Application to support design for additive manufacturing in conceptual phase of product development

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MASTER THESIS

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Abstract

Additive manufacturing (AM) is commonly related to rapid prototyping, although nowadays it is becoming a real option for small-batch production. The expansion of this technique is directly related with the production costs. However, with the supporting tool in the conceptual phase of design it is possible to guide the product developers at selecting the most appropriate material and AM technology to minimize the costs and at the same time fulfill technical criteria.

To make the phase of design easier for the developers, a new way to choose the best options for the manufacturing is needed. A web based application was created for that. The user inserts some of the design characteristics and then the software returns which options are the best in every case. The application offers general guidelines for design for additive manufacturing too.

Keywords: Additive Manufacturing (AM), production cost, conceptual phase of design, web application

Sammanfattning

Additiv tillverkning (AM) är vanligtvis relaterat till snabb prototypframställning, även om det nu för tiden blir ett verkligt alternativ för mindre serieproduktioner. Expansionen av denna teknik är direkt relaterad till produktionskostnaderna, men med rätt verktyg i designfasen är det möjligt att även hjälpa utvecklarna av en produkt att välja vilket som är det bästa materialet eller AM-tekniken för att minimera kostnaden så mycket som möjligt.

För att göra designfasen lättare för utvecklarna behövs ett nytt sätt att välja vilka de bästa alternativen för tillverkningen är. Så en hemsida kommer att skapas. Användaren kan fråga efter vissa egenskaper och sedan återkommer programvaran med vilka alternativ som är de bästa i varje respektive fall. Programmet ger även ytterligare information om hur man designar rätt del beroende på valet som gjorts av utvecklaren och även några allmänna regler för design för additiv tillverkning.

Nyckelord: Additiv tillverkning (AM), produktionskostnad, konceptuell designfas, webbapplikation

Preface

This Project came from a great desire to study abroad, in a country that would be completely different to Spain. From the first moment I thought of Sweden, and Lund ticked all the boxes for what I was looking for. It is a small city with a renowned university. In order to make my six month stay official, I had the complicated task of finding a supervisor that could offer me a master thesis without having previously met, as I was still in Spain by then. Luckily, I contacted Joze and he offered me a proposal that caught my interest.

This proposal consisted in developing a website that allowed to ease the design faze by using AM. I had already worked with these technologies in previous work experiences, although in a much smaller scale than the one suggested by Joze. Even though I wasn't too familiar with IT and web design, I consider this a challenge that can become very useful in the future for new projects.

For all this, I would like to thank all the help that I have received from Joze, who has been a guide in this whole experience. Also, to Guillem, Jordi, Ramon and Per, who have answered many IT inquiries that would pop up. To Josep, for giving great feedback in the transcription of this project. But overall gratitude to my family, without who this would have not been possible.

Thank you all.

Lund, April 2022

Manel Martí Rosich

Table of contents

List of acronyms and abbreviations

AM	additive manufacturing
BJG	binder jetting
CAD	computer-aided-design
CNC	computer numerical control
DfMA	design for manufacturing and assembly
DP	design principle
DR	design rules
EBM	electron beam melting
FDM	fused deposition modeling
LOM	laminated object manufacturing
RP	rapid prototyping
SLM	selective laser melting
SLS	selective laser sintering
SLA	stereo lithography apparatus
UAM	ultrasonic additive manufacturing
VP	vat photopolymerization

1 Introduction

1.1 Background

Additive manufacturing (AM) is commonly related to rapid prototyping, which was its first use. Previous studies have demonstrated that the expansion of AM depends on the production costs. But with a correct design phase and helping the developers with cost estimation and process selection, AM could be more competitive. There is a multi-criteria AM function which helps to compare how processing and product design affect the product cost. It will support the product developers in the conceptual phase of design, where the space is still wider. This will give a fast cost estimation of the product and can transform AM to a real option for small-batch production.[1]

Further expansion of AM from prototyping to production of final products in small batch quantities is closely correlated to production costs. Competences of product developers and competitive production costs are key drivers that will expand the use of AM. Application of AM can be competitive to traditional manufacturing methods only if the product is designed for AM already from the beginning. The aim of the paper that inspires this thesis is to increase cost awareness in the conceptual design phase and support product developers at AM cost estimation. It cannot be emphasized enough the importance of the early life phases for the product’s success. Any mistakes made here can be corrected later only with great effort. [4] [10]

AM was applied first for rapid prototyping (RP). Prototypes are typically produced in low quantities and costs are not the most critical parameter. The added value of RP is early feedback information to product developers and for communication with customers. The product must be designed and optimized for the manufacturing process that will be applied in a serial production and not for prototyping. However, AM is increasingly used as a production technology and the industry must change the perception that AM is cost efficient only for RP. Demonstrating a real added value for production with 3D printing at scale will increase the use of 3D printing for production [4] [11]

In the paper that inspires this thesis, a model for a computer aided tool was developed that aids the cost awareness of the product designer. As AM is not the best option for each product, the product design must be evaluated first according to different criteria. If the product does not contain specific design features that can be manufactured only with AM then applicability of other manufacturing processes must be explored. Moreover, product design can significantly influence the AM processing cost. The product designer must ensure that the advantages and limitation of AM processing were considered. Product re-design must be conducted if design for AM was not already applied. [4]

In the second step, a selection of a proper AM technology is done according to the product design requests such as mechanical properties, tolerances, temperature resistance, maximum size, etc. As the choice of AM technology has significant influence on product cost, it is important that the product only meets the most crucial requirements. [4]

In the last step, a case study of cost assessment is conducted based on a defined part geometry and AM processing technology. The presented approach will be implemented as a Web-based application. New technologies and materials are being developed and their costs are reducing; therefore, it is necessary to regularly update information. A special multi-criteria function is introduced that helps to consider several criteria concurrently. The key idea of the presented tool is to support the product developer and increase AM cost awareness in the product conceptual design phase. [4]

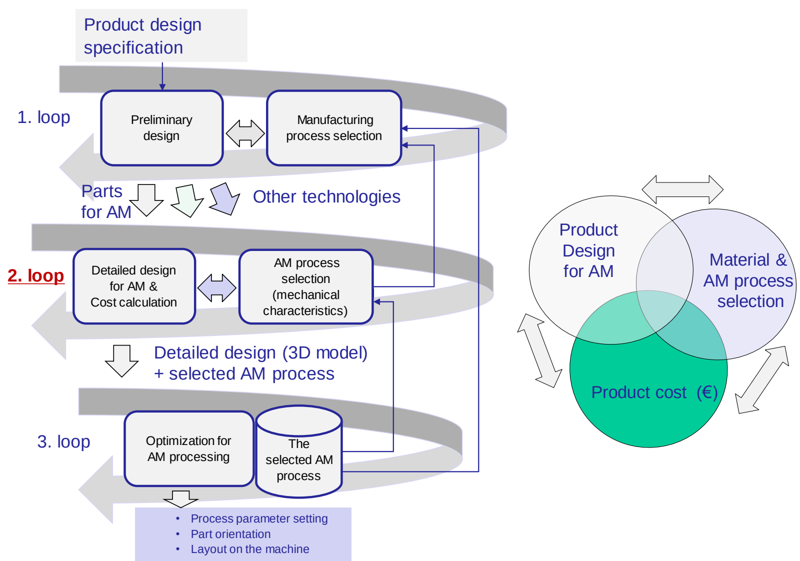


Figure 1: Detailed design for AM and costs calculations is in the second loop of product development process [4]

1.2 Overall goals and issues

- End user support with design for AM principals (links to the catalogue of design rules)
- AM part cost estimation based on input data: part volume, material, AM processing technology
- AM process selection based on technical characteristics: mechanical properties, quality level, temperature, resistance, isotropy request.
- Web based application: central database for storing and updating AM materials and AM technologies (different AM machines)

1.3 Structure of the report

Additive manufacturing has been in use for three decades, but its potential is not fully utilized. Information on AM technologies and design for AM are spread around different sources what make it difficult to apply in an optimal way.

There is a plan to check the state of the art, collect knowledge on Design for AM, available technologies for AM and integrate into a user-friendly application. The final solution will consider approaches from design methodology.

The planned activities contain:

1.3.1 **Phase 1: Checking the state of the art**

- Review of tools and guidelines for design for additive manufacturing
- Summary of available technologies for AM and technical characteristics
- Selection of programing environment for development of WEB base application.

1.3.2 **Phase 2: Model development**

- Development of concept: how to support the product developer and how to integrate supporting tools into product development process.
- Development of data model: what data needs to be collected, how to search for information, how to store data and present it to end user.
- Development of a model for costs calculations at AM.

1.3.3 **Phase 3: Software development**

- Development of a Web based application, implementation of a model developed in phase 2. The application need to confirm practical benefits

2 Checking the state of art

2.1 Additive manufacturing

2.1.1 **History**

Additive manufacturing, also known as 3D printing, is a technological advancement that made the transition from analog to digital processes possible. This process uses a design made by computer, like computer-aided-design (CAD) or 3D scanned objects to directly deposit materials, layer by layer, to precisely reproduce the object.

This method is actually not very new; it had been used for several years. In 1980 Hideo Kodama files the first 3D printing patent application; it was a system that used UV light to harden the material, but this was never commercialized.

In 1983 Charles Hull invented the first stereo lithography apparatus (SLA) and in 1986 he was granted the first patent for that machine.

Finally in 1992 the first SLA machines were commercialized, those machines weren't perfect and the pieces presented some defects and imperfections.

In 1999 the AM started to seem like an option for medicine to print organs for transplants, but until 2002 this didn't happen.

After that in 2005 Adrian Bowyer invented the RepRap open-source concept to create a self-replicating 3D printer process. This allowed the creation of other 3D printers.

Then in 2006 comes the selective laser sintering (SLS), this technology allows melting metals during the process. So, the fabrication of prosthesis and industrial pieces started to be a real option.

In 2011, AM was already in many types of industries, and it was then when the investment in these technologies increased and with that also the production. [12]

2.1.2 **Technologies**

2.1.2.1 Material Extrusion

This type of technology uses filament or thermoplastic material to create parts. The material is heated and layered through a nozzle to create the final product. This is the most common technology and also known as fused deposition modeling (FDM).

It is also common to use a support for the product, and when the printed process is done, this support can be broken or dissolved. Usually, the support is built with a different nozzle or at least with a different material. [13][14]

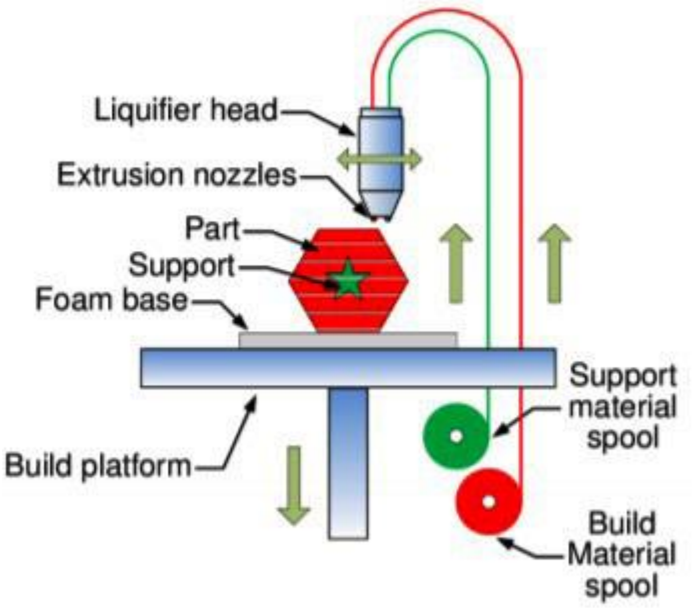


Figure 2: Material extrusion process [15]

FDM can be used with several materials like carbon fiber, Kevlar, glass gilled, metal, etc. One of the most challenging problem of this method is the tendency of being anisotropic (the parts are weaker in the vertical axis). So this is a very useful technology for parts under compression but less for parts under tension.

Also one of the main problems of FDM is the low quality of the surface. It is also important to say that it is a problem of all the AM technologies.[13][14]

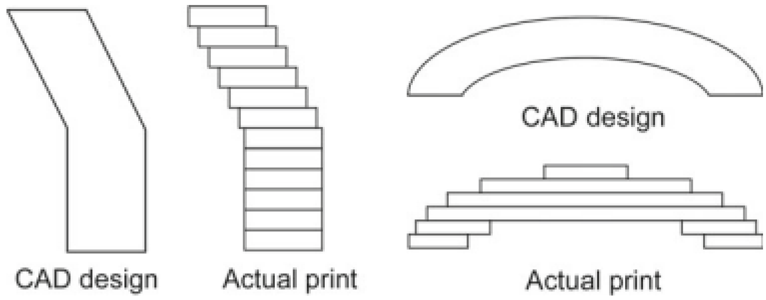


Figure 3: Step-stair effect [13]

Those are the main pros and cons of material extrusion

Pros	Cons
Most affordable machines, particularly with the advent of desktop machines (though desktop machines are not generally considered suitable for manufacturing)	Most anisotropic process. Substantial weakness in Z direction
Prints in standard engineering thermoplastics	Poorest surface quality process
Low cost material available for desktop 3D printers	Requires support material for overhangs
Easy to use machines	Potentially difficult polymer support material removal, unless they are soluble

Table 1: Pros and cons of material extrusion [13]

2.1.2.2 Powder Bed Fusion

This technique uses either a laser or an electron beam to melt and fuse material powder together to make the product. There are two types of powder bed fusion:

- Electron beam Melting (EBM): this is used to melt particles together in specific areas. The beam can be manipulated very fast so it allows multiple melt pools to work simultaneously.
- Selecting laser melting (SLM) or SLS: it is used to heat materials in a powder form into 3D products. This technique consists in compiling layer by layer. This technology doesn’t require support.

