processes.

Introduction

During this course, we have seen that additive manufacturing is already very broad. We've seen processes using a photo-resist as base material, extruded solid, powder deposited in a thin bed or by a nozzle, which involve also different principles of consolidation : Chemical reactions, Liquid phase bonding and Indirect bonding/brazing. And all these categories will have different constraints and requirements that the designer en engineer will have to take into consideration while designing the pocesss.

Nowadays, additive processes enable the fabrication of almost any kind of geometry. They offer a solution to produce freely optimized design and parts with integrated functions. Nevertheless, the available materials are limited, the consolidation might be problematic and AM are still relatively random processes that are difficult to control. That is why we choose the subject of Design for additive manufacturing, rules to follow.

Design for Additive Manufacturing (DfAM) describe design processes to develop additive manufacturing's unique capabilities, like design flexibility or material efficiency. This approach goes beyond general Design for Manufacturability (DFM), focusing specifically on maximizing the potential of additive technologies. Common DfAM tools include topology optimization, lattice structures, multi-material design and part or supports consolidation. DfAM can intersect with traditional DFM because some products combine additive and subtractive manufacturing steps. However, DfAM uniquely emphasizes optimizing designs specifically for AM.

We are also enthusiast to study this subject as most of our group is part of the Conception and production specialization here at EPFL. Knowing that there are freely accessible 3D printers in this school, we are also motivated to use what we learned during this class and report for other courses, associations or personal projects in the future.

1 Design Specificities - Lucie's Part

1.1 Design for Additive Manufacturing recommendations

Additive Manufacturing (AM) offers unique possibilities over conventional manufacturing ,including geometric freedom, increased customization and rapid prototyping. Design for Additive Manufacturing (DfAM) has for objective to fully help designers get the most out of the AM processes while negating some of its possible drawbacks. To achieve this, DfAM includes a specific set of rules that should be followed when using Additive Manufacturing processes.

However, DfAM is much broader than simply applying rules. Indeed, DfAM appears before the initial assumption that AM is used for the production of a part. It begins with the process selection phase, when AM might be one of the options. Choosing AM requires careful consideration of both the functional and economic aspects to ensure it aligns with the goals of a specific project. Thus, an essential step in any project likely to include AM is assessing whether this type of manufacturing is relevant for the project.

Furthermore, after a choice is made in favor of AM, the design process itself DfAM principles Without a distinctive AM mindset, it is challenging to make complete use of AM's advantages.

This section will explore these two foundational DfAM steps: selecting an AM process and applying an AM-specific design mindset, with a particular focus on lightweight designs.

As DfAM doesn't stop here, the subsequent sections will expand on the next steps of design for AM. Section 2 addresses the specific geometric constraints that are essential to keep in mind when creating AM designs. Once the design is finalized, a final check is conducted, and further optimization is applied when possible to enhance compatibility with the chosen AM process and achieve the best part quality. This optimization no longer concerns the design itself but everything that surrounds it including the machine's characteristics, the material of the build, the placement of a part and the post-processing steps. Each of these subjects will be covered in sections 3,4 ,5 and 6 respectively.

1.1.1 Choosing whether to use AM

When deciding if AM is appropriate, a few categories can be taken into account : the technical suitability and the economy standpoint being the most relevant among others (sustainability, ease of access ...).

Cost of AM For a given project, many different costs can arise. Some of them are directly linked to the AM process like the cost of the material, the process, the labor, the design phase... While others can be described as indirect cost, like the cost of post processing (cf part 5), the cost of computation (especially when using light-weight design softwares), the risk costs (related to build failure)... [1] Furthermore depending on the scale of the project traditional manufacturing might be more appropriate. This is especially the case when the project calls for large series which are not adapted to AM. However, if the demand is for one or a few complicated and possibly customizable parts, or even remote production, AM can be the most cost-effective manufacturing technique.

Technical suitability of AM To choose AM is to assume that the part is suitable for AM requirements and that AM will enable improvements. These improvements can correspond to the customization ability of the design, the use of internal channels, the consolidation of multiple parts into one or the ability of light-weighting designs.[2, 3]

Additionally, one must choose the relevant AM process between the existing ones. This can stem from the wanted material of the final product, the final application or the accessibility of said process.

1.1.2 The mindset needed to apply DfAM

Once the choice to use AM is made, a shift in design mindset is essential to fully leverage AM's unique capabilities. DfAM often requires an approach that diverges from traditional design paradigms, calling for creative rethinking of design processes. [1]

The design rules for AM differ significantly from traditional methods because the process itself allows for freedom in creating complex geometries, internal features, and structures that would be challenging or impossible with traditional methods. Designers must, therefore, abandon conventional limitations and adapt to AM's capabilities. For example, it would be unthinkable to stick with the original design when printing a previously casted part. This would completely neglect the design benefits that can come with AM. It is therefore essential to use efficiently a maximum of the advantageous features of AM, especially when light-weighting designs (cf Part 1.2), one of the principle applications of AM.

Before addressing lightweight designs, one can make an emphasis on **design for part and functionality consolidation**. Using AM, it is possible to create a unique multifunctional part from an original assembly of multiple different parts. This enables a reduction of the number of components as well as simplifying assembly and potentially enhancing durability and reliability. Thus, it is crucial that designers identify every opportunities to consolidate parts and integrate functions, even if this means expanding the scope of their research.

1.2 Light Weight design

One of the defining characteristics of Design for Additive Manufacturing (DfAM) is the focus on mass reduction. Unlike traditional manufacturing, where design is constrained by the need for molds, tooling, or machining accessibility, additive manufacturing (AM) frees designers to place material precisely where it is structurally and functionally essential. This results in lighter components that can maintain or even enhance structural integrity. Achieving these outcomes typically involves advanced digital softwares, which allow engineers to optimize the shape, the internal structure, and the material distribution at a level impossible to replicate with conventional manufacturing methods. The main light-weighting strategies – topology optimization, generative design, lattice structures, and customizable infill patterns – will be addressed in this subsection. Theses strategies empower designers to achieve optimal weight, time and resource efficiency as well as increased performance.[2]

1.2.1 Topology optimization

Topology optimization is an advanced, automated design tool that relies on a process of simulation within an iterative optimization loop. Topology optimization aims to create highly efficient structures by minimizing material use while maintaining or enhancing structural properties. It often relies on the finite element method (FEM) for its calculations, enabling the algorithm to determine areas where superfluous material can be removed without compromising the component's integrity. Through successive iterations, unnecessary material is eliminated within a defined system, following specific volume, force, and process constraints.

An example of the steps needed for topology optimization can be found in the Altair study of an Airbus A320 nacelle hinge bracket. [4]

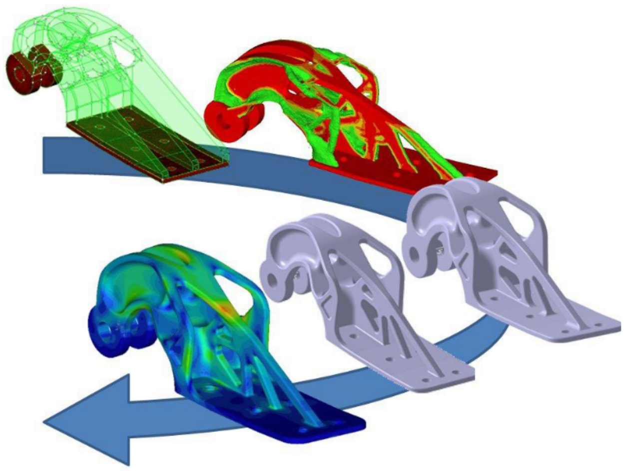


Figure 1: Example of topology optimization for an Airbus A320 nacelle hinge bracket [4]

Topology optimization begins with an existing CAD model of a part.
First, you need to define the goals of the design i.e. **Set the Objective**, such as minimizing weight, maximizing stiffness, or achieving a specific mechanical property. In their case the objective was "to produce a viable part with as little material as possible", i.e. minimum weight.
Then, you must **Define the constraints** of your optimization. These constraints can be set in regards to the physical properties of the part, like maximum allowable stress or displacement, or can constrain the optimization freedom by defining a *design space* and *boundary conditions*. The design space permits the restriction of the area or volume in which the structure can reside. The boundary conditions include any forces that will be applied to the structure, as well as fixed parts of the structure that should not change. In the Altair study, the maximum allowed displacement was $\pm 10\%$ to ensure stiffness of the part, the maximum stress was set to $1000MPa$ for static load and $350MPa$ for fatigue, and the boundary conditions can be seen in Figure 1

(fixed structures shown in maroon).
The next step is to **Run the material distribution and optimization algorithms**, where material is iteratively removed from areas where it does not contribute and sometimes (in advanced 2.0 topology optimization) added in areas where it improves strength or reduces deflection.
Next, the part goes through a **refinement** process until an optimal configuration is obtained. Usually, this process leads to organic complex shapes that are stronger, lighter or more efficient then the initial design.
Finally, the designer needs to **verify if the obtained shape respects manufacturing considerations** and if it is not the case, adjustments are mare to ensure that the part meets all requirements for manufacturing.

