



Project

Master in Product Design Engineering

Design evaluation on the production of sloping walls without support structures in  
additive manufacturing

Inês Carolina Ribeiro Lemos

Leiria, 29 September of 2018





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Project Report developed under the supervision of Professor Henrique de Amorim Almeida and co-supervision of Professor Mário António Simões Correia, professors at the School of Technology and Management of the Polytechnic Institute of Leiria.

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Muito Obrigada,  
Mãe, Pai, Irmão, Rodolfo



## Resumo

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As tecnologias em geral têm avançado significativamente ao longo dos anos. A fabricação aditiva é uma das tecnologias que está em constante crescimento numa questão de aplicações, materiais, processos e máquinas. Existem alguns constrangimentos em consequência do crescimento acelerado, sendo que em alguns casos os modelos precisam de construir estruturas de suporte o que torna o processo de produção mais lento. É necessário entender este tipo de limitações. A fabricação aditiva tem a capacidade de produzir partes geométricas através de um modelo CAD criando protótipos rapidamente por união de materiais, camada a camada, para representar modelos ou até para testar a sua funcionalidade. É uma tecnologia capaz de imprimir peças geométricas e complexas com uma extensa liberdade, mas com a necessidade de produzir estruturas para suportar a peça. A tecnologia de FDM é um processo de fabricação aditiva que produz o modelo com a conexão de materiais poliméricos camada a camada. O programa da máquina lê e manipula os ficheiros STL de maneira a definir as melhores condições para a impressão do modelo pretendido, também define a necessidade de produzir estruturas de suporte. É relevante estabelecer diretrizes de design para alcançar um melhor resultado. Assim sendo, o foco desta tese é avaliar a necessidade da existência de estruturas de suporte num conjunto de modelos definidos com uma geometria específica. O trabalho consistiu por produzir modelos com paredes inclinadas através do processo de FDM em diferentes máquinas para perceber os diferentes comportamentos das formas e concluir até que ponto é possível produzir a peça sem estruturas de suporte dentro dos parâmetros definidos.

*Palavras-chave: Fabricação aditiva, FDM, material de suporte, paredes inclinadas.*





## Abstract

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Technologies have been advancing significantly over the years. Additive manufacturing is a technology that is in constant growth in the matter of applications, materials, processes and machines. In spite of its advanced technology, in most cases the produced models need to build with support structures which slows down production. Hence it is necessary to understand this type of limitation. Additive manufacturing has the ability of producing geometrical parts from a CAD model, creating rapidly physical models by joining materials, layer by layer, to represent models or even to test its functionality. It is capable of printing geometrical complex parts with an extended design freedom, but in some systems, needs to build support structures to support the part during production. The FDM technology is one of the additive manufacturing processes that produces the model by connecting polymeric materials one layer at a time. The machine software reads and manipulates the STL file to define all the proper conditions to print the required model, as well as defining the need to build support structures. It is relevant to establish design guidelines to achieve an improved result. Therefore, the focus of this thesis is to evaluate the need of support structures in a set of defined models with designated geometric characteristics. The work consisted in producing models with sloping walls using the FDM process in different machines in order to understand the different behaviours of the shapes and to conclude at which point it is possible to produce a geometric feature without support structures while maintaining geometric accuracy.

*Keywords: Additive manufacturing, FDM, support material, sloping walls.*



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## List of Acronyms

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AM – Additive Manufacturing  
3D – Three Dimensional  
CAD – Computer Aided Design  
STL – Stereolithography File  
SLA – Stereolithography  
UV – Ultraviolet  
MPSL – Mask Projection Stereolithography  
SLS – Selective Laser Sintering  
DMLS – Direct Metal Laser Sintering  
SHS – Selective Heat Sintering  
SLM – Selective Laser Melting  
EBM – Electron Beam Machining  
3DP – Three-Dimensional Printing  
MJM – Multi-Jet Modelling  
LOM – Laminated Object Manufacturing  
FDM – Fused Deposition Modelling  
ABS – Acrylonitrile Butadiene Styrene  
PLA – Polylactic Acid





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# 1. Introduction

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In the last decades, the knowledge about Additive Manufacturing (AM) technologies has improved and has enabled to produce new and geometrically complexed parts with single or multiple materials. Several studies are focused on improving additive manufacturing technologies and comparing different processes with each other or to conventional processes (Vayre, Vignat, and Villeneuve 2012).