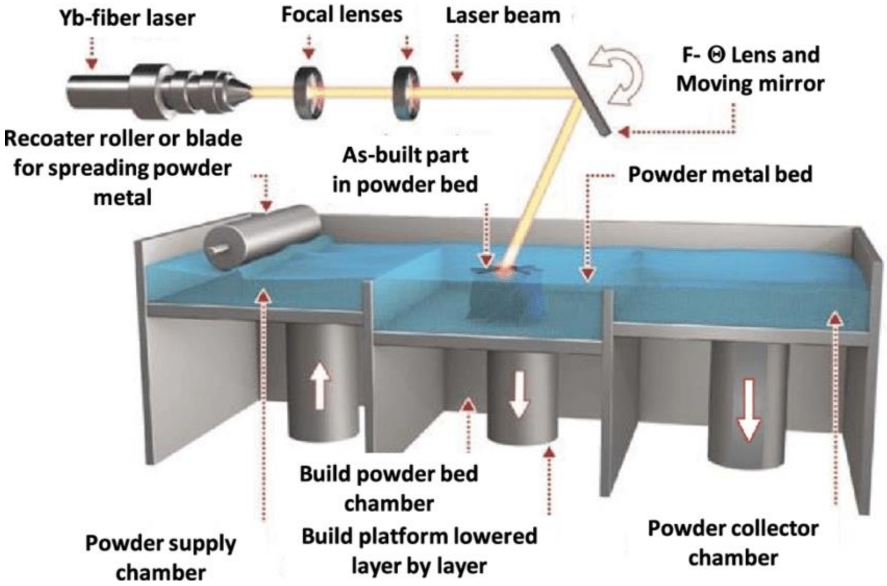


Figure 4: powder bed fusion process [16]

This technology also has anisotropy in the vertical axis but if the part is well designed this can be minimized a lot. Powder bed fusion also has the stair-step effect on the curved components. [13][14]

Pros	Cons
From a material point of view, one of the lowest cost production technologies	Metal PBF requires support material for heat transfer, and can require considerable effort to remove
Produces strong and durable parts	
No support material required for polymer powder bed fusion	

Table 2: Pros and cons of powder bed fusion [9]

2.1.2.3 Vat photopolymerization(VP)

This method uses a liquid resin which is applied layer by layer, and after that, a UV light hardens the resin to finally create the part. This step is done for every slice of the model.

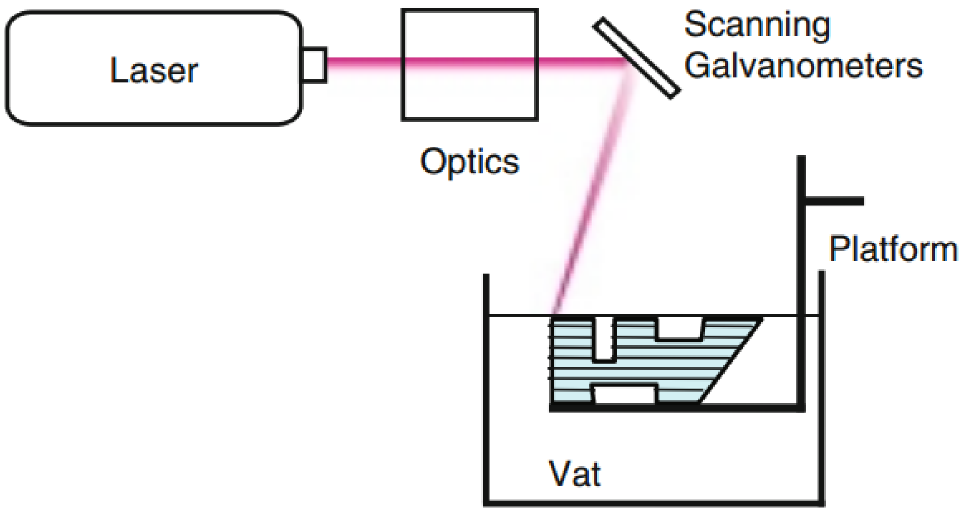


Figure 5: VP process [17]

VP has a high resolution but also needs a support that should be manually removed, and after that, it needs to be post-cured in a UV oven to finish the treatment. [13][14]

The objects made with this technology can be damaged by ambient UV light.

Pros	Cons
Best surface finish of any AM technology (together with material jetting)	Material properties change over time
Can make clear parts	Resin is messy and can be hazardous when removing parts from machine and when post-processing
	Requires support material for overhangs

Table 3: Pros and cons of VP [13]

2.1.2.4 Material jetting

It works on the same way as inkjet printers; liquid radiation-sensitive material is dispensed from a print-head. Also it is exposed to radiation to solidify the layer while it is being deposited. The print-head is designed to deposit material for the object and the support.

Material jetting can produce high-resolution parts with many different materials. Unlike VP, this technology doesn't require post-curing. But the support needs to be removed by hand, normally with a water jet. [13][14]

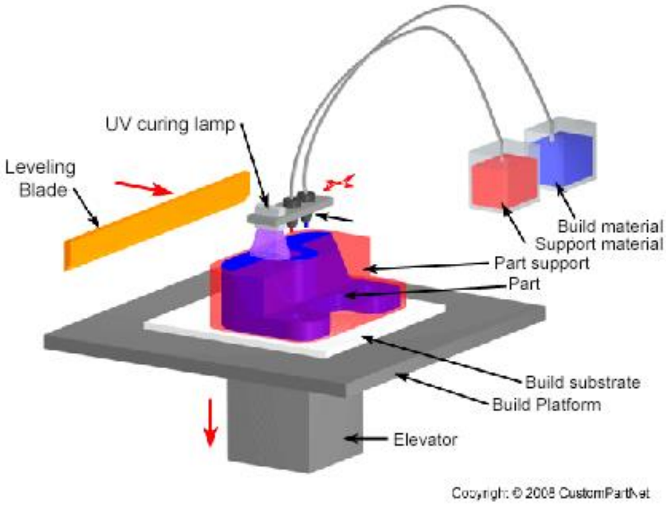


Figure 6: Material jetting process [18]

This method is also affected by ambient UV light.

Pros	Cons
Best surface finish of any AM technology (together with vat photopolymerisation)	Material properties change over time
Can make clear parts	Elastomeric materials are weak under tension
Can make multi-material and full-colour parts	Resin is messy and can be hazardous when removing parts from machine and when post-processing
Can make wax parts for investment casting	Requires support material for overhangs

Table 4: Pros and cons of material jetting [13]

2.1.2.5 Directed energy deposition

This method consists in using powder or metal wire to add material onto an existing part or to create a new one. It can produce accurate parts but with a poor surface, so it requires a post-processing operation. [13][14]

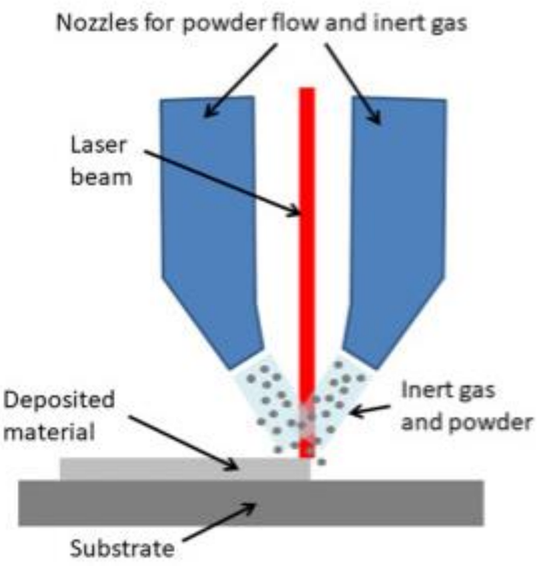


Figure 7: directed powder deposition process [19]

Pros	Cons
Fast process	Near net-shape surface finish that, in most cases, will require machining
5 axis process so can be used to repair worn or damaged parts without needing to machine the surface flat	

Table 5: Pros and cons of direct energy deposition [13]

2.1.2.6 Binder jetting (BJG)

Binder jetting uses an ink-jet print head to print a binder onto the powder which unifies the metal particles in a green state. After that, the part is removed from the powder bed and must go to the oven to make it harder. [13][14]

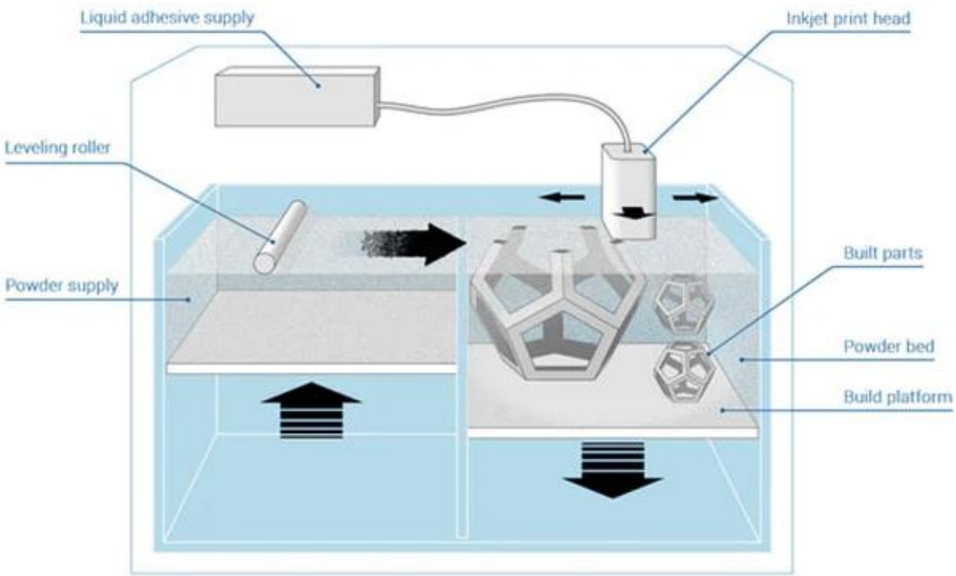


Figure 8: Bin der jetting process [20]

Pros	Cons
If printing in gypsum or PMMA powder the process can produce full colour parts	If printing in gypsum, the parts are very fragile, and will require infiltration of a strengthening resin
Can make metal parts (but will require sintering as a secondary operation)	Powders that require sintering after the green part is printed may shrink by up to 20%
Can create sand molds and cores for conventional metal casting	
Can produce investment casting patterns in PMMA	

Table 6: Pros and cons of binder jetting [13]

2.1.2.7 Sheet lamination

This technique uses paper or polymer film, cut with the appropriate shape and then added to the part using an adhesive. The shape of every layer is cut with a blade depending on which slice of the model is needed. [13][14]

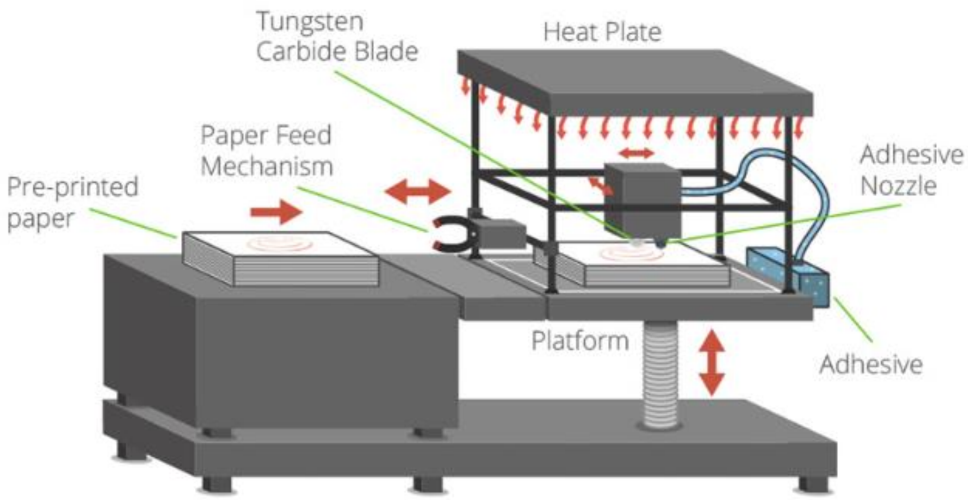


Figure 9: Sheet lamination process [21]

This method includes:

- Laminated object manufacturing (LOM): doesn't require any special tool and is time efficient.
- Ultrasonic additive manufacturing (UAM): uses an ultrasonic welding to bind the metal sheets together.