The topology optimization approach is particularly valuable when combined with additive manufacturing (AM), where the method's inherent geometric complexity and design freedom can be more readily achieved. AM enables layer-by-layer construction, which means complex shapes that are non-intuitive and challenging to create with traditional manufacturing methods can be directly manufactured from topologically optimized CAD designs. However, while optimized structures are theoretically ready for production, practical challenges remain. There is often a need for post-analysis and iterative redesigns to ensure the structure meets all functional and manufacturability requirements. [5]

Several manufacturing constraints must also be accounted for in the optimization process. For instance, the creation of supports structures must be taken into account to avoid any deformation or overhang, and to ensure even heat diffusion. It is also essential to restrict the optimization to geometries that are thicker than the minimum thickness achievable. Plus, the orientation of the build has a significant impact on the optimized end-part as it changes the solution space. Thus, as any AM parts, topologically optimized parts need to follow the geometric constraints that will be seen in Section 2.

As of today, topology optimization is still under development, the complexity of the mathematical models and the high amount of variables that need to be included in each simulation makes it hard to develop competent and fast converging topology optimization algorithms. Nonetheless, topology optimization offers many opportunities for the future innovations in Design for additive Manufacturing, particularly in the field of multi-material optimization. [2, 6, 7]

1.2.2 Generative Design

Generative design in additive manufacturing is a design exploration method that integrates multiple predefined parameters and performance criteria into a geometry definition process. This process can stem from a set of rules, algorithms or artificial intelligence techniques. Generative design allows for the creation of complex geometries and internal structures that are impractical or impossible to achieve with traditional manufacturing methods. Different algorithmic methodologies for generative designs include cellular automata, genetic algorithms, shape grammars, L-systems, and swarm intelligence. These techniques use algorithms or artificial intelligence to generate models from the input design parameters provided by the user. [8]

For a given set of parameters, generative design creates a large number of alternative design proposals or solutions from which the user can choose. Figure 2 from the study by A.N. Pilagetti et al. illustrates the multiple generative design outcomes for an ultralight aircraft tail landing gear. Generative design offers increased freedom and flexibility by providing multiple valid solutions whereas topology optimization which focuses on creating a single optimal solution. This multiplicity of solutions allows for a broader exploration of potential designs and makes generative design well-suited to AM. In some cases, multi-objective topology optimization may also be incorporated within generative design to refine and enhance solution diversity. [9]

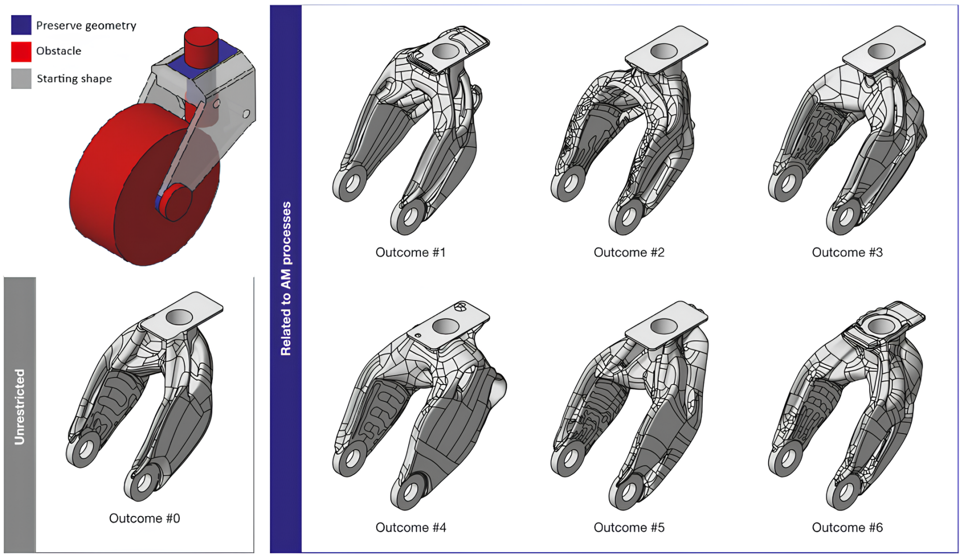


Figure 2: Different outcomes of a generative design for the tail landing gear of an ultralight single-seater aircraf [10]

Currently, generative designs typically use only one of the aforementioned approaches for a given piece of software. However, combining different methods could enable the exploration of a more diverse space of solutions and ensure that the solutions are heterogeneous, giving the user a wider range of options to choose from.

However, even though generative design methods permit the creation of multiple solutions, the question of choice still remains and becomes a critical step. Which option should be chosen ? An example of choice methodology can be found in the study by A.N. Pilagatti et al. [10]. In this study, the authors sort the different solutions according to their weight and rank them according to relevant criteria, the final decision being based on this ranking. Depending on the study, the method of choosing may vary. Designers must then rely on their knowledge and apply expert judgment to evaluate and select the optimal solution among many alternatives (aprocess that can be arduous and time-consuming). It is thus essential to keep this in mind while using generative design in Design for Additive Manufacturing (DfAM) as not all designs are equal.

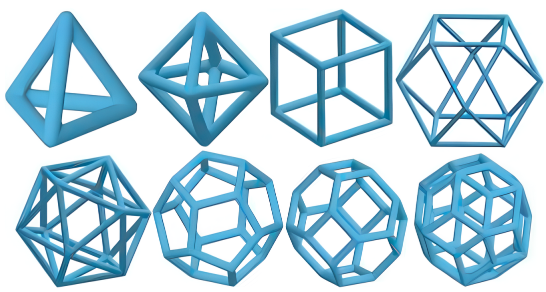
Although generative design provides a powerful mean of creating multiple viable designs, each design still requires verification to ensure it meets manufacturing constraints. Moreover, similarly to topology optimization, even the most promising generative design solution will undoubtedly need to be subject to a redesign and refinement phase as it is difficult to include all the needed constraints.

1.2.3 Lattice Structures

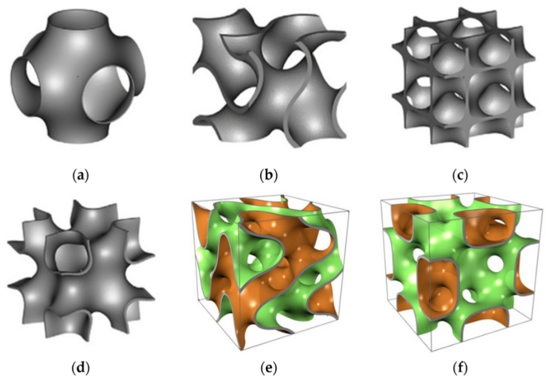
Lattice structures, also known as network structures, are advanced geometries used in additive manufacturing (AM) to replace solid volumes with porous unit-cell configurations. These intricate structures not only create lighter products but also impart additional characteristics such as improved compression, energy absorption, impact protection, adhesion, and thermal conduction. By distributing material efficiently throughout the structure, lattice designs do not compromise the structural integrity of the part.

Furthermore, lattice structures can be engineered with unique properties, such as a negative Poisson's ratio, which allows them to expand laterally when stretched. Their network architecture often eliminates the need for supports during the printing process, making them particularly advantageous in AM.

Generated using algorithms, lattice structures can vary widely in design. They can be uniform or non-uniform, homogeneous or non-homogeneous, composed of random cells or of regular prisms. Essentially, a lattice structure is defined by a repeating sequence of unit cells in three-dimensions. The norm ISO/ASTM 52900:2021 [11] defines lattice structure as such "geometric arrangement composed of connective links between vertices (points) creating a functional structure". Examples of lattice structure unit-cells are shown in Figure 3.



(a) Geometric wire frame unit cells



(b) Mathematical algorithms unit cells

Figure 3: Wire frame and algorithm generated unit-cells [12]

These intricate, sometimes bio-inspired configurations are ideal for applications requiring high strength-to-weight ratios, such as in aerospace, automotive, and medical implants. For instance, bone prostheses benefit from lattice structures as their particular design enhances integration with the body. [12]

However, one limitation of lattice structures is the intense computational demand that is associated with their creation. Designing, optimizing, rendering and simulating these structures can be quite complicated and energy-intensive.[2]

1.2.4 Part Infill

Part infills in additive manufacturing refer to the internal structure of 3D-printed objects. They are primarily used to reduce material consumption, print time and weight. Infill patterns provide basic internal support, enhance the strength as it does not leave only the outer shell, and prevent warping and deformation during printing. However, infills aren't typically optimized for specific material properties. They're commonly used in prototyping, non-structural components, or parts where the internal structure is less critical.