Since it is a subject that has been growing, it is necessary to analyse the limitations and constraints about additive manufacturing technologies. From a design perspective, the challenge of additive manufacturing is to understand the limitations and opportunities of the new processes and on how to use them in the right applications (Klahn, Leutenecker, and Meboldt 2015).

However, to create complex geometries, sometimes it is essential to have support structures, not only for supporting the piece being built but also to ensure accuracy while the part is being built. The support structure is an additional printed structure, needed to support the model onto the platform during the building process. Without support structures, parts of the model that have not yet achieved their full strength may collapse during the process (Ezair, Massarwi, and Elber 2015). Specifically, the manufacturing material cannot be deposited on a layer where there is insufficient material on the previous layer (Hu, Jin, and Wang 2015). The disadvantage of support structures is that it slows down the process during and after the building stage, namely their removal, increasing production times, energy and material wastage.

It is important to study the impact of support structures. From a designer point of view, it is imperative to have this knowledge. This work seeks to identify and to study the limitation of the support structures used in Fused Deposition Modelling (FDM) systems in order to create a design guideline.

## **1.1. Global Objectives**

This work pursues to add knowledge on support structures studies regarding geometrical limitations in models produced by FDM processes. In some situations, it is not possible to eliminate completely the support structure needed to print the desirable model which could create a limitation in the final part. In other cases, it is possible to ignore the production of support structures during printing.

The purpose of this work is to evaluate and compare the geometric behaviour of a set of models with defined geometric characteristics, such as wall angles. In this research work, the parts were printed in two different FDM machines and in the same material, namely ABS.

## **1.2. Thesis structure**

Besides the Introduction, Conclusion and suggestions for Further Work, this project report has in addition of 3 chapters:

The second chapter describes the state of the art of additive manufacturing technologies. Introduces and categorizes the existing additive manufacturing technologies explaining their advantages, disadvantages, applications and geometrical concerns of each technology that are relevant for this research.

The third chapter refers to the experimental set-up describing the selected design, materials of choice, methods and all the equipments used for the case study. It also refers to the selection and creation of the designs for the experiments based on the research on the geometrical concerns described in the previous chapter.

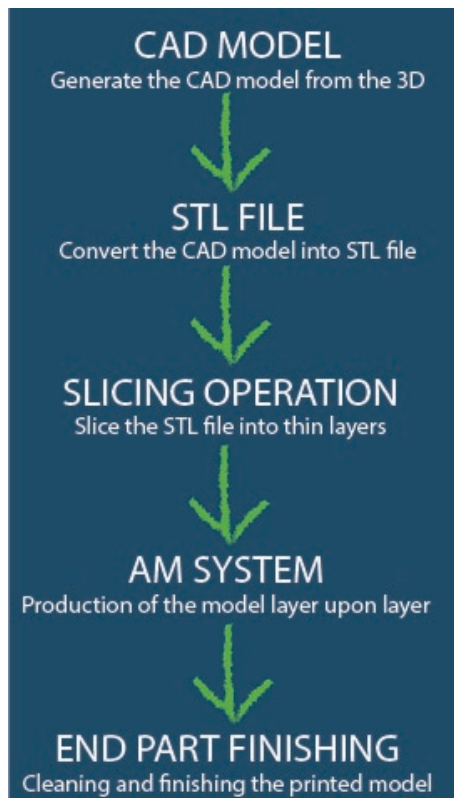
The discussion of the experimental results is explained in chapter 4. The Stratasys – Mojo and Hello Bee Prusa were used to print the parts. The parts were then scanned by a 135 ATOS Core system in order to evaluate their geometric deviation between the printed parts and the 3D CAD models.