Pros	Cons
Benefits include speed, low cost, ease of material handling, but the strength and integrity of models is reliant on the adhesive used	Finishes can vary depending on paper or plastic material but may require post-processing to achieve desired effect
Cutting can be very fast due to the cutting route only being that of the shape outline, not the entire cross sectional area	Fusion processes require more research to further advance the process into a more mainstream positioning
	Limited material use

Table 7: Pros and cons of sheet lamination [13]

2.1.2.8 Hybrid additive manufacturing

This is the combination of powder or wire based directed energy deposition and computer numerical control (CNC). One of the main advantages of this system is that the parts are ready to use when they come out of the machine if a heat treatment is not needed. But also the mechanical properties of the parts are still an unknown factor. [13]

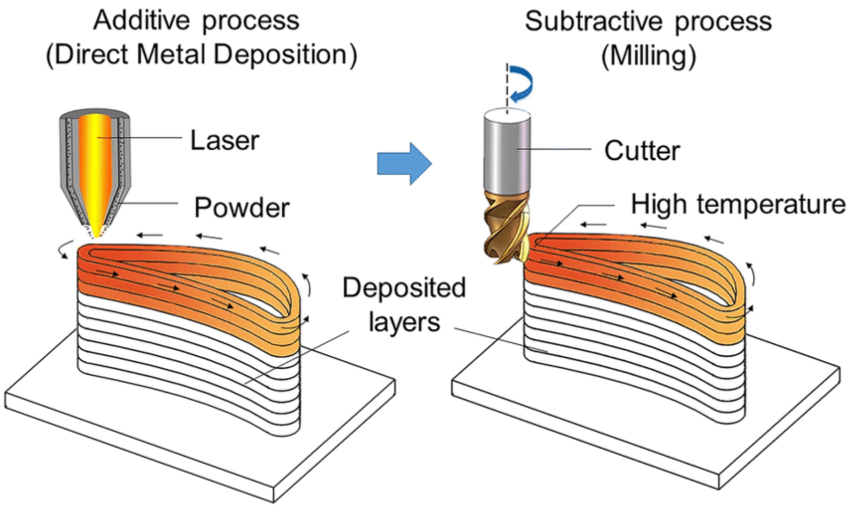


Figure 10: Hybrid AM process [22]

2.2 Design for AM

Last year, the term of design for AM has been a regular topic in research, but there were only a few attempts to define it. AM can create many different types of features with many different constraints, but this requires different process-specific design rules. At the same time, all the current technologies which are available to use in AM have different batch sizes, cost, production and post-processing times. Therefore, the only stage where we can study all the possibilities and try to incorporate new materials and considerations to overcome what has been usual in the past years is on the stage of design.

AM offers many possibilities of materials and geometries. The range of materials that commercial AM machines can use is large. It is possible to use polymers, metals and ceramic materials. But also, with sheet lamination it is also possible to use paper, wood, cork, foam and rubber. And some new technologies also allow the use of food like chocolate or pasta. Also with adding color to the raw material AM processes can create products in full color and combine more than one color in a part. With the right choice of material and technology, it is also possible to make unique geometric forms. That is why it is already used in the jewelry or even in the fashion industry and also for creating wiring conduits for industrial robots. So we can see that the use of AM is very wide with a correct design.

It is possible to create custom alloys and composite materials, using for example powders and binders. Therefore a new range of mechanical characteristics can be achieved easily. It is also possible to modify the properties making a post-processing treatment after each layer.

Some AM processes can produce parts with different materials or properties using different feedstock or binders.

Design for manufacturing and assembly (DfMA) is defined as design and optimize a product considering its system of production, so it is possible to reduce the costs and increase the performance. There are usually three levels of abstraction:

- First level: offers concrete tools, techniques and guidelines to adapt the design to the desired properties. Usually these guidelines are specific for every process, feature or activity.
- Second level: This level tries to quantify the effect that the design has over the production process. This is needed to keep improving the manufacturing system.
- Third level: this level studies which relation has the design process with the manufacturing.

Nowadays there are existing guidelines for helping the developers in the phase of design for AM. Most of those guidelines are specific for every technology, but the truth is that you can extrapolate the information to different technologies.

2.2.1 **Approach 1: Focus on general parameters**

2.2.1.1 Avoid failures

Also, one of the most usual troubles of the guidelines is that instead of giving tips to create an optimal design they are used to give information about how to avoid or reduce the number of printing and prototyping failures.

These types of guidelines differentiate between various features. [23]

2.2.1.2 Complexity

Complexity is the study which decides if the part is complex enough to be built by AM.

If the part has the same shape as common stock materials or is 2D there is no point in using AM. But if there are interior features or the surface curvature is too complex to be machined in the traditional way it is a nice candidate for AM. AM allows the manufacturing of new shapes that were too hard to cut or fabricate in the traditional ways to manufacture. [23]

Figure 11: Example of simple shape

Figure 12: Example of complex shape

2.2.1.3 Functionality

This is a parameter which has been used for the last years. It considers how many cycles will the part have or if it will experience large forces. But nowadays with the new technologies AM has become a real option for also this kind of functions, with a good design of every part and choosing the material that has the required characteristics the piece should be able to effort large forces and endure for many cycles. [23]

2.2.1.4 Material Removal

It studies if the piece needs some kind of support to be built. In the past, the use of supports could ruin the surface finish, but nowadays this does not happen for every technology.

It has to be considered if the part which requires a support is smaller than the support because in that case you should consider redesigning the piece, or if the support material can be easily removed. [23]

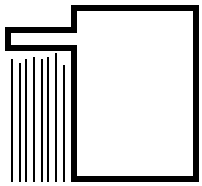


Figure 13: Example of smaller part than support

2.2.1.5 Unsupported features

This parameter studies if there are unsupported features that could drop. It is not a huge problem to have a design with this form but it is recommended to use a sloped support or the overhanging features should have a minimum of 45º. Using that and with the correct choice of technology it is possible also to avoid using a support, SLS technique for example doesn’t need support if the overhanging features are well designed. [23]

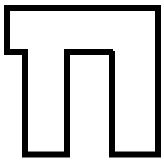


Figure 14: Example of unsupported features

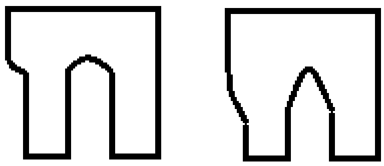


Figure 15: Example of well supported features

2.2.1.6 Thin features

If the part has thin features it is more prone to break, so depending on which force the part efforts, the thickness has to be designed in order to accomplish that goal. [23]

Also you can avoid this choosing the correct orientation of the part. In AM it has an important effect on mechanical properties.

2.2.1.7 Stress concentration

In order to avoid huge stress concentration, the interior corners must have chamfers, fillets and/or ribs. [23]

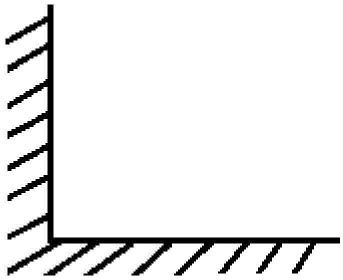


Figure 16: Example of corner without reinforcement

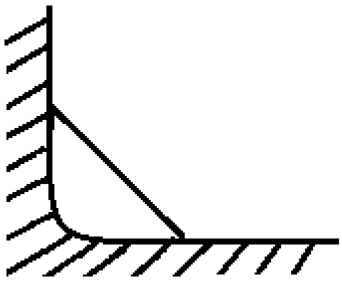


Figure 17: Example of a well reinforced corner

2.2.1.8 Geometric exactness

Large and flat areas tend to warp, so this has to be considered when the developers are designing a new part.

Also another import parameter is that the parts which have to be ensembled don't have the same size. So it is important to have a tolerance. [23]

2.2.2 **Approach 2: Give basic advices for powder bed fusion**

There are some guides which are really specific for a technology, for example it is possible to find numerous design guides for powder bed fusion, either for plastics or metal parts. Most of these guidelines describe limitations on feature types, geometries and dimensions.

The use of selective sintering or melting powders with laser, the laser spot size, the layer thickness, the mean size of powder particles and the thermal environment in the built chamber are working together to limit the minimum size of the piece, including small rods, holes, slots and thin walls.

Also metal powder bed fusion places additional restrictions on part features and sizes, supports are needed in this kind of technique. The use of a support avoids that the high residual stresses from melting and solidifying metals in a layer-by-layer fabrication break the piece. Supports are also used with oversized holes to provide a proper thermal environment and prevent a collapse.

There are other guidelines which put their effort in orienting the parts correctly in the build chamber. Normally it is possible to build flatter surfaces if the flat planes are orthogonal to the build surface. [24]

2.2.3 **Approach 3: Choose the processing technology depending on the working properties of the part.**

There are other guides which put their focus on which technology fits better with the piece that is required. These kinds of guides don't pay attention to if it is a good call using AM and decide the best technology according to different parameters.

2.2.3.1 Material

The type of material runs a very important role in the decision because not all the technologies can be used for all the materials. For example ceramic materials can be a better option for a BJG process than for the others.

But if the material is a metal there are many technologies available, so it is necessary to take a look at the characteristics of the material. For example EBM is not the best option for Magnesium or zinc processes due to its low melting point.

Another point to consider is the service requirements. If the material used is Al-12Si, the parameters of the materials are different depending on the technology. For SLM the yield strength is between 235 MPa and 290 MPa, the ultimate strength can be between 220 MPa and 460 MPa and the ductility is between 2,8% and 9,5%. This variety can be achieved modifying the microstructure during the fabrication process. And no other technologies can give this variation of properties. [25]

2.2.3.2 Technological limitations

Here is other parameter that should be considered before choosing a technology, for example, it is technically possible to build a 316L with stainless steel. However the cost that it would take makes the option of AM almost impossible. [25]

2.2.3.3 Surface quality

The use that the part will have plays a big role in the technology choosing. A part used for construction is not the same as for a biomedical procedure. The one used in construction should have strong mechanical properties, but the one used for biomedical procedures shouldn't present any internal porosity or defect on the surface. [25]

2.2.4 **Approach 4: General specifications and special specifications depending of the working material**

This fourth example presents different rules, once applicable to all geometries and materials, and other more specific.

2.2.4.1 General rules

- **Rule 1**: the minimum hole size or slot size is related to the thickness of the part. The same happens with the clearances between moving parts.
  In Figure 18 it is demonstrated that every time that the thickness of the part increases the surfaces of the holes are approaching so finally it is not possible to make holes depending of its size.

Figure 18: Hole size depends on material thickness [26]

- **Rule 2**: this rule analyses if AM should be used in the first place. Almost all the pieces can be manufactured with AM, but if it has a non-complex shape there are other technologies which are faster and cheaper than AM. But when the complexity starts to be the main characteristic of the part then AM becomes a main option for the manufacturing.
  Also with Am it is possible to give a unique aesthetic to the piece without an extra cost, so it is a very useful technology to insert logos, instructions, etc. to the pieces. [26]
- **Rule 3**: it is important to round all the sharp edges. Mostly to reduce the stress concentrations in the corners but also to make the piece more ergonomic.
  In the internal corners it is where the stress concentration will occur so it should be always rounded.
- **Rule 4**: every design for AM should think of the print orientation. If the choice of printing orientation is correct it is possible to avoid the use of supports.
  Also printing orientation marks which will be the direction of the anisotropy, so it is important to choose the parts whose will have more strength as the horizontal ones. It is also important to mention that there are some technologies like powder bed fusion that can reduce the anisotropy making some post-processing treatments.

Also the holes are better printed in vertical orientations, because if are printed in horizontal the stair-step effect will appear.
Obviously the height of the piece is related with how many layers will be needed, so it is important to try to minimize this parameter choosing the better orientation.

- **Rule 5**: minimize the used material. This rule includes the material of the part but also the material used for the support. In AM unnecessary materials add print time and cost so it should be avoided.
Also, as it was commented in Rule 4 choosing the better orientation helps to reduce the support material, and it reduces print time and cost to the manufacturing process. [26]

2.2.4.2 Design for polymers AM

This section covers almost all the polymer AM technologies but there are some other specific parameters depending on which processing technology is used.

Normally wall thickness with polymer AM should be similar to those used with injection molded. The range of the thickness goes from 0.6 to 5mm, being the first half of the range for light-weight products and the second for industrial products. For large and flat areas is recommended to use ribs in order to reinforce the wall. This is because polymers AM are less rigid than other methods. [26]

Thickness of the ribs: 75% of wall thickness	
Height of ribs: <3 x thickness	
Rib spacing: 2> x thickness	
Always round the point where ribs meet the wall	

Figure 19: Characteristics of the ribs [26]

The only processing technologies that can avoid the use of support in polymer AM are powder bed fusion and some binder jetting technologies. As it was commented before it is important to choose the correct orientation for the manufacturing in order to minimize the material consumed by the support.

The holes printed in the horizontal position can suffer stair-step effect so it is important to try to do it in the vertical direction. Also at the time of manufacture a hole can be undersize so it would be recommended to oversize the hole in the CAD version around 0,1mm.

There are also specific parameters to consider depending of which processing technology is used:

Material extrusion: Is the most used technology for thermoplastic polymers, sometimes it uses the same material for the piece and the support, but is recommended to use a different material in order to remove the support easily.

In order to choose the layer thickness it is important to know before which shape has the piece. So if it has many rounded parts or curved surfaces a thinner layer will reduce the stair-step effect and be a better choice. But if it has flat geometric features in the vertical direction a thicker layer will not deteriorate the surface and will reduce the printing time. [26]

This technology also allows the user to choose if the piece should be printed as a solid part or if the interior should be filled with a scaffold structure. This depends of the infill percentage that the user wants to cover.

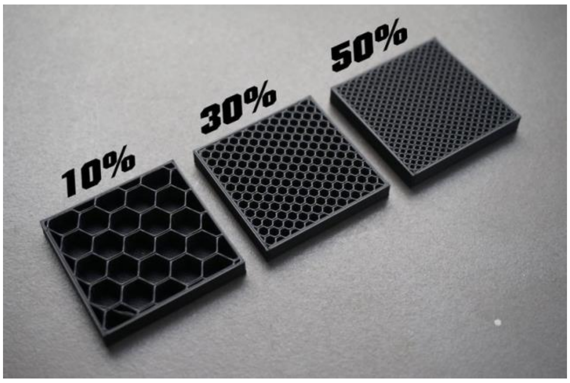


Figure 20: Different infill percentages [27]

Other characteristics for the material extrusion are [26]:

- **Vertical wall thickness** depends of the layer thickness, but for the most usual layer thickness of 0,25mm the minimum wall thickness is 0,5mm and the recommended is 1mm.
- **Horizontal walls** have to be at least 4 layers of material minimum.
- **Support material overhang angles:** the minimum angle is 45º in respect to the horizontal plane; angles under that number will require support material to build the part.
- **Clearance between moving parts:** this parameter depends on which type of support is used and the layer thickness. If it is a soluble support and the usual layer thickness of 0,25mm is considered then the minimum clearance is 0,5mm in horizontal and 0,25mm in vertical. But if the support is removed by breaking-away with the same layer thickness the clearance is 0,5mm in horizontal but the vertical depends on the access to facilitate supports removal.
- **Vertical circular holes:** the recommended minimum diameter is 5mm but it is necessary to consider that the CAD model should have 0,2mm more

of diameter, because during the manufacturing time the holes usually suffer undersize.