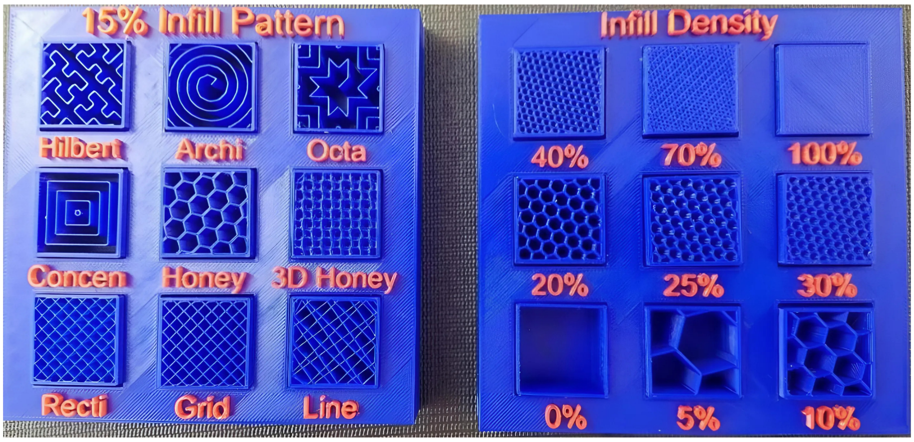


Figure 4: Infill patterns and density options [13]

Infill patterns differ from lattice structures by their 2D structure and simpler designs. Common infill patterns include *Grid*, *Honeycomb*, *Cubic*, *Triangular* and *Gyroid*. These infill patterns are usually applied uniformly across the interior of a part. The density of the pattern can be adjusted in a slicer software, typically 5-20% density is suitable for non-structural or aesthetic applications, 30-60% balances material and time save for functional parts and 70-100% creates parts that approach near solid structure and that can withstand higher loads. [14, 13] Figure 4 shows infills for different patterns and densities for an FDM print.

2 Geometric constraints - Tania's part

Additive manufacturing enables the production of complex geometries, but understanding its limitations is essential for achieving optimal part design. Critical factors the specific AM process used, nozzle size and layer height directly impact the final outcome. Additionally, considerations like overhangs, tolerances, and the spacing between features play a crucial role, as overlooking these elements can result in print failures or reduced part performance. And these are the details that we are going to talk about in this first part.

2.1 Sizing walls and layer thickness

As explained in the introduction, when designing for additive manufacturing (AM), several critical rules must be considered to ensure the quality of builds, and this also concerns features such as walls and holes.

2.1.1 Wall Design

The thickness of walls in AM is a crucial aspect of design. Let's start with the example of Fused Filament Fabrication (FFF). It is an additive manufacturing process that builds parts by extruding a thermoplastic filament layer by layer through a **heated nozzle**. It is one of the most widely used 3D printing methods. In this processes, wall thickness should be an integer multiple of the extrusion width. For example, if you are using a 0.4 mm extrusion width, wall thicknesses of 0.8 mm or 1.2 mm are recommended to ensure structural integrity [15]. Thinner walls risk being fragile, while thicker walls increase print time and material use. It would also be impossible to create a thickness smaller or slightly bigger than the nozzle size. This is not a problem for thick pieces but if it is for something small and precise or for incredibly thin wall the nozzle used has to be taken into consideration.

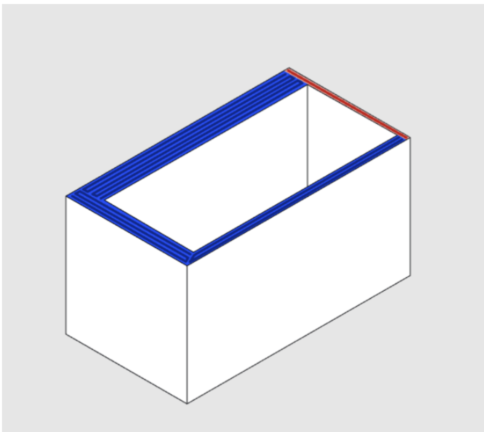


Figure 5: Wall thickness representation [15]

If we take an inclined wall, the resolution is limited by a stair effect. It is proportional to the layer thickness e. We are never going to have a perfect slope and even if we cannot see the stair because there are thousands of steps, we could still feel it with a finger which could maybe be problematic depending on the goal of the product.

In other AM methods, such as laser powder bed fusion (LPBF), the available wall thickness depends on the machine's resolution. The finer the laser or nozzle, the more precise the wall thickness can be. However, for large builds, especially when transitioning to other processes like Selective Laser Sintering (SLS), wall thickness should be optimized to maintain structural integrity and avoid deformations. For instance, it is recommended that walls surrounding holes be at least 3 mm thick in SLS printing to prevent deformation.

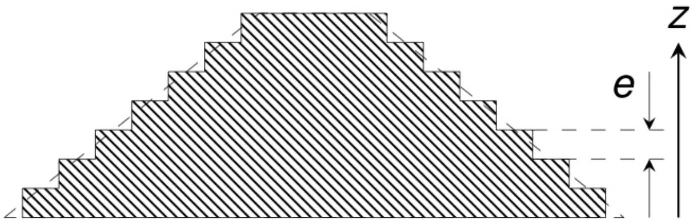


Figure 6: Stair effect [16]

2.1.2 Layer Thickness

In additive manufacturing (AM), filament thickness, or layer height, significantly influences both the appearance and mechanical properties of a printed part. When dealing with complex geometries such as curved surfaces or horizontal holes, thicker layers can result in a pronounced "stair-stepping" effect. This occurs because the 3D slicing software divides the model into horizontal slices, and these stacked layers create uneven edges on sloped surfaces. The more curved or intricate the part, the more noticeable this effect becomes. To reduce this, using a lower layer height improves the smoothness and accuracy of the print, leading to higher-quality finishes. For instance, technologies like Selective Laser Sintering (SLS) typically use layer thicknesses between 50 μm and 150 μm to find a balance between detail and print speed. [17]

In addition to surface finish, the choice of **filament thickness** has a direct impact on the mechanical properties of the printed object. Research indicates that using thinner layers improves critical mechanical aspects, such as microhardness, tensile strength, and overall durability. This is because thinner layers enhance the bonding between individual layers, reducing internal stresses and increasing the part's structural integrity. For example, in processes like Fused Deposition Modeling (FDM), reducing the layer thickness can lead to stronger parts, with better load-bearing capabilities and less risk of defects such as warping or cracking. However, thinner layers also mean longer print times, so there's a trade-off between quality and production efficiency.

The ideal layer thickness also **depends on the specific AM technology and material** being used. In binder jetting or lithography-based ceramic manufacturing (LCM), for example, layer thickness is influenced by the particle size of the powder or resin being used. For optimal results, the layer height must always be thicker than the largest particle size to avoid defects like clumping or poor fusion [18]. In these cases, while thin layers are preferable for achieving fine details and higher resolution, the material's properties set practical limitations on how thin the layers can be. This makes it essential to carefully consider the balance between layer thickness, material characteristics, and the desired mechanical and aesthetic properties when designing a part for additive manufacturing.

2.2 Holes Design

Designing holes in AM involves attention to orientation, size, and proximity to other features. Unlike traditional manufacturing, where holes are drilled after the part is made, in 3D printing, holes are built directly into the part layer by layer. When using processes like SLS, holes smaller than 1.5 mm may fail to materialize, as the resolution of the printer cannot accurately reproduce such small features. For better results, holes should be vertically oriented, as this ensures tighter tolerances and better overall resolution. [19]

For Fused Filament Fabrication (FFF) printing, the rule of thumb is to design vertical holes with a minimum diameter of 2 mm to avoid structural weaknesses. Horizontal holes may require additional supports or design modifications like **teardrop-shaped arches** to reduce overhangs and prevent sagging during printing. Other shapes exists that can be found online. [15]

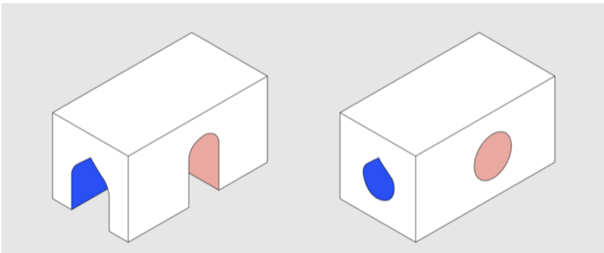


Figure 7: teardrop-shaped arches and holes [15]

2.3 Supports

Let's start with a definition : in additive manufacturing (AM), a support structure is an added component that provides support to overhanging sections or bridge-like structures of a 3D model when it is sliced for printing. Supports become necessary when dealing with overhangs, bridge structures, or hollow sections in relatively simple designs. In more complex or irregular structures, it is essential to integrate support throughout the design to maintain stability. After the printing process, these supports are typically removed, but they are essential for preventing collapse during the build.