## 2. Additive Manufacturing

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In the late 1980s, it is when the first additive manufacturing technology became visible and presented commercially (Guo and Leu 2013). However, additive manufacturing technology goes back earlier into previous decades. From the 1960s to the 1970s, additive manufacturing for many were only registered patents not worthy to be recognized. Until the late 1980s and early 1990s, AM technologies experienced an accentuated growth in patents and research publications. Since that time, the number of new technologies and the integration of different materials in diverse processes increased significantly and its advances continuous to growing every day. With its evolution and diversification, soon there will be a time where these technologies will be called as common technologies in any production line.

Additive manufacturing or 3D printing (3DP) is a technology defined as a process capable of producing 3D models by uniting materials, layer by layer without requiring the use of individual tools. AM technologies have been qualified to produce parts of polymers, metals, ceramics and composites. AM technologies also requires a 3D modelling software (Computer Aided Design or CAD) and other conventional manufacturing technologies such as machining equipments. First, a digital model is developed, then the CAD model must be converted into a file that the 3D printer software can read, usually a STL file. The STL file consists of the model in triangular facets approximating the shape of the object. The 3D printer software reads the STL, processes the data and defines support structures if required. The next step consists of the production of the physical model. Finally, the model is removed from the building platform and all the support material is eliminated when required. The support material is removed depending on the process and material. The model is cleaned and treated (Figure 1). The support generation in some processes of AM is usually required. The support structures can be manually removed, water-soluble or during post-processing which can cause marks/sinks damaging the desired part. The main function of support structure is to anchor the model to the building platform, also to provide a structural stability during production to avoid geometric innacury. There are several aspects to considered to minimize the amount of material used to support the part, and it can be calculated through the software but it depends on the shape, orientation and size of the part.



*Figure 1 - General steps of Additive manufacturing.*

However, it is relevant to analyse AM's advantages pros and cons limitations in general. AM has advantages as it can build small batches of customized low-volume parts that cannot be economically produced by other traditional methods. Also, can build intricate and complex geometries without the need of assembly, therefore, producing almost any shape. Integrates different fields and industries, for example, design, fashion, medicine, automobile, among others. Can detect early flaws and errors that can be amended before the mass fabrication stage. Since it doesn't need tooling and moulds, because it is a direct production there are no additional costs, beside the building machine equipment. On the other hand, in some processes the cost of machinery and materials is high. The orientation of the part during production influences its mechanical performance, making the part less resistant in other directions. The orientation of the part also influences the geometric quality some geometric features due to the stair case effect. Usually, the built surface is rougher than the machined surface. In some cases, the support structure materials can't be recycled being necessary to minimize them during production and also to reduce the production time. In some materials the mechanical and thermal properties are not suitable, because they can be brittle.

A designer is able to create a truly additive design when he understands the characteristics of additive manufacturing (Klahn, Leutenecker, and Meboldt 2015). The awareness about AM challenges is important to minimize the impact on production and to create an optimised part. Selecting the optimal 3D printing process for a particular design can be difficult (Redwood, Schöffner, and Garret 2017). The choice of material and process is relevant to achieve a good result, being important to analyse different printers and processes.

The range of 3D printing methods and materials means that often several processes are suitable, with each one offering variations in properties like dimensional accuracy, surface finish and post processing requirements (Redwood, Schöffner, and Garret 2017). There are several geometric aspects to consider for AM processes when designing a part: the orientation, geometric tolerance, material, support structure, among others such as geometric aspects that are going to be referred according to each process.

It is possible to classify AM Technologies into different categories: powder, liquid and solid-based systems according to different materials. It is easy to find several ways to classify these systems. One possible classification is presented in Figure 2 and it is obvious the variety of existing processes.