- **Circular pins:** the minimum diameter for ether vertical or horizontal pins is 2mm.
- **Screw threads:** The minimum diameter is 5mm and it can't start at the base of the part, it is necessary to leave 1mm of separation.

Powder bed fusion: The most used material is nylon (polyamide), but there are other polyamide based materials that include fillers like glass, carbon, etc. This technology usually doesn't need supports due to the powder that surrounds the piece and remain unfused can work as a support. Also it has a pronounced granular roughness on the surface, but I can be solved with a post-processing treatment. [26]

The layer thickness of this technique is usually 0,1mm but can also be 0,06mm, this technology reduces the stair-step effect until the point that it is almost not visible. Like other technologies powder bed fusion needs to avoid large masses of material in order to not increase the cost of the piece. But if it happens, the most typical way to remove these large masses is to shell the piece.

Also this technology works with polymer powder, so it is very common to use used powder and new powder for manufacturing the part. Normally they use between 20% and 35% of new powder.

Other characteristics for the powder bed fusion are [26]:

- **Wall thickness:** the minimum wall thickness is between 0,6mm and 0,8mm, but the recommended one is 1mm
- **Clearance between moving parts:** the minimum clearance is 0,5mm for horizontal and vertical directions.
- **Circular profile through holes:** the minimum diameter of the holes depends of the direction and the wall thickness.

Wall thickness	Vertical hole minimum diameter	Horizontal hole minimum diameter
1mm	0,5mm	1,3mm
4mm	0,8mm	1,75mm
8mm	1,5mm	2mm

Table 8: Minimum diameters depending on the wall thickness and the direction of the hole [26]

- **Square profile through holes:** the minimum size of the holes depends of the direction and the wall thickness.

Wall thickness	Vertical hole minimum side size	Horizontal hole minimum side size
1mm	0,5mm	0,8mm
4mm	0,8mm	1,2mm
8mm	1,5mm	1,3mm

Table 9: Minimum side sizes depending on the wall thickness and the direction of the hole [26]

- **Circular pins:** the minimum size for circular pins is 0,8mm independently if it is vertical or horizontal.
- **Hole proximity to wall edge:** Larger holes require more distance between it and the wall edge. For a hole of 2,5mm of diameter the distance should be minimum 0,8mm and for a 10mm hole the distance should be 1mm.

VP: This processing technology allows manufacturing a piece with a very high resolution. Depending on the shape of the part, if it has few curves or details the difference between 25 µm and 100 µm will be very little, so it is important to know which will be the laser spot size before starting the operation. If the developer wants to add some details on the surface they have to consider to make them at least of 0,1mm of height above the surface to ensure that can be visible. The best way to orientate the parts using this technology is minimizing the cross-sectional area along the vertical axis. [26]

VP requires support material for the overhanging features and using the correct support can lead to avoid overhangs. It is also one of the only processes that can build a piece relatively isotropic due to the layers chemically bonding to one another during the printing.

Other characteristics for the VP are [26]:

- **Wall thickness:** the minimum wall thickness is 0,4mm but the recommended minimum is 0,6mm
- **Circular holes:** the minimum diameter for horizontal and vertical holes is 0,5mm.

2.2.4.3 Design for metal AM

The materials used in metal AM technologies include stainless steel, tool steel, aluminum, titanium alloys, nickel-based alloys, cobalt chrome and precious metals. This technology usually requires a support that is removed manually after the process. It is important to understand that the printing phase is only a small part of the process, and the pre-processing and the post-processing treatments should be considered. This is one of the most complex technologies and there are several factors that can affect the AM part quality. The main potential defects that can affect the piece using this technology are unmolten powder particles, lacks of fusion, pores, cracks, inclusions, residual stresses and poor surface roughness. But also there are some advantages using metal AM, which include:

- Fine microstructure, due to the rapid solidification process.
- A slight anisotropy in vertical axis.
- Can reach densities of 99,9%

Determine if the powder fuses or not is important to regulate the energy density. Controlling the energy density allows to give enough energy to melt the powders of the current layer and the layer before in order to merge both layers. But it is important to not use an excessive energy density because it can cause vaporization and create defects and reduce the density of the material. [26]

Supports in metal AM are very critical and it is one of the factors that influence more de design phase, because it is the angles and the surface are of overhanging parts which determines if the use of support will be needed. But the supports also have other functions in metal AM:

- Strengthen and fix the part to the building platform.
- Conduct excess eat away.
- Prevent warping and build failure.
- Prevent the melt-poll from sinking down into lose powder.
- Resist mechanical force of the powder spreading mechanism in other parts.

It is important to mention that if in the phase of design the overhang part has an angle greater than 45º this part will not need to be held by a support. And something similar happens for the bridges, where the maximum allowed unsupported distance is around 2mm.

Most of the times metal AM has to solve problems of residual stress and stress concentrations. [26]

Residual stress appears during the manufacturing phase. These tensions have to be relieved with a heat-treatment before removing the piece from the build plate. The residual stress occurs when there are different temperature gradients in the surface and in the center of the AM or if there is some kind of plastic deformation or structural change. The best way to avoid this problem it is try to eliminate it through the design phase, the actions that can be used are:

- Eliminate areas that have different thickness.
- Avoid large changes in cross-sections.
- Pre-heat the build plate.
- Heat the build chamber.
- Work with smaller hatch patterns, it will reduce the residual stress but increase the fabrication time.

Stress concentration appears in the part where stress is concentrated. This areas are more likely to suffer fatigue crack so it is important to relieve this tensions for minimize this defects. As it was commented before, the best way to avoid this kind of troubles is replace the sharp corners for a more rounded shape.

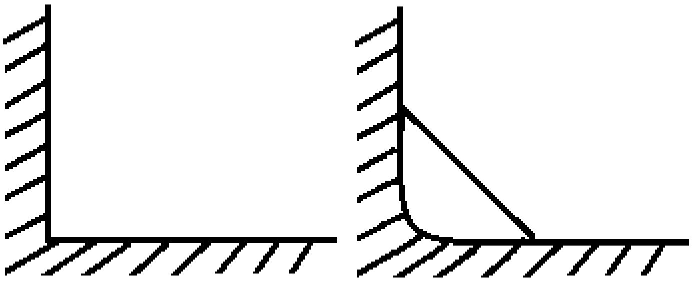


Figure 21: Example of how to avoid stress concentration

As for the polymer AM there are specific parameters depending on which processing technology is used. [26]

Laser powder bed fusion: The guidelines will vary from machine manufacturer and other variables, so in case of doubt it is recommended to verify the parameters of design. But the basic guide to follow is [26]:

- **Wall thickness:** the minimum is 0,3 mm but is recommended to use 1mm. If there is an extended surface of unsupported walls it is recommended to use reinforcement.
- **Overhang angle:** the angle is measured horizontally and it depends of which material is being used. For DMLS stainless steel, titanium and cobalt chrome is 60º and for DMLS Inconel and aluminum is 45º.
- **Clearance between moving parts:** it depends of which direction is, if it is horizontal the minimum clearance is 0,2 mm and if it is vertical it is necessary to adapt the distance in order to remove the support material easily.
- **Vertical slots and circular holes:** the minimum width for slot is 0,5mm and the minimum diameter for a hole is also 0,5mm.
- **Vertical bosses and circular pins:** the minimum width for boss is 0,5mm and the minimum diameter for a circular pin is also 0,5mm.
- **External threads** should always be built vertically.

EBM: in this technology the partially sintered cake built around the piece provides similar characteristics than a support, so the only support that is always needed is the one which anchors the piece to the platform and to some downward facing surfaces. Also other parameters are [26]:

- **Wall thickness:** the minimum is 0,6 mm but is recommended to use 1mm. All the corners should be rounded
- **Circular holes:** the minimum diameter for circular holes is 0,5mm but for vertical holes is 1mm. But if the walls are thicker than 2mm the hole has to be bigger than 2mm if it is vertical or 1mm if it is horizontal.
- **Clearance to remove powder:** the minimum clearance is 1mm, independently if it is horizontal or vertical.
- **Screw and threads** should always be built vertically.

BJG: during the process of metal BJG the part achieves the called green state, where it is very fragile until it is infiltrated or sintered. Due to this fragility certain geometries can't be supported, maybe it can be printed well but it could not handle it before it gets hard. Because of that it is recommended to use ribs or reinforcement walls in the design. [26]

Other design parameters are:

- **Wall thickness:** The wall thickness depends of the built size, and if it is smaller than 152mm it needs a reinforcement wall. Also all the internal corners should be rounded at least with 1mm.

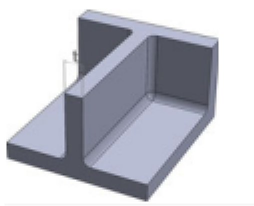
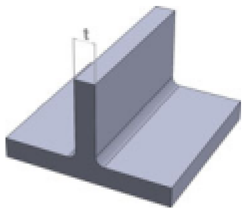
Build size	Minimum wall thickness	
3-75mm	1mm	
75-152mm	1,5mm	
152-203mm	2mm	
203-305mm	3,2mm	

Table 10: Minimum wall thickness depending of the build size [26]

- **Overhang:** the overhang thickness depends of the width of it, so the minimum thickness for a width of 25mm is 2mm. If the overhang is smaller the thickness can be thinner.
- **Holes:** the minimum diameter for an horizontal hole is 2mm and for a vertical hole is 1,5mm. But if the walls are thicker than 3mm the vertical holes need to be smaller than 2mm.

2.2.5 **Approach 5: Categorized fundamental principals**

This approach collects information about design guidelines, and then extracts the most common information and creates another category, design fundamentals. After that the design principles (DP) are created, which represent the correlation derived from the design guidelines and corresponding design fundamentals. The last step is providing the developers meaningful changes in the part geometry, the design rules (DR). [28]

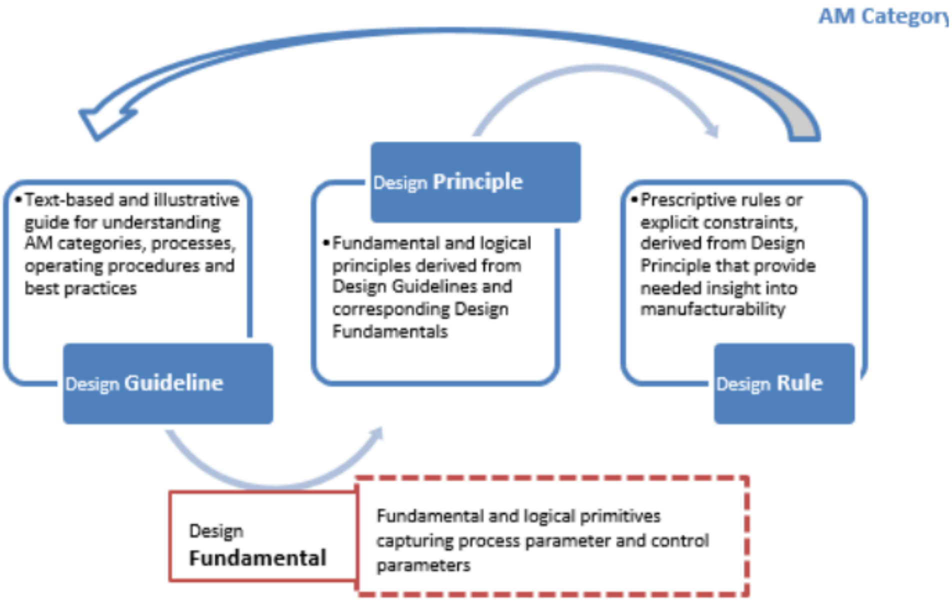


Figure 22: Schema followed by the approach 5 and the methodology used [28]

The design guideline is used to give relevant information about parameters that are necessary for establishing the process dependent relationships. For example, hollow cylinders should not be below the minimum wall thickness.

The design fundamental is categorized in two parts, features influence the geometry related parameters and the material parameters are related to the machine parameters.

DP is a function that derives from the design guidelines and corresponds with the design fundamentals. For example, Equation 1 represents the DP for thin walls, where t is the wall thickness, **β** is the orientation, h is the height, z is the powder size, *f* is the flowability of the powder, P is the laser power, S is the scan speed and ***t*** is the layer thickness. The specific values depend on process, machine manufacturer or user, but the basic premise supports the tailoring of customized rules.

$$DP_{thinwall} = f(t, , \boldsymbol{\beta}, h, z, f, P, S, \boldsymbol{t}); \text{ If } 90° \geq \beta > 30° \text{ then } \mathbf{t} \text{ is } 0.4 \text{ mm}$$

$$\text{If } \beta = 30° \text{ then } \mathbf{t} \text{ is } 0.3 \text{ mm for metal PBF process}$$

Equation 1: Example of DP equation for the wall thickness [28]

DR is a specific correlation which provides an insight into manufacturability. For example, using laser beam, it will identify the offset and scaling value that can improve the geometric accuracy of the part. [28]

2.2.6 **Approach 6: Guidelines extracted from trials**

This approach consists in guideline made from trials and the study of those results. In order to study all the spectrum of standard elements that affect AM they divided it in three groups:

- Basic elements: elementary geometrical shapes, for example a cylinder. Thereby there are three different types of basic elements: double-curved elements, simple-curved elements and non-curved elements.