For AM processes that need supports, the 45° rule serves as a **general guideline** for determining when support structures are needed. This rule suggests that overhangs greater than 45° typically require supports. However, the complexity of the design and the material properties will ultimately dictate the necessity of supports.

To further illustrate the necessity for support structures in additive manufacturing, the 'YHT' principle serves as a visual guide. When models are conceived as 3D prints in an upright orientation, the letters Y, H, and T demonstrate common shapes where support structures are required. Each letter signifies **different scenarios**: the Y has arms that may require support at their junction, the H shows how the crossbar can cause a need for supports beneath it, and the T emphasizes the need for support at the intersection of its components.

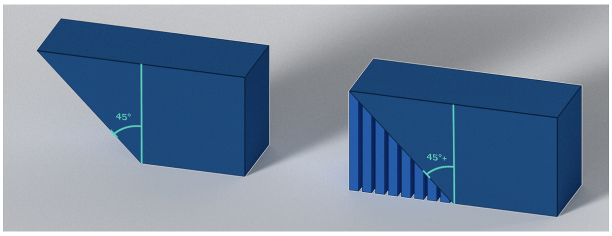


Figure 8: The 45° rule [20]

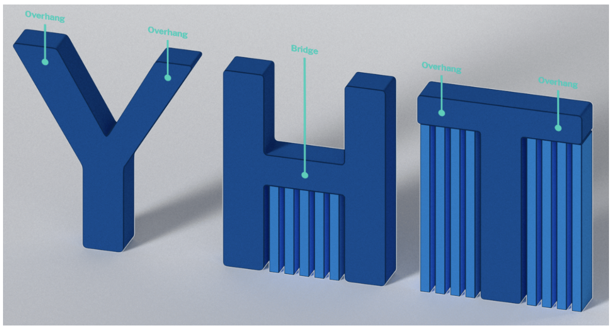


Figure 9: The YHT rule [20]

In additive manufacturing (AM), the design of support structures is highly dependent on both the shape of the printed part and the specific AM method used. Different shapes and designs of supports are more or less suited to various geometries, making some easier to remove than others. These support designs can be broadly categorized into two main types: trees and fences. Tree supports resemble branches, making them ideal for angled or complex surfaces as they can reach over distances to provide support. However, tree supports can sometimes be more difficult to remove, especially if not perfectly aligned with the part geometry. On the other hand, fence supports resemble walls, often featuring a lattice structure, and are printed perpendicular to the part's surface. They are generally easier to remove than tree supports, making them a better option for cosmetic pieces where surface quality is not negligible. Each additive manufacturing method uses variations of these support designs, but the choice between trees and fences depends largely on the specific requirements of the part being printed.

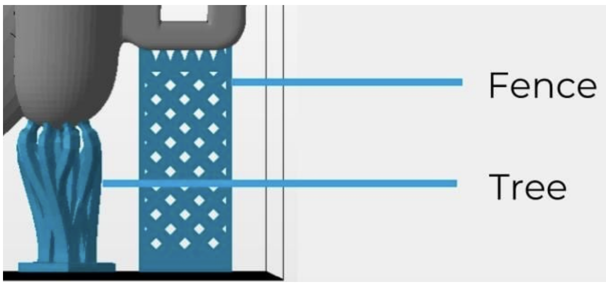


Figure 10: Fence and tree supports [20]

When designing a part that requires support structures, it is vital to account for the additional material and time that will be necessary during the printing process, as well as the post-processing efforts required to remove these supports. This integration of supports into the design process not only affects the physical attributes of the part but also has implications for production efficiency and material usage. Therefore, the careful planning of support structures or alternative strategies like bridging is an important part of the design as it can minimize the volume of material used while maintaining the quality of the final product.

While many AM techniques necessitate support structures, it is essential to recognize that not all methods require them. Technologies such as Multi Jet Fusion (MJF) use a powder bed to print parts, where the powder itself provides support during the build process. This characteristic allows for greater design flexibility. In powder bed fusion methods, like Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM), supports are required not only to stabilize the part but **also to reduce thermal stresses** that could lead to distortion. Here supports are used to prevent issues such as cracking or warping due to heat dissipation.

In Fused Deposition Modeling (FDM), for example, breakaway or **dissolvable** supports such as High-Impact Polystyrene (HIPS) and Polyvinyl Alcohol (PVA) are commonly used. These supports can really easily be removed after printing, often without damaging the part.[21]

2.4 Global sizes

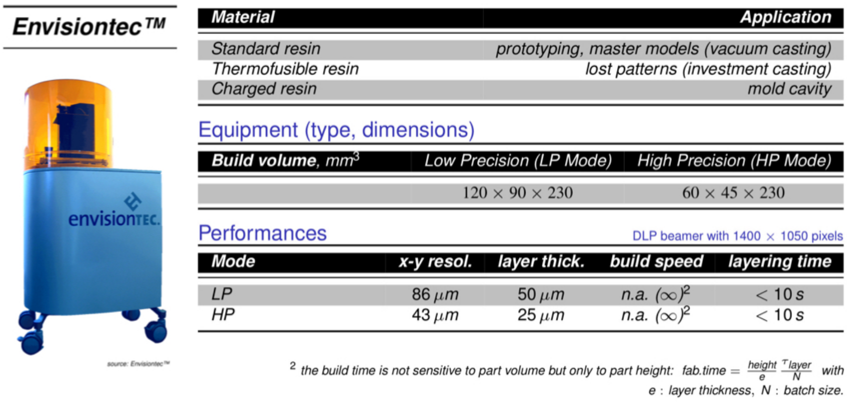
Similarly to the constraints due to the layer thickness described before, another problem is the build volume of the machine. The build volume defines the **maximum size of the part** that can be manufactured in a single process. For example, metal-based AM technologies like Metal Big Area Additive Manufacturing (mBAAM) have **larger build volumes but lower resolution** due to the larger deposition rates, meaning the design needs to incorporate post-processing techniques like machining for finer details. [22]

These size constraints also depend on the material used. For instance, Powder Bed Fusion (PBF) processes typically offer higher resolution but smaller build volumes. In processes like Fused Deposition Modeling (FDM). Machines typically have smaller build volumes than some other AM methods, which constrain the overall size of the part. For larger designs, the part may need to be printed in segments and later assembled. Additionally, the deposition process in FDM can introduce challenges with layer adhesion and part strength, especially as part size increases. The anisotropy of FDM parts also means that certain design rules—such as avoiding large flat horizontal surfaces without support are critical to maintaining part integrity.

As we have seen in class, for one equipment, the build volume will change depending on parameters. For example, in Digital Light Processing (DLP), if we study the technical data of the *Enviosionic*, one of the machine used for this process, the build volume is of 120x90x230mm3 in low precision mode, against 60x45x230mm3 for high precision mode[16].

Each AM method has **its own trade-offs** regarding build volume, layer thickness, and part accuracy, which impacts design choices. In applications requiring large, structurally robust components, such as in aerospace or automotive, build volume can be a limiting factor, as some designs may need to be broken into smaller parts to fit within the machine's build envelope.

This particular problem is a geometric constraints due to the machines limitations, therefore it will be covered in more details in the following section of the report.