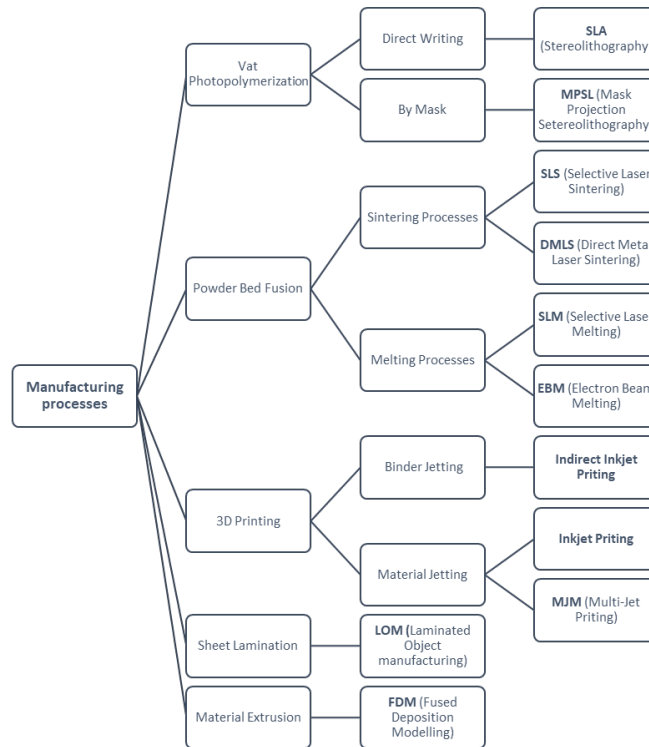


Figure 2 - Manufacturing processes.

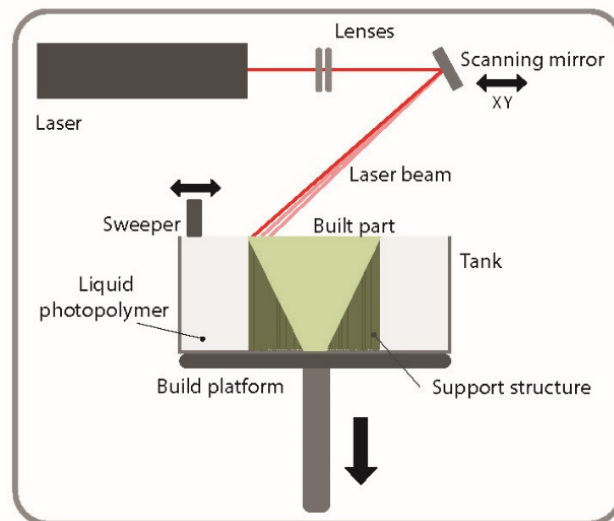
## 2.1. Vat Photopolymerization

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### 2.1.1. Direct Writing - Stereolithography

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Stereolithography (SLA) processes produces 3D models by turning a liquid photopolymer resin into the solid state, solidifying it, with the aid of an ultraviolet (UV) laser beam. A tank is filled with a liquid resin where the building platform is submerged. The system starts mapping each layer in the building platform by solidifying the material. After this step, platform lowers letting a new layer of resin to stream over. This process is duplicated layer upon layer until the part is fully printed. Illustrated in Figure 3. After production, the post-processing is performed, namely the removal of the excess resin and support structures and then cleaned with a solution to eliminate existing residues. Afterwards, it goes through a curing process to fully solidify. SLA requires support structures otherwise the part may collapse during production. In the vat photopolymerization process, the support structures are built in the same material as the model part, but in a thinner thicknesses so that it can be removed manually without damaging the part when done carefully (Almeida and Correia 2016).



*Figure 3 - SLA process scheme.*

SLA is a process that may be used for jewellery (investment casting), dental and medical applications (hearing aids). As advantages, the building speed is high, and it is capable of producing small and intricate models with smooth surface finish and accurate detail. On the other hand, adding to the limited range of materials, the materials are also



expensive. The SLA process is limited to photopolymers. As mentioned before, SLA requires support structures and consequently during their removal, if not carefully removed, the part may end up with superficial defects. Advisedly, the support structures should be created at the least visible surfaces.