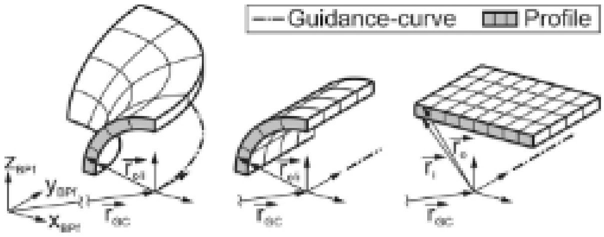


Figure 23: Double-curved, simple-curved and non-curved elements respectively [29]

- Element transition: areas where basic elements are combined. It is possible to differentiate between two elements transitions: transitions of firmly-bounded and transitions non-bonded elements. The first option consists in two basic elements united in an edge corner for example. The second type has a gap between the two basic elements, and this gap characterizes element transition.
- Aggregated structures: arrangements of two or more basic elements and its transitions. This third group includes islands, the part start in a higher building height than the main part structure; overhangs, elements that overtop the part layers in parallel direction to the building plane; and material accumulations, small regions where a huge amount of material is accumulated.

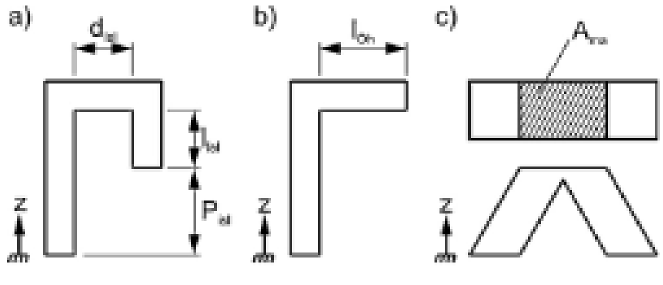


Figure 24: Example of island (a), overhang (b) and material accumulations (c) according to approach 6 [29]

In order to make a test for the experiment, this approach used three different processing technologies, SLS, SLM and FDM. And they also tried different types of operations:

- Thicknesses of transitions of firmly-bonded elements.
- Edges of transitions of firmly-bonded elements.
- Gap heights of transitions of non-bonded elements.
- Gap widths and lengths of transitions of non-bonded elements.
- Lengths of overhangs.
- Starting-positions of islands.
- Dimensions of material accumulations.

From all this different experiment results the guideline for AM design showed in the Table 11 and Table 12 was extracted where it is appreciable which standard element is the case of study in every case and which attribute is described in the different cases. Also there is a differentiation between in which processing technology it is possible to apply every consideration.

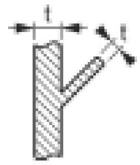
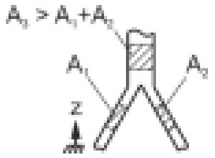
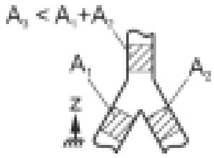
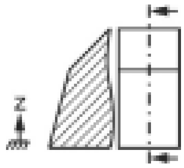
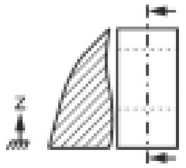
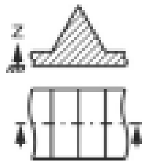
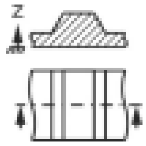
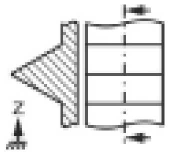
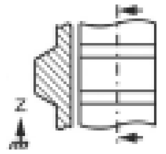
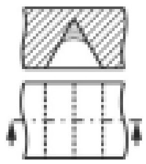
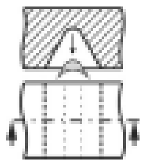
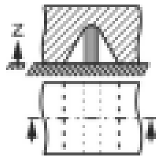
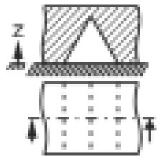
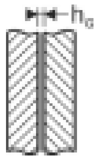
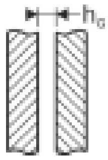
Group	Typ	Attribute	Description Regular Special	Design for manufacturing Unsuitable	 Suitable	LS	LM	FDM
Element transitions	Firmly bonded elements	Thickness	Element transitions' thicknesses can be chosen freely as they do not influence element's form accuracies.			X	X	X
			Element transitions' thicknesses should be chosen so that the cross sectional areas in the building plane remain of the same size or become smaller.				X	
		Edge	Sharp (outer and inner) edges should be avoided. In order to receive better form accuracies edges should be rounded. The rounding radii correlate with the outer radii of simple-curved elements.			X	X	X
			Edges that form vertical extreme points should be blunted parallel to the building plane. The dimensions of the blunted areas should be larger than non-curved elements' thicknesses.			X	X	X
			Edges that form horizontal extreme points should be blunted orthogonal to the building plane. The dimensions of the blunted areas should be larger than non-curved elements' thicknesses.			X	X	X
			Inner edges should be rounded or blunted in order to simplify the removal of disperse support structures (e.g. powder).			X	X	
			Inner edges should be sharp in order to avoid surfaces that have to be underpinned with solid support structures.				X	X
	Non-bonded elements	Gap height	Minimal gap heights should be kept in order to receive small dimensional deviations and to ensure the removal of disperse support structures (e.g. powder) LS: $h_G \geq 0.6$ mm LM: $h_G \geq 0.2$ mm FDM: $h_G \geq 0.4$ mm			X	X	X

Table 11: Guideline used in the approach 6 [29]

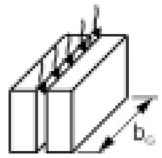
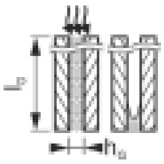
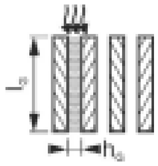
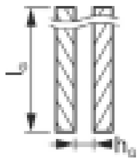
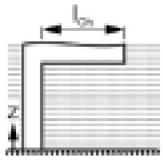
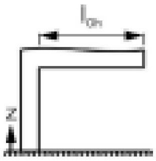
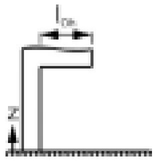
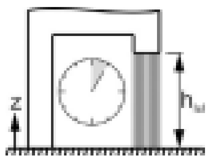
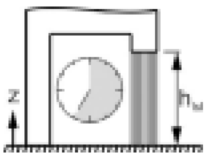
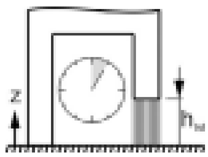
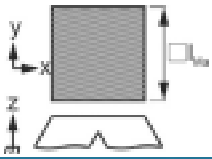
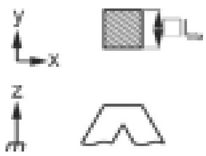
Group	Typ	Attribute	Description Regular Special	Design for manufacturing Unsuitable	 Suitable	LS	LM	FDM
Element transitions	Non-bonded elements	Gap width	If accessibility to the gap is given along the complete width, the gap width can be chosen freely.			X	X	X
		Gap length	Gaps' lengths need to be short enough to enable a robust removal of disperse support structures which are contained inside the gaps. LS: $l_G \leq 8.0\,mm$ ($h_G = 1.2\,mm$) $l_G \leq 30.0\,mm$ ($h_G = 1.8\,mm$) $l_G \leq 50.0\,mm$ ($h_G = 2.4\,mm$) (max. tested length) LM: $l_G \leq 50.0\,mm$ ($h_G = 0.2\,mm$) (max. tested length)			X	X	
			Gaps' lengths can be chosen freely because no disperse support structures are contained inside the gaps.					X
Aggregated structures	Overhang	Length	Overhangs' lengths can be selected freely because required stabilizations of the overhangs are provided by the disperse support structures.			X		
			Overhangs' lengths should be short enough to ensure a robust manufacturability given by part layers that do not bent out of the building plane (LM) or filaments that do not "fall off" their nominal positions (FDM). LM: $l_{Oh} \leq 2.0\,mm$ FDM: $l_{Oh} \leq 1.8\,mm$				X	X
	Island	Starting positions	Islands' starting positions can be chosen freely as they do not influence the building time significantly.			X	X	
			Islands' starting positions should be as low as possible because higher positions increase the number of tip switches for the creation of solid support structures; that again leads to increased building times.					X
	Mat. accum.	Dimensions	Material accumulations should be avoided. Maximal dimensions have to be kept to receive suitable manufacturabilities. LM: $l_{Ma} \leq 20\,mm \times 20\,mm$				X	

Table 12: Guideline used in the approach 6 [29]

2.3 Cost calculation

Proper design for AM has a significant influence on costs, but calculate the cost before verify if the piece accomplish the basic rules of AM is not the best option.

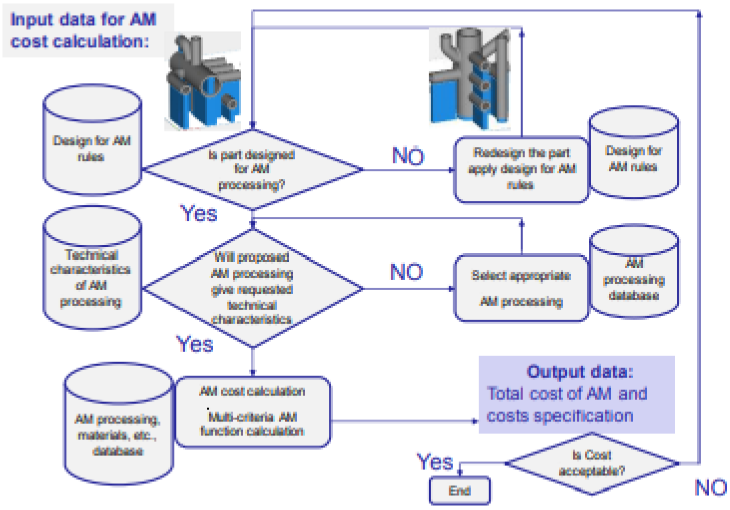


Figure 25: Integrated process of design for AM and cost calculation [4]

Once the design is approved it is possible to approximate the cost of the piece. It is important to differentiate between the cost of the material, the cost of the processing and the cost of the post/pre-processing treatment.

Symbol	Characteristic	Units
V_p	Volum of the part	cm3
C_m	Material cost	€/cm3
δ_m	Density	kg/cm3
C_p	Processing cost	€/h
C_t	Processing time	h
t_{12}	Post/pre-processing time	h
C_{op}	Operator cost	€/h

Table 13: Legend for the equations

$$\boldsymbol{C_{mp} = V_p \times C_m \times \delta_m}$$

Equation 2: Material cost calculation [4]

$$C_{pp} = V_p \times C_p \times C_t$$

Equation 3: Process cost calculation [4]

$$C_{12} = t_{12} \times C_{op}$$

Equation 4: Post/Pre-processing treatment cost [4]

3 Methodology

This project has two different parts. The first part consists in review all the literature of AM, studying different technologies and design methodologies. The second part is about design and develop the website. In order to accomplish these two parts a mixed- methods based research will be done. The first part corresponds on the qualitative research, and the second is more similar to quantitative research. The qualitative research explores the situation and then the quantitative research tries to test the model.

The thesis has been divided in different activities.

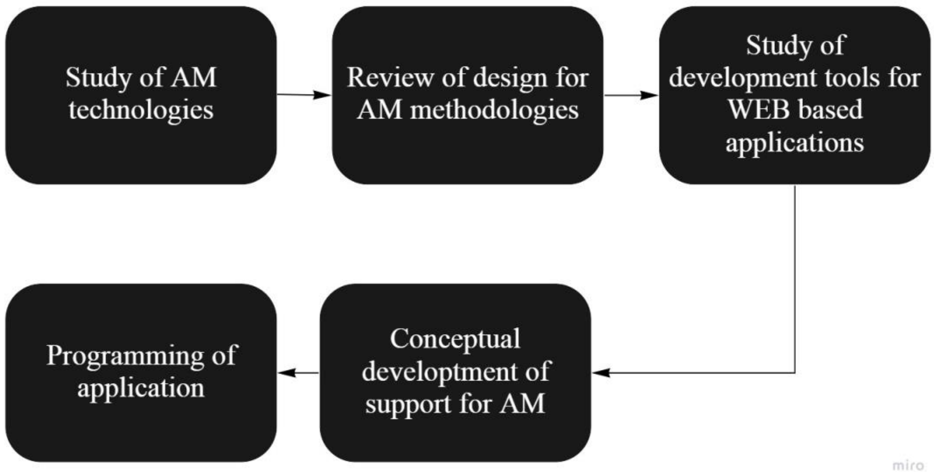


Figure 26: Schema of the methodology

The first two parts corresponds to checking the state of art. The first step is to know which are the parameters and characteristics of the different processing technologies for AM. And after that review which are the different guidelines developed during last years in other to have a backup of information and parameters that the developers should follow.

Once all the information is recovered it is important to choose which tools will be used in order to develop the WEB based application.

Once the different tools are chosen, the next step is to create the conceptual development of support for AM using information about the first and the second step.

The last step of the thesis is to program the application in order to make the fourth step possible.

4 Programming environment

Before present the different options that were choose in this thesis it is important to mention that the selection of the programming environments is not a research topic, so all the selected options have the aim to achieve the set goals: supporting AM design.

In order to be able to develop the website correctly a preselection of various tools that could facilitate the process was done. But it has to be an online site, so it cannot be only available in local. The free tools that were able to satisfy these conditions were severely limited.

The main idea of the project is to have a database where there are various materials and processing technologies that can work with those materials. And depending on the parameters or physical characteristics that are needed the application will give some advice on which is the best choice.