Material	Application
Standard resin	prototyping, master models (vacuum casting)
Thermofusible resin	lost patterns (investment casting)
Charged resin	mold cavity

Equipment (type, dimensions)

Build volume, mm^3	Low Precision (LP Mode)	High Precision (HP Mode)
	$120 \times 90 \times 230$	$60 \times 45 \times 230$

Performances — DLP beamer with 1400×1050 pixels

Mode	x-y resol.	layer thick.	build speed	layering time
LP	86 μm	50 μm	n.a. $(\infty)^2$	$< 10\,s$
HP	43 μm	25 μm	n.a. $(\infty)^2$	$< 10\,s$

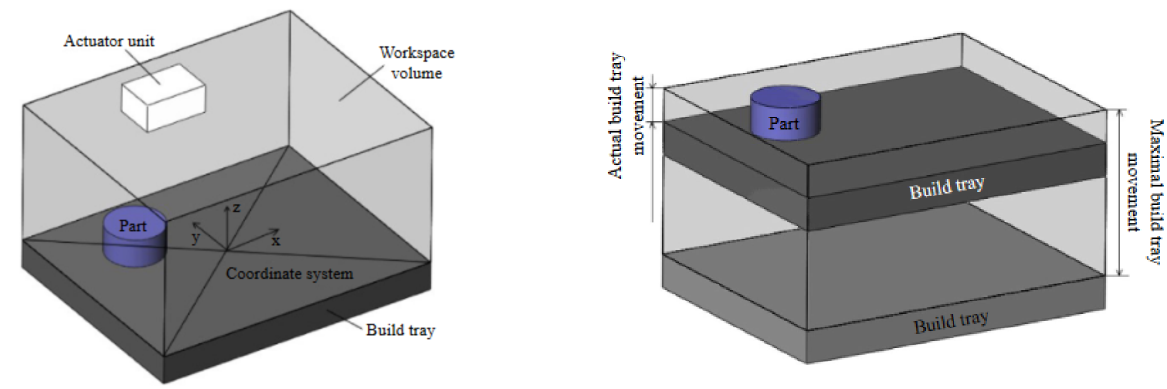
[2] the build time is not sensitive to part volume but only to part height: fab.time $= \frac{height}{e} \frac{T_{layer}}{N}$ with e : layer thickness, N : batch size.

Figure 11: Envisiontec technical data [16]

2.5 Manufacturable Volume (written by Josh)

The available volume for manufacture, more commonly called Printing Volume, remains the most obvious limitation of additive manufacturing devices. While a good indicator of the state of a particular technology at a specific point in time, it is not a metric that should be considered alone when evaluating the absolute performance of the additive manufacturing area. That being said, printing volume still is a main constraint for designers, and specification for producers of AM tools.

The available volumes of various AM technologies differ greatly, however, the architecture of the manufacture area is similar across techniques. It can be represented as a box (square or Cylindrical) with a moving build tray in one direction (generally the Z-axis), as shown in the figures below [23].



(a) General AM machine's schematics

(b) Maximal and actual workspace volume

Figure 12: General schematics of an AM machine [23]

This architecture, combined with the correct technology like FDM or DED, can make for some theoretically infinite build volumes, with the limit only being the size of the frame of the machine, and its ability to support itself. This is specific to certain techniques in additive manufacturing, specifically those based upon material deposition, and that do not require an enclosure. Indeed, processes like stereo-lithography (SLA) or powder bed fusion (PBF), require an enclosure in order to properly operate, due to the volatility of their base material, and the sensitivity of the process itself to external disturbances (dust, light, vibrations).

Of course, simply making an AM machine bigger doesn't guarantee a larger build volume, as considerations on the process itself must be taken in order to ensure the proper functioning of the machine. With a larger build volume, comes an **increased printing time**, and the risk of **accumulating defects** in the part manufacturing [23]. Some other aspects of AM machines that limit the workspace volume will be studied in further sections.

The requirements in build volume for designers will differ greatly upon the application, as private consumers and various branch of industry have different manufacturing requirements. For example, the aerospace industry boasts some of the world largest DED machines in the world, while other areas of industry might put an emphasis on speed and accuracy. Therefore, the first consideration in designing for additive manufacturing is the **choice of the machine** to use, and to make sure it is adapted to the project at hand. That being said, most users do not have the ability to change machines for every project, then **the designer has to be aware and mindful of his own machine's limitations** [24]. Additionally, it may be useful for some users to add a **visual representation of their workspace volume inside their CAD environment**. For over-sized parts, which cannot be manufactured simply by changing the orientation on the build platform, then the only option will be **splitting the part into producible pieces**. It is recommended to create the part with its split in mind, and to have a reassembly technique suited to the intended use of the part. Splitting the part after design can be effective but may lack the structural soundness needed.

3 Machine Characteristics and Limitations - Josh's part

3.1 Speed and Accuracy

Manufacturing speed and accuracy are two critical factors on their own, but are **intimately linked**. The study on speed and accuracy [23] seems to show that **increasing speed leads to reduced geometric accuracy**. The exact results of any combination of settings on any machine will vary with their design, materials and capabilities. The final quality of the final product is a representation of the **compromises between speed and accuracy** the design and manufacturing teams will have chosen to make with regards to the specific geometry to the part at hand. To achieve optimal results, **intimate knowledge of one's own machine's behavior is paramount**.

Obviously, for industrial actors with a less demanding set of specifications, who wish to manufacture complex non critical components in high series, speed may take the hand on accuracy. Indeed, while decreasing accuracy, **increasing speed increases throughput**. As stated previously, this also **increases the rate of appearance of defects** in the production, if speed is a primary concern, this can be remediated through the implementation of **quality monitoring** [25], both during and post manufacturing. The **optimization of the parameters** of the process are also key in maintaining a steady production quality, but heavily machine specific.

3.2 Differences between the design and the final printed part (written by Tania)

In AM, the final printed component often differs from the original model due to various factors that affect dimensional accuracy and geometry. One key reason is the layer-by-layer building process, which can introduce issues such as dimensional distortion, surface roughness, and even anisotropy. These problems arise because AM technologies, particularly those that rely on STL files, approximate the model's geometry by converting curves and smooth surfaces into small triangles. This approximation can result in a loss of fine details, especially in curved or highly complex regions, further affecting the final part's precision .

In **metal 3D printing**, particularly with materials like Aluminum, thermally induced stresses play a significant role in the differences between the designed model and the final printed part. This manufacturing process involves layer-by-layer powder melting, which then solidifies as the part cools down. The repeated heating and cooling cycles introduce thermal stresses, which can lead to distortions, warping, or even build failures. A design that doesn't account for these stresses, especially one with sharp edges or large accumulations of material, is particularly prone to deformation[26].

In addition to managing these thermal stresses, dimensional accuracy is another critical factor in metal 3D printing. Although metal 3D printing offers high precision, deviations from the nominal dimensions can still occur due to the process-specific constraints and the material's behavior during cooling. Therefore, understanding the tolerances specific to the size of the printed part is essential, as large thermally induced stresses can also lead to form deviations. [26]

3.3 Precision, Defects and Maintenance

Like any other manufacturing process, additive manufacturing suffers from the occurrence of defects within the parts it produces. However, unlike other processes, the fact that additive manufacturing is in great part automated, and the small scale of the operations of the machine, defects can be hard to identify, and to remediate. We can denote three most common defect types in additive manufacturing: **Porosity Defects**, **Warping**, and **Surface Roughness**.

3.3.1 Porosity

Porosity defects are more common in powder based processes, it consists in an **uneven density of the material in the part**. This can be the result of a problem in the amount of powder applied for melting, or an uneven heating of the particles causing some of them to not melt properly and bind with the rest of the material. Porosity defects can be critical, as they may affect the structural integrity of a part, as well as the geometric accuracy of the production. Since most of the technologies that suffer from this are metal AM techniques, porosity can be serious issue to solve, and not an easy one to notice as porosity defects can be invisible to the naked eye.

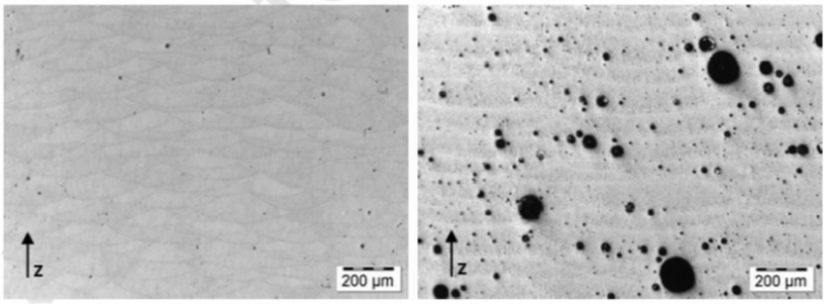


Figure 13: Nominal sample (left) and Porous sample (right) of AlSi10Mg SLM processed [27]

The occurrence of porosity defects in additive manufacturing can be solved through **optimizing with the parameters of the machine**. The main parameters to tune will be the **mass flow of material** through the nozzle as well as the **speed** of manufacturing, and **cooling system**. Some external parameters should also be checked for, for instance, the **quality and homogeneousness of the base material** should be verified, the energy intensity deployed for the process should be optimized, and the tool-head (nozzle, laser, etc) should be **properly calibrated before each use** [28] [29].

3.3.2 Warping

This type of defect, occurring mainly in FDM machines and some metal AM processes (such as DED), is caused by the **uneven cooling of a part** during the manufacturing process. The uneven cooling of the part leads to some residual thermal stresses as part of the material contracts. These stresses in turn warp the part, changing its final shape. This defect is crucial to avoid as any warping occurrence leads to a wasted part, due to the **change of external geometry**.