There are many options for running a database in a local system, many programs like DB Browser or Postgresql allow the user to host and works with database. But with these types of programs the only way to have access to the database is having the file in a local server. The project has to be open to the developers so this kind of programs is not useful in this case. For these reasons Supabase will be used during the development of the application. Supabase is a website that provides a free service with low requirements. After the development it is necessary to look for another server with better capacities.

https://app.supabase.com/

Regarding which language will be used on the project, due to a previous knowledge about it, because it is not a very complex programming language and it is also compatible with SQL language python has been chosen as the best option for the project. But also html language will be used for the web design.

Another factor to consider is that there are not many options to host a website freely and open to everybody. But Heroku is an online platform which allows launching applications and websites with different programming languages including python, the one which will be used. In this case, it is possible to use the free plan because by the moment the project is non-commercial. But it would be necessary to find another host for the website.

https://heroku.com/

In order to fetch the files where all the programming code is written GitHub is used. GitHub is a repository of code where file with code can be uploaded easily. A file with a license is also added to the repository in order to make all the files public in the future.

https://github.com/

Relating all this software's it is important to understand that at runtime data from SupaBase is fetched directly by heroku. Data management is done directly in SupaBase web-interface. Then for the deployment the file on the local server are uploaded to GitHub, and after that heroku fetches these files from GitHub.

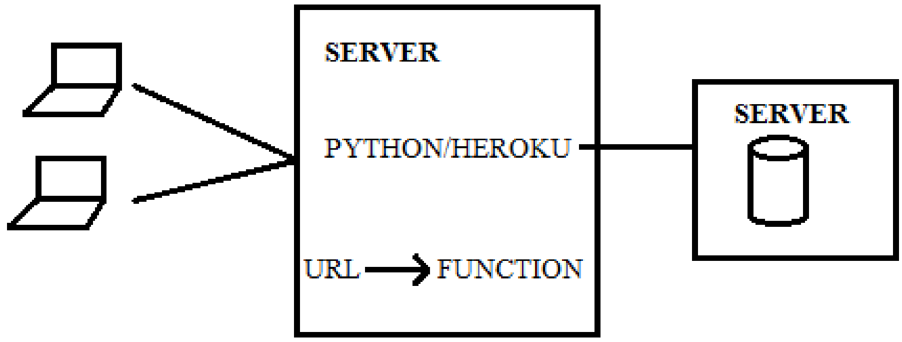


Figure 27: Relation of the differents softwares

5 Conceptual development of support for AM

In order to help the developers on the conceptual design phase it is important for them to know which will be the cost of manufacturing the part and adapt the design. Considering different requirements that the part should have it is possible for the designer to know the volume, and with that using other studies it is possible to know which will be approximately the cost of the piece.

The goal of the tool is to support the developers, so to accomplish the steps needed are:

- Concept identification
- Item construction
- Validity testing
- Reliability testing

In this project the two first steps will be done. To identify all the possibilities all the AM technologies and the materials will be studied, there is an extended list of materials so in order to test the function only a few of them will be stored. After that, the tool will be develop according to all the concepts identified.

5.1 Study of AM technologies

The main function of the application is helping de developer in the phase of design and give them information about how to make a correct design of the piece with some additional information about the approximate cost.

So in order to help the developers in the design phase it is important to know which are the main parameters required by the user. The parameters which had been chosen are:

- Strength: the maximum strength that the piece needs to support without breaking
- Working temperature: this is the maximum temperature that the piece will have to afford.

- Quality grade: if the piece needs to have a nice and high index of quality grade. It depends of the use that will have a high index of quality will be needed or not.
- Thickness: the thickness of the thinner part of the piece.
- Isotropy: the mechanical characteristics are different depending on the orientation of the part during the manufacturing, so it is important to know if it is isotropic or not.
- Hanging parts: it is necessary knowing if the piece has hanging parts because the piece might need a support depending of the technology choosed.
- Volume: volume of the piece for calculate the cost

These parameters have been considered as the most important in order to guarantee that the design will fit with the request of the designer. These parameters are also the most different between the options. For example, the working temperature of PVC is very different than stainless steel, but if a different parameter is studied it could be more similar.

The strength and the working temperature are the two most important parameters to choose a material. All the other parameters have been considered the most important to choose the technologies.

Using the schema in Figure 28 and using different tables the website will give which are the available options for fabricate the piece that is required. Or if is necessary to reconsider if the AM is the correct choice for developing that piece.

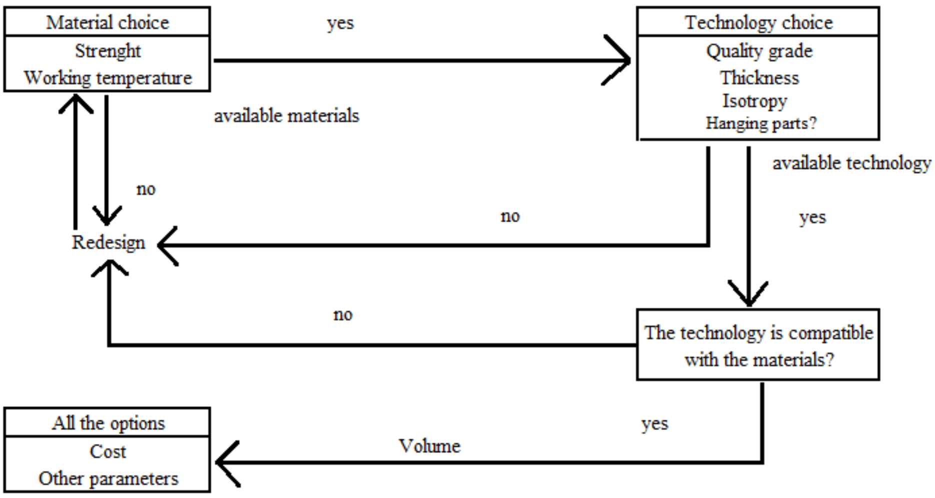


Figure 28: Schema that to follow for choosing the material and the technology

After going through the whole schema, all the available options appear on the screen including other parameters that the developer has to consider depending of the piece. This parameters include physical characteristics but also an approximation of the cost.

Also after considering all the available options, there is other information about some general advices about how to design, considering the shape, the corners, etc.

5.1.1 **Database**

There is database created to hosting the users of the website in one table, so that table hosts the name user, the mail and the encrypted password. However in order to accomplish the schema in the Figure 28 there are three different tables which have been used in one database. One table is for storing the materials, another for the processing technology and the last one to see which technologies are allowed to use specific materials.

1: Materials	**2: Processing technologies**	**3: Compatibility between materials and processing technologies**
Name	Name	
Type	Cost	
Strength	Quality grade	
Young module	Speed	
Specific deformation	Needs support	
Cost	Needs post-processing	
Melting temperature	Minimum thickness	
Density	Minimum hole size	
	Clearance between moving parts	
	Isotropy	

Table 14: Data mode for materials and AM processing technologies

5.1.1.1 Materials

The first database has information about the characteristics of some materials. This database includes:

- ID: a number in order to identify and relate the material with the others tables easily.
- Material name.
- Type material: information about which kind of material is. If it is a metal, plastic, etc.
- Strength: the strength that the piece will have to afford without breaking or suffering deformation.
- Young module
- Specific deformation
- Material cost: it is the approximated cost per kilo of the material
- Melting temperature

- Density

For make the choice of which materials can be used to build the piece the developer has to enter on the website only the strength and the working temperature. The other parameter will remain open until the last phase of the design.

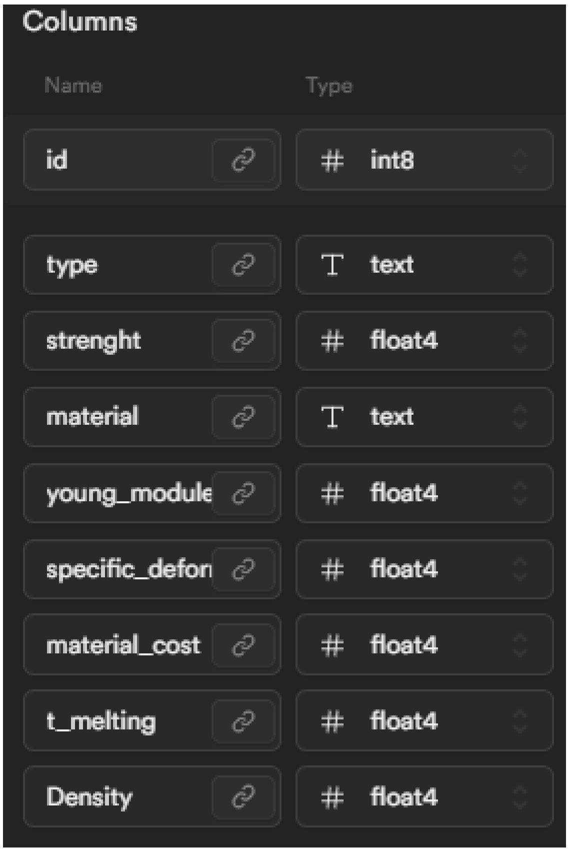


Figure 29: Data table for the materials in Supabase, including information about which type of parameter is stored.

5.1.1.2 Processing technology

The second database has information about the characteristics of the main technologies for AM nowadays. This database includes:

- ID: a number in order to identify and relate the processing technology with the others databases easily.
- Processing technology name.
- Processing technology cost: it is an approximation of the cost per cm^3 of the process

- Isotropy: characteristics that specifies if the piece will support the same effort depending of the angle of application.
- Quality grade.
- Speed: the number of pieces that the process cans afford per unit of time.
- Post processing needed: if the piece needs a support to be built it also requires some extra time to remove that support or if it needs some kind of treatment to have a better surface roughness.
- Minimum thickness of the wall.
- Minimum hole size
- Clearance between moving parts: if the peace have enough space between the moving parts in order to separate the parts easily.

The inputs that are used to take the decision of which technology fits with the desired characteristics are isotropy, quality grade and the thickness in the thinner part of the piece.

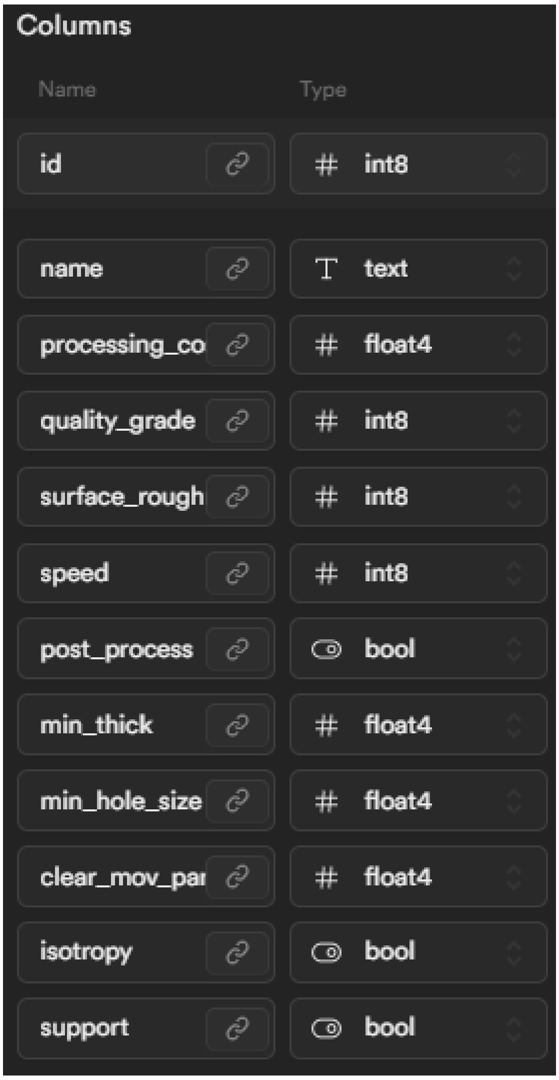


Figure 30: Data table for the processing technologies in Supabase, including information about which type of parameter is stored.

5.1.1.3 Technologies and materials

This database gives information about which technologies can work with different materials, obviously not every material can be treated with all processing technologies.

So those are the currently materials that are allowed to be used with the processing technologies commented in the chapter 2.1.2

5.1.1.3.1 Material Extrusion

Material extrusion	
ABS/ASA	Clay filled polymer
Polycarbonate	Brick filled polymer
Nylon	Wood filled polymer
PPSF/PPSU	Metal filled polymer
ULTEM 9085 and 1010	Concrete
PLA	Polyurethane foam
Metal filled polymer filament (bronze, steel, stainless steel, cooper, etc)	Silicone
	Epoxy
	Bio-materials
	HPA/PCL

Table 15: Materials used with material extrusion

5.1.1.3.2 Powder bed fusion

Powder bed fusion	
Nylon 12, 11 and 6	Stainless steel
Glass filled with nylon	Maragin steel
Heat resistent nylon	Titanium 64
Polypropilene-like nylon	Aluminium
Alumide	Tungsten
Carbonmide	Nickel-based super alloys
	Cobalt chrome
PEEK	Copper
	Gold

Table 16: Materials used with powder bed fusion

5.1.1.3.3 VP

VP
UV curable photopolymer resin
A number of ceramic filled resins
Polyurethanes for CLIP

Table 17: Materials used with VP

5.1.1.3.4 Material jetting

Material jetting
Digital ABS polymer
High-temperature transparent polymer
Rigid opaque polymer
Polyurethanes for CLIP
Simulated polypropilene polymer
Rubber-like polymer
Wax
Bio-compatible polymer
Metals

Table 18: Materials used with material jetting

5.1.1.3.5 Directed energy deposition

For this processing technology almost any metal that is weldable and available in powder can be used

5.1.1.3.6 BJG

BJG	
Gypsum	Sand-casting sands
Starch	Ceramics
PMMA	Glass
Metal powders	Hydroxyapatite

Table 19: Materials used with BJG

5.1.1.3.7 Sheet lamination

The main materials used with sheet lamination process are paper plastic film and metals.