To solve this, many AM devices have implemented a **heating bed** for the build area, which helps keep the temperature of some materials in the good range to avoid warping. For larger scale machines, a solution will be to **confine the manufacturing area in an enclosure**. This enclosure helps maintaining the whole build volume at a controlled temperature throughout the manufacture of the part, this helps avoid any uneven cooling of the part [29].

3.3.3 Surface Defects

The surface finish of additively manufactured parts can vary from technology to technology, but is **generally considered pretty poor** when compared to other manufacturing processes. Indeed, the very nature of the technology, gives this unavoidable layer by layer effect on the produced parts. Some technologies do manage impressive results like SLA, where current machines can have a layer height thin enough to barely be noticeable by the human eye. While this may be fine for aesthetic applications, parts intended for mechanical applications, or with specific requirements on surface finish **will need to go through a post-processing phase**.

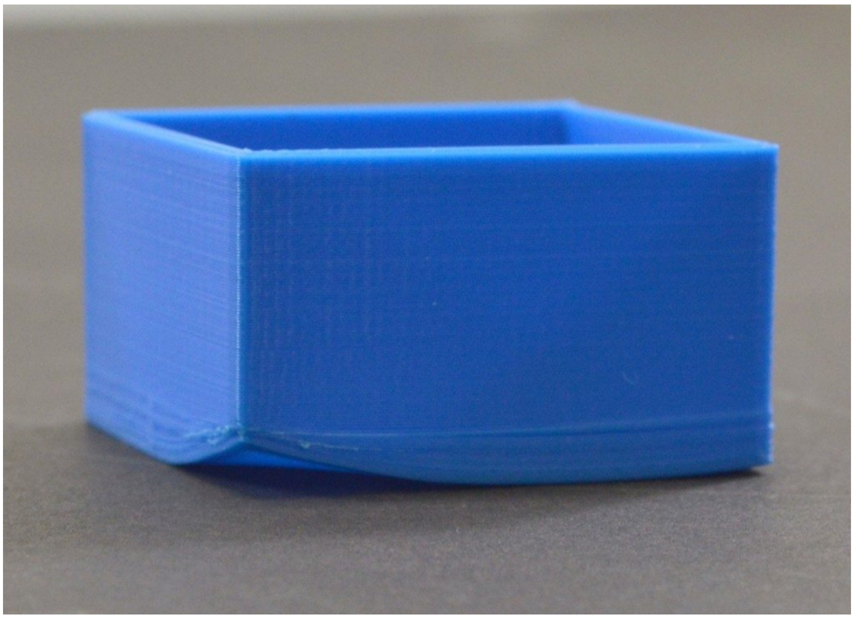
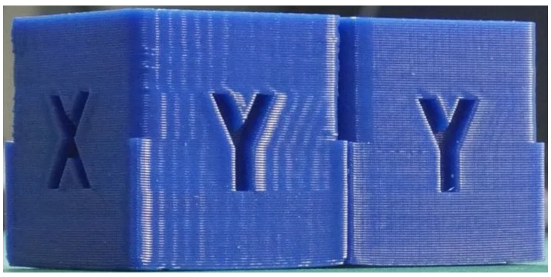
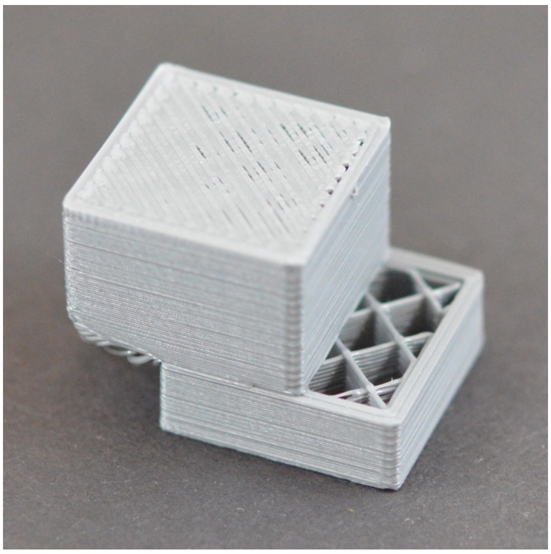


Figure 14: Warped additively manufactured product [27]

In addition, surface defects can appear in various ways and for various reasons, and will be one of the first symptoms of an error in the manufacturing process. Surface defects come in a wide range of flavors, such as (but not limited to) **over-extrusion**, **ghosting**, **layer shifting** and **layer-separation**. Ghosting, for instance, is an issue that has plagued most consumer 3D printers in the early days of the technology. These defects are typically due to either a software or pre-processing error, or a physical perturbation during the manufacturing process (like an external push, or a clog in the mechanism of the device). This sensitivity to external inputs during the manufacturing process highlights **the importance of the set, settings and the maintenance** necessary for a well performing additive manufacturing setup.



(a) Ghosting defect [30]



(b) Layer Shifting defect [31]

Figure 15: Examples of surface defects

Like any other mechanical machine, an AM device needs **regular maintenance**, this starts from basic operations such as simply **cleaning**, visually **inspecting** or **calibrating** various aspects of the machine [24] [23]. The frequency of these operation will depend of the type of **technology**, **materials** and the **frequency of use**. Inevitably, machines will break down and be in need of more important repairs. Many consumer grade devices have taken this in stride and made their designs of AM machines easily accessible and repairable, while other companies still opt for a closed and proprietary approach.

3.4 Evolution over time

Now a more mainstream manufacturing process, additive manufacturing as we know it today began in the 1980's with technologies such as FDM and SLA. The early stages of AM and its very **limited capabilities restricted the process to rapid prototyping applications** [24]. Overtime, new technologies for additive manufacturing emerged, giving way to **expanded capabilities, materials and precision**. These improvements allowed a slow transition to the production of **functional prototypes and small-scale end-use components**. Additionally, advancements in computational control systems in terms of size and power have allowed an **increase in accuracy and reliability**, opening AM processes to higher-value, more demanding sectors such as aerospace and medical [24].

Nowadays, additive manufacturing has taken its place as one of the most popular manufacturing methods, especially for private consumers, as it allows the production of complex parts easily and , without the need for advanced machining experience. The industrial sector, is also opening up more widely to AM processes, being used primarily for parts that can not possibly be realized through traditional machining. Other factors specific to parts may in fact push industry towards AM, especially when AM allows for cheaper production than its traditional counterparts. We can cite in the aerospace industry, Relativity Space's Stargate printer, one of the largest DED printers in the world, which allows the company to manufacture components faster and more efficiently than before.

One thing remains sure, it is that AM's evolution is not finished, recent improvement have opened the market for various new features in all areas of additive manufacturing. Material advancement and the possible use of advanced composite materials, high-strength alloys or ceramic blended polymers allow for the expansion of the possible applications. The continuous advancements in computer control also allow more capabilities and efficiencies in new AM machines, which yields faster, more accurate, more precise and less wasteful machines helping improve production performance for consumers and industry alike. Finally , the endless imagination of engineers and designers allow for the arrival of machines with new specific features such as multi-material printing, automation capabilities the integration of topological optimization,and many more.

In summary, it seems clear that additive manufacturing is a young, but capable process. Compared to traditional manufacturing methods, AM has the advantages of versatility and automation, those qualities combined with large public acceptance has made AM one of the most popular production methods. It still, however remains a fickle and internally complex process, and many defects can happen for many reasons as we've stated before, therefore the process still relies on experience and attention to detail from the machine operator.

4 Properties of Additive Manufacturing Materials - Jolan's Part

4.1 General Overview

Additive manufacturing (AM) employs various materials, each characterized by unique properties that influence their applications and performance. This section details the properties of ceramics, metals, and polymers, focusing on their thermal, mechanical, and electrical characteristics. Understanding these properties is crucial for selecting the appropriate material for specific applications, particularly in high-performance environments. Here are the most used materials for each class of material :

4.2 Mechanical Properties

Ceramics: Ceramics, such as Alumina (Al_2O_3), Zirconia (ZrO_2), and Silicon Carbide (SiC), are characterized by their exceptional hardness and high compressive strength, making them ideal for wear-resistant applications. However, their brittleness limits mechanical flexibility. For instance, SiC has been employed in cutting tools and abrasives due to its hardness, but its susceptibility to cracking poses challenges in structural applications. The high compressive strength of ceramics can reach values above 2000 MPa, but their tensile strength is typically less than 100 MPa, limiting their use in tension applications.

Metals: Metals like Titanium, Aluminum, and Stainless Steel are known for their superior mechanical properties. Titanium is favored in aerospace due to its high strength-to-weight ratio, with a tensile strength reaching up to 1400 MPa. Aluminum is often used in lightweight structures due to its excellent thermal conductivity (up to 237 W/m·K) and formability. Stainless Steel provides significant corrosion resistance, making it suitable for various industrial applications. Each metal's microstructure, influenced by printing parameters, significantly impacts its mechanical performance [32].

Polymers: Polymers, including ABS, PLA, Nylon, and Polycarbonate, offer lightweight and versatile options for various applications. ABS is known for its good impact resistance and ease of processing, making it popular for consumer products. PLA, a biodegradable option, is increasingly used for environmentally friendly applications. Nylon is favored for its tensile strength and flexibility, making it suitable for functional prototypes, while Polycarbonate is recognized for its toughness, boasting impact resistance that is 200 times greater than that of glass [33].

Material Type	Materials
Metals	Stainless Steel (SS) Aluminum (Al) Titanium (Ti) Inconel (Ni-Cr alloy) Cobalt-Chromium Copper (Cu) Magnesium (Mg) Tool Steel Nickel (Ni)
Ceramics	Zirconia (ZrO_2) Alumina (Al_2O_3) Silicon Carbide (SiC) Silicon Nitride (Si_3N_4) Boron Carbide (B_4C) Hydroxyapatite Glass-Ceramics Mullite
Polymers	Polylactic Acid (PLA) Acrylonitrile Butadiene Styrene (ABS) Nylon (Polyamide, PA) Polyethylene (PE) Polypropylene (PP) Thermoplastic Polyurethane (TPU) PETG ASA PC-ABS PEEK

Table 1: Commonly Used Materials in Metals, Ceramics, and polymers for Additive Manufacturing

4.3 Thermal and Electrical Properties

4.3.1 Thermal Conductivity

Metals, ceramics, and polymers exhibit distinct thermal conductivity properties, influencing their applications across various fields.

Metals: Metals typically possess high thermal conductivity, which is essential for heat dissipation in electronic applications and heat exchangers. For instance, aluminum is commonly used for heat sinks due to its excellent thermal conductivity (around 237 W/m·K). This property allows metals to efficiently transfer heat away from sensitive components, ensuring optimal performance.

Ceramics: Ceramics generally exhibit low to moderate thermal conductivity, making them suitable for thermal insulation applications. This characteristic is particularly beneficial in high-temperature settings where heat retention is crucial. Zirconia (ZrO_2), for example, is utilized in thermal barrier coatings because of its low thermal conductivity (approximately 2-3 W/m·K), which helps protect underlying structures from extreme temperatures [34].

Polymers: Polymers typically have low thermal conductivity, ranging from 0.1 to 0.4 W/m·K. While this property makes them suitable for insulation applications, their effectiveness can vary based on the type of polymer and additives used.

4.3.2 Electrical Conductivity

The electrical conductivity of metals, ceramics, and polymers varies significantly, affecting their suitability for electronic and electrical applications.

Metals: Metals are generally excellent conductors of electricity, making them ideal for use in electronic components, wiring, and electrical contacts. Copper, for example, is often chosen for electrical wiring due to its high conductivity (approximately 59.6 x 10^6 S/m). This high conductivity allows for efficient current flow and minimal energy loss.

Ceramics: In contrast, most ceramics are insulators with very low electrical conductivity, making them suitable for applications requiring electrical insulation, such as insulators in power lines and electronic devices. Certain ceramic materials can be modified to exhibit semiconducting properties, but they still fall short of the conductivity levels seen in metals [35].

Polymers: Polymers are typically insulative, with electrical conductivity values often below 10^{-12} S/m. However, advancements in material science allow for modifications that improve the electrical conductivity of polymers. For instance, incorporating conductive fillers like carbon black or metallic powders can transform a non-conductive polymer into a conductive composite suitable for various electronic applications [36].

5 Post-Processing Techniques - Jolan's part

Post-processing is a critical stage in additive manufacturing, directly impacting the performance and surface quality of printed parts. Each material requires specific techniques to enhance properties, achieve desired surface finishes, and prepare parts for functional use. Proper post-processing can lead to significant improvements in mechanical properties and the overall performance of AM parts.

5.1 Ceramic Post-Processing

Sintering: Sintering is essential for ceramic parts, as it densifies the material and enhances mechanical properties by reducing porosity. This process involves heating the ceramic material to a temperature below its melting point, allowing particles to bond together. Effective sintering can significantly improve the strength and durability of ceramic components [37].

Surface Finishing: Due to the brittleness of ceramics, surface finishing can be challenging. Techniques like grinding and polishing are often employed to achieve a smooth surface finish. These methods must be applied delicately to avoid damaging the fragile parts. Advanced techniques, such as laser polishing, are being explored to improve surface quality while minimizing the risk of fractures.

Support Removal: Removing support structures from ceramic parts requires care to avoid damage. This process often involves manual techniques and specialized tools designed to preserve the integrity of the delicate ceramics. Innovative approaches, such as soluble supports, are being investigated to facilitate easier removal without compromising part quality [38].

Hot Isostatic Pressing (HIP): HIP is a post-sintering process that applies heat and isostatic pressure to ceramic components, further reducing porosity and improving material density. This technique enhances the mechanical properties, such as toughness and resistance to stress-induced cracking. HIP is particularly valuable for applications requiring high reliability and strength, such as aerospace or biomedical ceramics.

Chemical Treatments: Chemical treatments like chemical polishing and etching are employed to refine surface smoothness and remove surface defects in ceramic parts. These processes involve using controlled chemical reactions to selectively dissolve microscopic surface imperfections, resulting in a polished and defect-free finish. Such treatments are advantageous for improving the aesthetics and functionality of ceramic components used in optics or electronics.

Ultrasonic Machining: Ultrasonic machining uses high-frequency vibrations to shape ceramics by grinding away material through abrasive particles suspended in a liquid medium. This technique is gentle on fragile ceramics, reducing the risk of fractures and allowing for precise machining of complex geometries. Ultrasonic machining is particularly useful for intricate ceramic components in medical devices or microelectronics.

Polymer and Metal Infiltration: Polymer and metal infiltration processes involve introducing reinforcing materials into the microstructure of ceramic components. By filling pores and microcracks with polymers or metals, these methods significantly enhance the strength, toughness, and wear resistance of ceramics. Metal infiltration, in particular, is used in applications like cutting tools or armor, where high performance under stress is critical.

5.2 Metal Post-Processing

CNC Machining and Grinding: For metal parts, post-processing typically includes CNC machining and grinding to achieve precise dimensions and smooth surfaces. These processes remove any imperfections and allow for tighter tolerances, which are often necessary for functional components. CNC machining is particularly effective for producing intricate geometries, while grinding ensures a high-quality surface finish suitable for critical applications.

Heat Treatments: Heat treatments, such as annealing and quenching, are frequently applied to metals to relieve internal stresses and enhance mechanical properties. Annealing helps to soften the material and improve ductility, making it easier to machine or form. Quenching, followed by tempering, enhances toughness and strength, which are crucial for applications where metals are subject to dynamic loading [39].

Support Removal: The removal of supports in metal parts can be accomplished using CNC machining or Electrical Discharge Machining (EDM). EDM is particularly suitable for intricate parts or hard-to-reach areas, as it uses electrical discharges to precisely remove material without affecting the surrounding regions. These techniques ensure the final part retains its desired shape and properties without compromising structural integrity.

Surface Treatments: Surface treatments, such as shot peening and sandblasting, are used to enhance surface hardness and fatigue resistance. Shot peening introduces compressive stresses on the surface, reducing the likelihood of crack propagation under cyclic loading. Sandblasting, on the other hand, cleans and smooths the surface, improving adhesion for coatings or paint and enhancing overall aesthetics.

Hot Isostatic Pressing (HIP): HIP applies high temperature and isostatic pressure to metal components, eliminating porosity and enhancing density. This process is especially beneficial for powder-based or cast metal parts, where internal voids can compromise strength and durability. HIP improves mechanical properties like tensile strength, making it a key step in producing high-performance components for aerospace and medical applications.

Deburring and Polishing: Deburring removes sharp edges and residual burrs from machining processes, ensuring safe handling and precise assembly. Polishing further refines the surface, achieving a smooth and reflective finish. This step is crucial for aesthetic and functional components, such as those used in medical devices, automotive parts, and consumer electronics.

Laser and Plasma Treatments: Laser hardening and plasma nitriding are advanced techniques used to improve surface hardness without affecting the core properties of the metal. Laser hardening involves using focused laser energy to heat the surface, followed by rapid cooling, creating a hardened layer. Plasma nitriding introduces nitrogen ions to the metal surface, forming a wear-resistant and durable nitride layer. These treatments are ideal for components exposed to high wear and tear, such as gears and cutting tools.