5.2 State of art review

In order to provide some additional information to the developers before the selection of the material and considering all the previous studies, the applications offers general tips in order to make the design economically viable and more efficient. All these advices are extracted from the different approaches viewed in the chapter 2.

5.2.1 **General parameters**

5.2.1.1 Shape information

It is important to well-choose when is possible to use AM or another manufacturing technology, so this part will provide information about if AM is the correct decision and which is the better way to design the part.

The main parameter to choose if AM is the best choice or not is the complexity of the part, if the part has a shape which is similar as a common stock of the material there is no point of using AM, but if it has complex features and curvatures then AM becomes the best option for the manufacturing. Also AM offers the possibility to give unique aesthetic to the parts without an extra cost, so it is becoming a real option for manufacture jewelry.

Figure 31: Example of complex design, good candidate for AM [30]

Figure 32: Sample of ring confectioned by AM [33]

It is important to try to avoid the use of supports, there are several technologies which now allow you to have a good quality surface using supports but it usually requires a post-processing treatment so it is preferable avoid that situation. Also there are some processing technologies which can avoid the use of supports but this information will be given in the next phase. However if it is not possible to avoid the use of a support it is important to design it thinking that the support has to be smaller than the part which needs it.

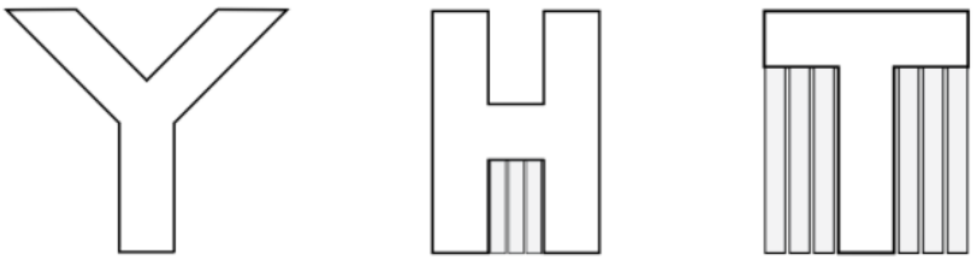


Figure 33: Example of when a support is needed [31]

It is also important to try to avoid the 90º corners. Those corners, especially the ones which are in the interior of the piece, suffer most of the effort of the piece and also if it has an overhanging part it is more likeably to break. In order to avoid that, the corners should be rounded or reinforced.

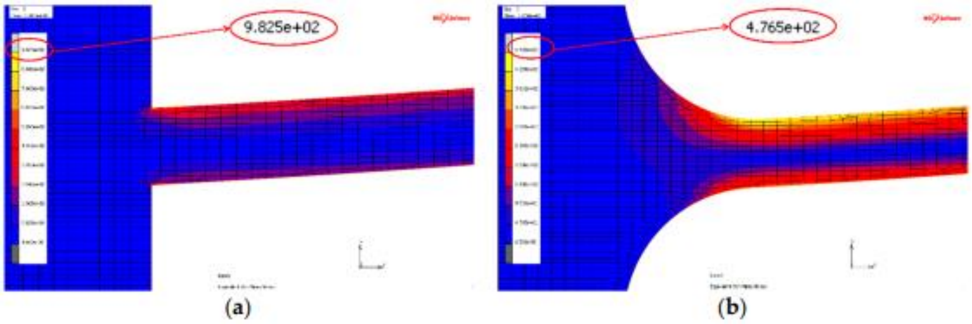


Figure 34: Map of equivalent von Misses stress: (a) sharp corner and (b) rounded corner [32]

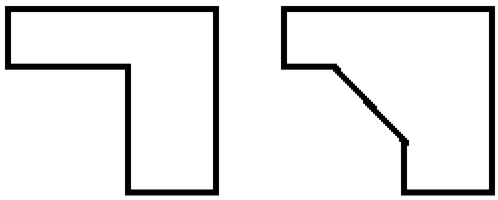


Figure 35: Difference between a support angle of 90º and 45º

As it is appreciable in the Figure 34 if the sharp corner is rounded it is possible to reduce the effort concentrate in one point to half of it and also distribute this effort to other parts of the piece.

Large and flat areas tend to warp, so it is important to avoid that kind of surfaces or if it is necessary make reinforcement with ribs.

In the design phase the developer has to consider if there are moving parts, so in order to ensemble or allow the movement between these parts it is important that the CAD version has tolerance. Also the clearance of the holes depends on the size and the thickness of the part, so if a small hole is required the thickness on that part should be thinner than if a bigger hole is placed there.

One of the most relevant parameters in the design phase is to choose which orientation will be used to print the part. The orientation marks the direction of the anisotropy, so the parts that receive more stress should be placed horizontal, in the building plane. Also the holes, pins and threads are better build in vertical direction.

AM allows to minimize the used material for a piece, and also to manufacture complex geometries in order to achieve the same resistance in front of hard tensions. So it is important to analyze which are the parts that suffer less effort and try to reduce the mass in those zones. Also optimizing the design more benefits are achieved:

- Creating lightweight structures
- Reducing processing time
- Saving fabrication materials
- Reducing physical test
- Saving processing energy

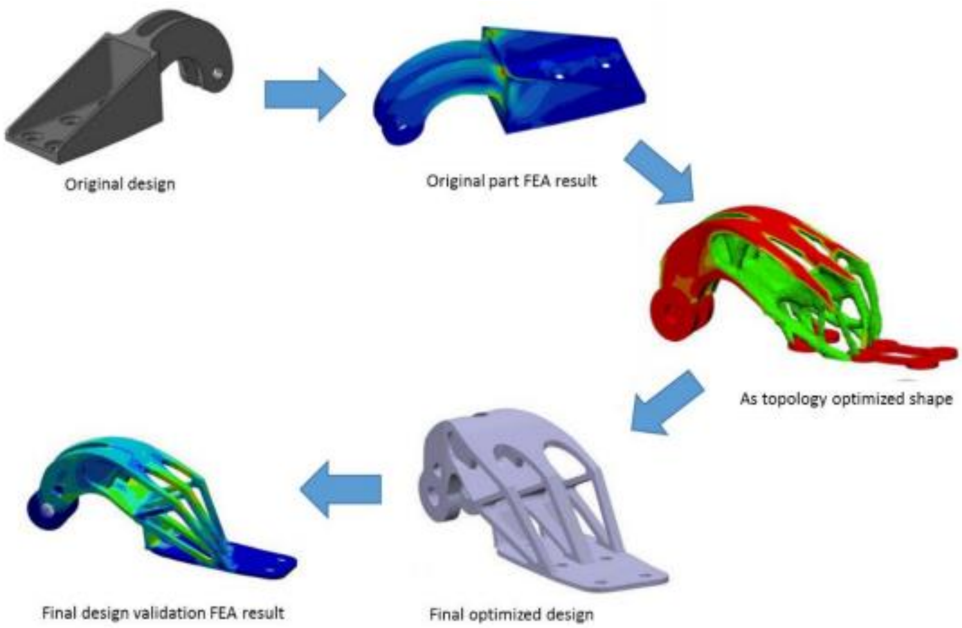


Figure 36: Example of optimized design starting from original design [34]

5.2.2 **Information depending on the result**

After make the search of which materials and processing technologies are available and which combinations are possible between them, some information regarding which are the design parameters for every combination will be shown.

5.2.2.1 Material Extrusion

- Most used for thermoplastics polymers.
- Recommended to use different materials for the support and the part.
- Use thinner layer thickness if the shape of the part is complex in order to avoid stair-step effect and thicker if the surface is flat. The recommended layer thickness is 0,25mm.
- Increase the infill percentage if the part has to resist high tensile efforts.
- Vertical wall thickness: 1mm
- Horizontal walls with at least 4 layers of material.
- Minimum 45º respect the horizontal plane for the overhanging parts in order to avoid the use of supports

- It is recommended to use a soluble support, with that the clearance between moving parts is 0,5mm in horizontal and 0,25mm in vertical.
- Minimum 5mm of diameter for vertical holes and 0,2mm more in the CAD version.
- Minimum 2mm of diameter for circular pins
- Minimum 5mm of diameter for screw threads and leave 1mm of separation between the start and the base.

5.2.2.2 Powder Bed Fusion

- It can avoid support if is well designed
- Recommended layer thickness: 0,1mm
- Avoid large masses of material
- Possible to recycle the powder
- Recommended wall thickness: 1mm
- Minimum clearance between moving parts: 1mm in both horizontals and verticals directions (it has to be possible to remove the support material)
- Minimum circular hole diameter: 0,5mm for vertical holes and 1,3mm for horizontal holes
- Minimum square hole side size: 0,5mm for vertical holes and 0,8mm for horizontal holes
- Minimum 0,8mm of diameter for circular pins
- 0,8mm of distance between the wall edge and a 2,5mm hole

5.2.2.3 VP

- Minimum 0,1mm of height for the details on the surface
- Recommended 0,6mm of wall thickness
- Minimum 0,5mm of diameter for circular holes

5.2.2.4 Material jetting

- Minimum 1mm of thickness for walls
- Minimum 0,5mm of diameter for pins and hole sizes
- Minimum 0,5mm of height for surface details
- Minimum 0,2mm of clearance between moving parts
- Best option for a nice surface quality but poor mechanical properties.

5.2.2.5 BJG

- It is important to be careful during the green state phase.
- It is recommended to use ribs and reinforcements
- Wall thickness (build size = minimum thickness): 3-75mm = 1mm; 75-152mm = 1,5mm; 152-203mm = 2mm; 203-305mm = 3,2mm
- 2mm of thickness for a 25mm of width overhanging part.
- Minimum 2mm of diameter for holes.

6 Results and discussion

During this thesis several troubles had to be solved. The two themes applied on the thesis were new for me. Starting for the part of additive manufacturing, it is a relatively new theme of research so it is no learned in the universities so I had to start studying this theme from a very basic point. It happen the same with the development of the website, the only experience that I had programming were basic notions of python.

After reading the new researches in additive manufacturing and also the first articles and papers I was able to have more consistent ideas about this theme. With this knowledge I could read about different guidelines for additive manufacturing and choose which the best advices are and which information has to be given to the developers.

The structure of the website it is very simple and easy to use in order to facilitate the task of design to the developers. The parameters that the application needs to start the selection process are considered as the most basic and important for the design. These parameters consider which will be the needs of the piece during the use of it but also which will be parameters that will affect to the costs.

Also in order to have some control about the users of the website it was considered necessary to have a database with the mail of the users, so if there is some kind of problem it will be possible to have a communication channel with them.

6.1 Website structure

In order to try to make a friendly-user application, the website is divided in different html pages. Every page has a different function.

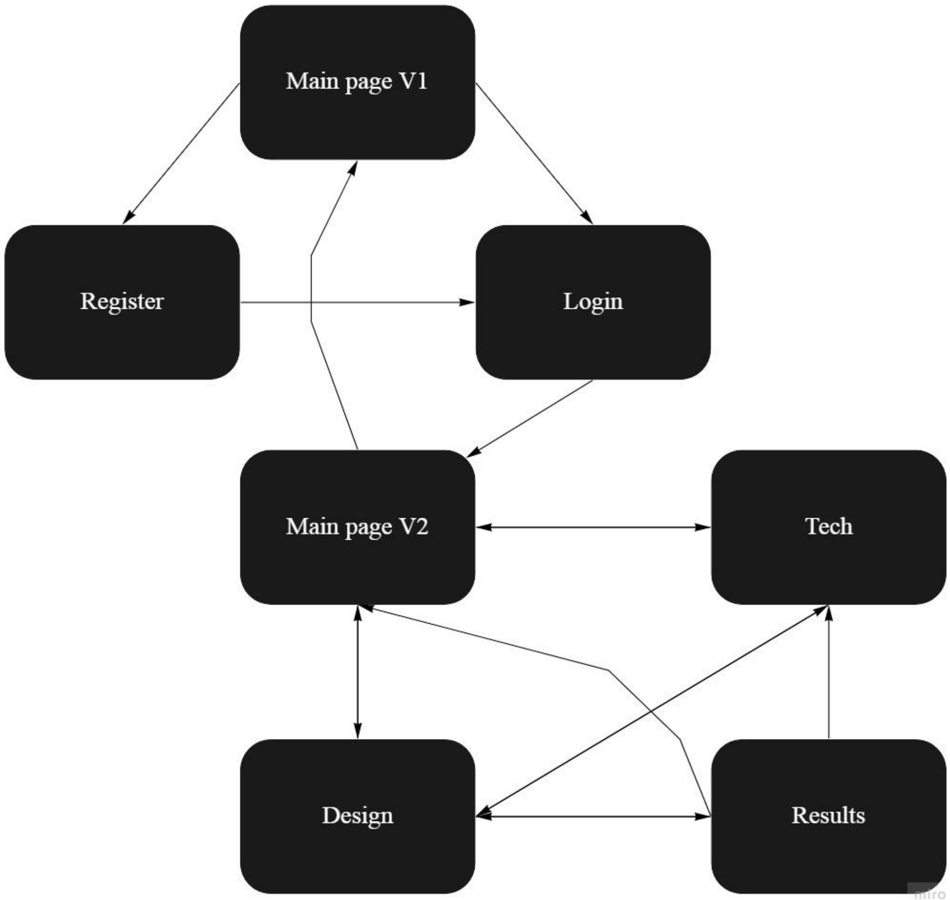


Figure 37: Schema that shows the connections between the different pages

6.1.1 **Main page**

The main page has two different versions. The first version that the user finds entering for the first time in the page is the one appreciable in the Figure 38.