5.3 Polymer Post-Processing

Surface Finishing: Polymer parts often require minimal post-processing, but techniques such as sanding and acetone vapor smoothing [40] (particularly for ABS) can enhance surface finish and appearance. These processes can improve the aesthetic quality of parts, making them more suitable for consumer-facing applications. Additionally, advanced methods like chemical polishing are increasingly used to achieve a uniform and polished look on complex geometries.

Annealing: For semi-crystalline polymers like Nylon, annealing can be used to enhance strength and dimensional stability. This thermal treatment involves controlled heating and cooling to relieve internal stresses and optimize the polymer's crystalline structure. Annealing can increase tensile strength by up to 20%, improve thermal resistance, and reduce the risk of warping during use, enhancing the material's performance in demanding applications [41].

Support Removal: Support removal for polymers is typically done manually, requiring careful handling to avoid damaging the printed parts. The choice of support structure design, such as using breakaway or soluble supports, can facilitate easier removal. Soluble supports, especially for dual-extrusion printing, dissolve in specific solutions, significantly reducing the risk of breakage and minimizing manual intervention, thereby streamlining the post-processing workflow.

Painting and Coating: Painting and coating are often used to improve the aesthetic appeal, UV resistance, and durability of polymer parts. Specialized paints and coatings designed for plastic surfaces provide added protection against environmental factors like moisture and sunlight, ensuring the longevity of parts used in outdoor or high-wear conditions. These treatments are particularly valuable for consumer products and automotive components.

UV Curing: UV curing is a critical step for resin-based polymer parts, particularly in processes like SLA or DLP printing. This method involves exposing the part to UV light to solidify the surface and enhance its mechanical properties. UV curing improves durability, provides lasting strength, and ensures better resistance to wear and environmental degradation, making it essential for high-performance applications.

Welding and Bonding: Welding and bonding techniques are used to join polymer components for functional assemblies. Methods such as plastic welding, which employs heat or ultrasonic energy, and UV bonding, which uses UV-curable adhesives, create strong and reliable joints. These techniques are essential for producing large, complex assemblies or ensuring the structural integrity of load-bearing parts in industrial and consumer applications.

6 Print Orientation and Mechanical properties - Jolan's part

Orientation Effects in Ceramics: In ceramics, vertical orientation often leads to improved compressive strength, which is beneficial for parts subjected to compressive loads [42]. Conversely, horizontal builds tend to enhance tensile strength. Understanding the loading conditions and application requirements is crucial in selecting the optimal print orientation for ceramic parts. Printing 90 degrees to the build plate results in stronger ceramic materials [42].

Orientation Effects in Metals: In metal additive manufacturing, vertical printing orientation can result in weaker tensile strength due to poor inter-layer bonding. However, post-print heat treatments can significantly enhance layer bonding and overall mechanical strength.

Orientation Effects in polymers: Print orientation in polymers directly affects mechanical strength. Horizontally printed parts generally exhibit higher tensile strength, as layers are aligned with the direction of the applied force, maximizing inter-layer bonding. Conversely, vertically printed parts are more susceptible to failure under tensile stress due to weaker interlayer adhesion. While vertical orientation may offer better compressive strength for certain applications, horizontal orientation is often preferred for tensile applications.

Conclusion

To conclude our research, we decided to try something a bit different then a simple paragraph. Our subject being Design For Additive Manufacturing (DFAM) : Rules To Follow, we decided to create a concise and practical list of the rules to follow. This approach allows us to synthesize the key takeaways from the various sections of this report. As said multiple times through our work, due to the diversity of Additive Manufacturing methods, the rules listed here bellow are intentionally broad, obviously not exhaustive and could still very much vary depending on the specific AM process employed. Furthermore, some of them should rather be interpreted as "recommendations" rather than rigid constraints.

Design specificities : The Choice of process and AM mindset

- Recognize that DfAM begins as soon as the process choice is initiated.
- Evaluate the feasibility of using AM based on cost and technical suitability.
- Shift the design mindset completely to align with the capabilities and principles of AM.
- Avoid recreating exact replicas of traditionally manufactured parts in AM; instead, leverage the unique possibilities AM offers.
- Consider neighboring components when designing new AM parts to explore opportunities for consolidation and integration.

Design specificities : Light Weight Design

- Always assess the manufacturability of designs generated by lightweighting software.
- Use engineering judgment and prior experience when selecting and approving a final design.
- Validate generated designs through physical testing after a successful print.
- Account for computational costs when choosing a lightweighting technique.

Geometric Constraints : Sizing Walls and Layer Thickness

- Ensure the nozzle diameter and machine resolution align with the desired wall thickness.
- Be mindful of the "staircase effect" and whether it impacts your design negatively.
- Consider both the structural integrity and appearance wanted for the part when selecting layer thickness and height.
- Evaluate the mechanical properties of the part. For instance, thinner layers can enhance micro-hardness and other properties.
- Each additive manufacturing method offers different properties; review them thoroughly before selecting one.

Geometric Constraints : Sizing Holes

- Think about what AM technics you will use and see if holes could be a problem or not.
- Plan the orientation of your part during manufacturing to align holes vertically whenever possible.
- Try to use teardrop-shaped holes to reduce the need for supports, but only if this change fits within your design requirements.

Geometric Constraints : Supports

- Analyze the geometry of your part and the AM method used to determine if supports are necessary, as they may affect precision. Aim to design features that minimize their need.
- Consider modifying your design to incorporate maximum 45° angles, which can often eliminate the requirement for supports.
- If supports are unavoidable, select their shape carefully, as this can influence surface quality, printing time, and other factors.

When it comes to machine constraints, specific rules to follow can help guide users in troubleshooting specific problems, however there remains one golden rule, common to all technologies and materials:

Know your machine, inside and out, front to back and top to bottom

Indeed, intimate knowledge of the user's specific machine is an essential part of well rounded functioning additive manufacturing setup. An experienced user should be able to optimize the various parameters of the machine reliably, for various applications.

Machine Constraints : Build Volume

- If possible, use a machine that can produce the part in whole.
- Add a representation of the available print volume to the CAD environment, this may help constrain the part into the feasible volume
- If the machine cannot fit the whole part, design the part in multiple pieces and use a mechanically sound method for reassembly.
- Avoid splitting the part post-design, as it leads to inefficient reassembly

Machine Constraints : Speed and Accuracy

- Inherent trade-off between manufacturing speed and the accuracy of the process.
- For basic, geometrically simple parts, speed can be increased as accuracy is less important.
- For intricate parts, with geometrically complex features, reducing speed will help insure that manufacturing follows design as closely as possible.

Machine Constraints : Defect avoidance

- Visually inspect the machine before starting any manufacturing operation.
- Ensure that all necessary (and ideally optional) calibration procedures are run and completed successfully.
- Ensure that the print file is correct, that pre-processing has been done correctly, double-

checked, and is coherent with the machine's specifications.
- Ensure a proper environment for the process, with as little passage, heat fluxes, perturbations (dust, water, etc...) as possible.
- Ensure the quality and the homogeneousness of the base manufacturing material.
- For heat based additive manufacturing processes, ensure the functioning and proper tuning of the cooling system.
- For warp sensitive materials, make sure the machine is equipped with the proper hardware (heated bed, enclosure).
- Proceed to the maintenance operations in due time (ideally straight after printing), this includes (but is not limited to) the cleaning of the build platform and nozzle (or equivalent), recalibration and the replacement of any component showing signs of malfunction.

Furthermore, the understanding material-specific properties, post-processing requirements, and print orientation is essential for achieving high-quality, functional parts. Materials such as metals, polymers, ceramics, and composites each offer unique advantages and challenges. For instance, metals excel in strength and thermal conductivity but often require stress-relief treatments, while polymers provide lightweight solutions with limited strength.

Post-processing, including surface finishing and heat treatment, plays a critical role in refining mechanical properties, aesthetics, and dimensional accuracy. Additionally, careful consideration of print orientation is necessary to mitigate anisotropy, enhance interlayer bonding, and align with load paths for optimized strength.

Common materials like titanium alloys, stainless steel, and ABS demonstrate the versatility of AM in applications ranging from aerospace to medical devices. However, the key to success lies in selecting the right material and design strategy tailored to the specific application.

By integrating these principles, engineers can maximize the benefits of AM, such as design freedom and material efficiency, while minimizing limitations like surface roughness or weak interlayer adhesion. Following these rules ensures reliable, cost-effective production and paves the way for innovative applications across industries.

In the end, it is quite difficult to make a list of rules that must be followed as they would easily vary depending en the method used, the shapes of the part, the dimensions and material needed. What can be done (and what we did) nevertheless is a list of recommendations or points to consider whenever designing a part.

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