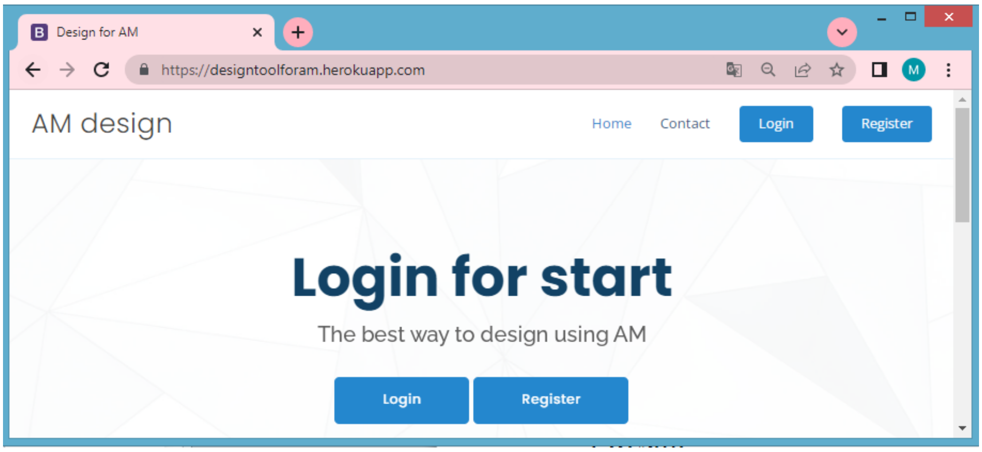


Figure 38: Main page of the application version1

The header of the website is fixed and it allows the user to move easily in the page. There are the buttons which redirect the user to the login or the register html and the buttons which allows the user to move in the main page. On the bottom of the main page there is some information about how to contact if there is some trouble and also for give information to add information to the database. The mail created in order to achieve that is AMdesigningphase@gmail.com.

Once the user is registered and logged the main page change. The button for logout appears in the right corner and also two different buttons in the center which redirect the user to the html which allows the user to enter the parameters that they need and also to see the design advices.

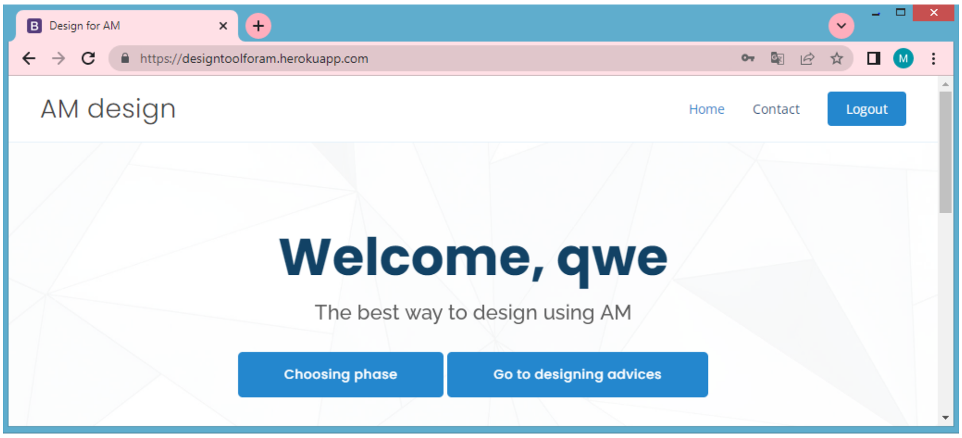


Figure 39: Main page of the website version2

6.1.2 **Login and register pages**

The pages for login and register are very simple. For the register there are four inputs in the screen, which will be stored in an external database. If the passwords inputs don't match an error will appear on the screen, and the same if the mail or the user are already used.

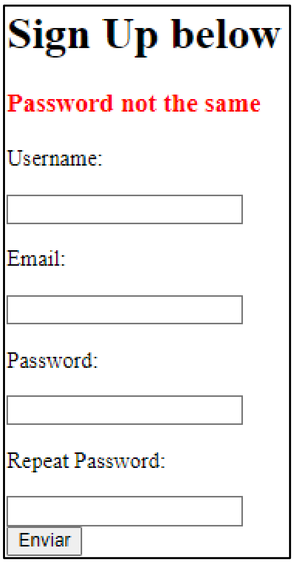


Figure 40: Register page with no matching passwords

For the login the user only has to enter the username and the password, which is encrypted for safety reasons. And if the user or the password is wrong a message of invalid credentials appears on the screen.

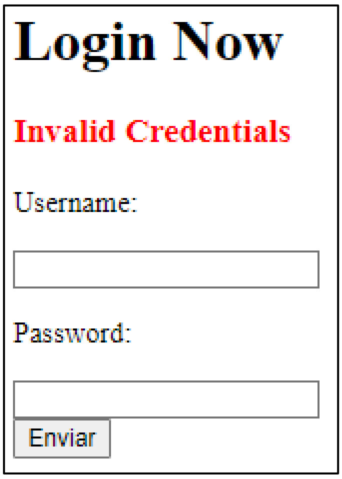


Figure 41: Login page with an invalid user

6.1.3 **Design page**

In the design page the parameters described before are asked. Also there is a button in the header which allows the user to go back to the main page.

There are five input boxes, one of itch corresponding to a different design parameter. It is important to put the numbers on the box as an integer, without decimals. If a different type of input is gave to the application an error message saying "Invalid value, must be an integer" will appear on the screen.

Also if any material or process fits with the parameters a message appears and ask to redesign or to send mail if the developer knows about some material that match with the parameters. So it would be able to add the material or the processing technology that the user proposes to the database.

If there is a material and also a process that can fit with the parameters but the material cannot be used with the corresponding technology the application display which are the allowed materials and the allowed processing technology.

Apart of the input boxes there are also to drop-down buttons with two options, depending on the necessity of the user corresponding to those parameters.

Once the users has uploaded the input and submit the information the next page is the results page.

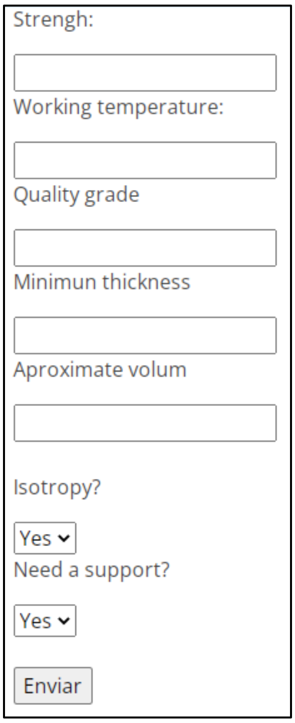


Figure 42: Input parameters in the design phase

6.1.4 **Results page**

This page will show the different options that fits with the parameters that the user needs in the piece. The columns represent which are the characteristic and its value and the rows which is the described option.

The Table 20 shows the viable options for these characteristics:

- Strength = 65Mpa
- Working temperature = 12ºC
- Quality grade = 17 µm
- Minimum thickness = 1mm
- Approximate volume = 200 cm^3
- Isotropy? = No
- Need a support? = Yes

The parameter of post-processing treatment depends on if the piece will need a support. If the developer consider that the piece will need a support but the corresponding processing technology can work without support the message is ‘Depend of the piece’, and the developer is able to see if the support will be needed or not in the design advices. But if the processing technology cannot avoid the use of support then the message is ‘True’.

Below the table there are two different buttons, one for going back and change the parameters and another for advance to the next page, which show the design advices for AM.

Figure 43: Buttons of the results html for move to the next phase or go back to the design html

Options characteristics

	Material:	Material type:	Young module:	Strengh that can afford:	Specific deformation:	Material cost:	Melting temperature:	Density:	Processing technology:	Processing cost:	Quality grade:	Speed:	Needs post-processing treatment?	Clearance between moving parts:	Minimum thickness:	Minimum hole size:	Does the technology manufacture with isotropy?:
Characteristics	Nylon	plastic	2.7	85.5	0.05	11.5	256.0	1.15	Material extrusion	0.98	14	127	True	0.5	5.0	0.5	False
Characteristics	ULTEM 9085	thermoplastic	2.4	70.0	0.054	84.0	186.0	1.4	Material extrusion	0.98	14	127	True	0.5	5.0	0.5	False

Table 20: Table with the options that fits with the developer needs

6.1.5 **Tech page**

This page shows first the general advices which can be applied to all the processing technologies and below this parameters there is a button where the developer is able to choose between different processing technologies. Depending on the chosen technology, the web based application show the corresponding design advices.

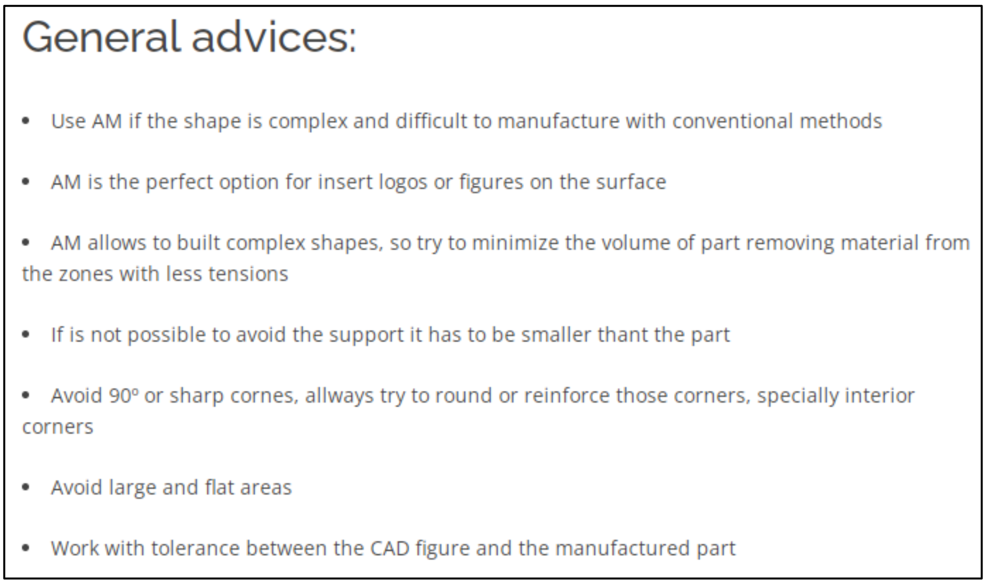


Figure 44: General advices of the web based application

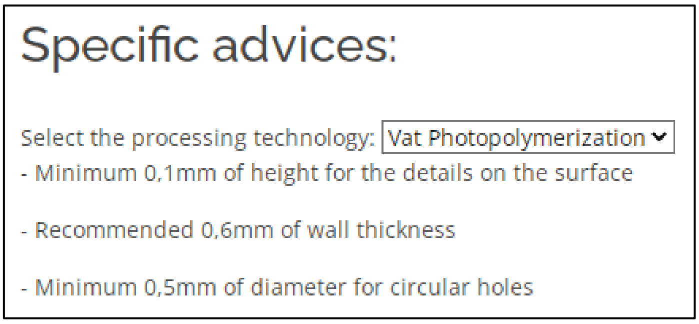


Figure 45: Specific advices depending of the processing technology of the web based application

6.2 Limitations

The purpose of the thesis is creating a web based application to help the developer in a conceptual design phase, giving information about the cost and some advices to them.

It is true that there are many papers and studies about designing phase for additive manufacturing, but it has been hard to relate all the approaches of the different researches because many times they say opposite things and it hard to know is more correct.

It is important to say that the purpose of this thesis was to create the web based application and to accomplish that it was necessary to create a database with some backup of materials and processing technologies. But this database is not complete; there are only a limited number of materials and information about material extrusion only to show how the application works, so it needs more information before launch a definitive version. One of the most complicated things will be to generalize the characteristics of the processing technologies, because these are not fixed parameters.

Also some of the technologies are relatively new, and there is not many information about how to design for those technologies. So it is not only necessary to keep updating the database, it will be also necessary to update the advices gave to the developers.

7 Conclusions

7.1 Achievement of goals

Recalling the individual goals set at the beginning of the report to determine their fulfillment.

> End user support with design for AM principals (links to the catalogue of design rules)

This first goal has been modified in order to facilitate the use of the application. Instead of add links to the different catalogues of design rules this catalogues had been studied and synthetized in a list of designing advices. This is a more friendly-end-user way to give the information because the developer doesn't need to look in different places for the information. This is an application in the first part of design, so due to the lack of materials on the database it hasn't been tested by users. All the trials had been committed by the developer to test the functionality.

> AM part cost estimation based on input data: part volume, material, AM processing technology

Once all the parameters are introduced in the application in the table of the results there are two different columns that show the costs, one corresponding on the material cost and the other on the processing technology costs.

AM process selection based on technical characteristics: mechanical properties, quality level, temperature, resistance, isotropy request.

The information that the developer has to introduce to the applications doesn't include this parameters. However on the results table it is possible to take a look to all of these parameters and with this information take a better decision.

Web based application: central database for storing and updating AM materials and AM technologies (different AM machines)

There is an existing database which includes 3 different tables, one for the materials, another for the processing technologies and a third one which relate those tables. This database is not fixed, so it is possible to update the database every time that a new option is available.

7.2 Future research and investigations

The design for additive manufacturing has been a currently topic of investigations for the researches. However it is necessary to keep studying this theme in order to find new and better ways to design the parts, and have more information related with a specific technology instead of general rules. For example have a guideline specific for material extrusion using polymers, another for powder bed fusion using metals, etc.

Every time that a new guideline will be published the application should be updated with the new information in order to keep it actualized and useful for the developers. Anyways not only these new technologies should be incorporated to the application. There are many materials that are not in the database and it is necessary to add in there for offer to the end-user more options that can fits with the needed part. It is the same for the processing technologies, by the moment there is only information about material extrusion in order to check the well-function of the application, so it is necessary to add information for all the other processing technologies.

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