### 2.1.2. Mask Projection Stereolithography

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Similar to SLA, the Mask Projection Stereolithography (MPSL) produces the physical models by solidifying photosensitive resins. In this case, each layer is produced in one single instant. Each layer section results from a sliced cross section stored as bitmaps to be displayed on the dynamic LCD mask. UV radiation reflects off of the “on” micro-mirrors and is imaged onto the resin surface to cure a single layer. The building platform slides upward providing a thin layer of new resin between the previous layer and the bottom of the resin tank, building the part upside down. In some systems, such as the VFlash system, the part is not produced in a liquid resin tank but produced with the aid of a cartridge that provides a resin film for each layer. In either system, this process continues until the entire part is built (Gibson, Rosen, and Stucker 2010). Figure 4 illustrates the MPSL process. Support structures are often necessary which have to be removed during the post-processing of the part.

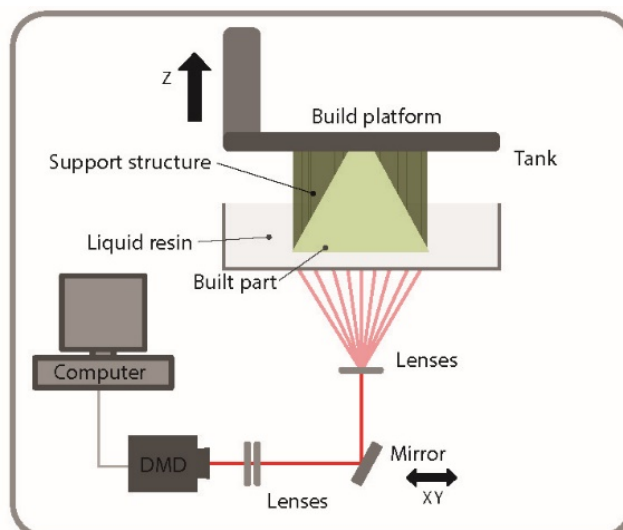


Figure 4 - MPSL process scheme.

MPSL is essential for electrical and automotive parts. This technology, comparing to the SLA process is faster but it is also limited to the same material constraints, photopolymers and cost.

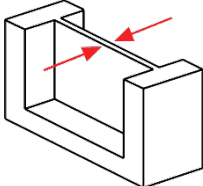
### 2.1.3. Geometric aspects

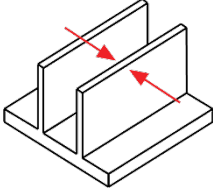
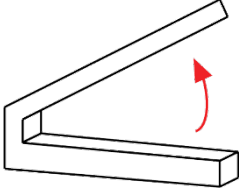
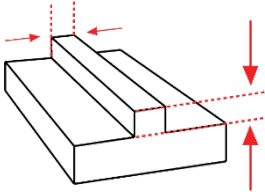
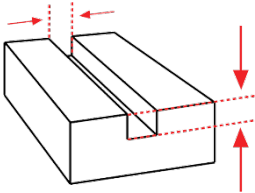
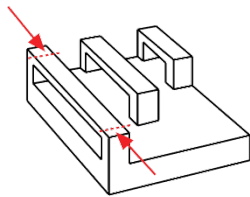
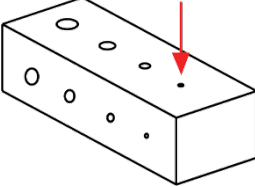
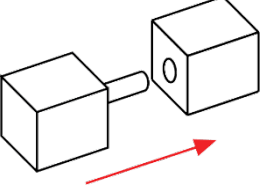
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For both SLA and MPSL the support structures have a big effect on the surface finish. Since the support material is the same as the build material but thinner to facilitate their removal, and since it is performed manually, the removal of the support structures may leave marks on the surface of the part if not done properly. This issue is strongly influenced by the orientation of the part during production. If the part is strategically oriented, it ensures that the important surfaces are not in touch with the support structures in order to obtain a smooth surface. Complex details in inaccessible areas will make removal of support structures difficult and increases the likelihood of damaging the part (Redwood, Schöffner, and Garret 2017). The support structures secure the part from collapsing during production, therefore it is difficult to produce hollow parts because it is not possible to remove the support structures within the interior of the part. It is important to make sure that the interior doesn't need support structures. For MPSL, since it prints micro parts, support structures become more difficult to remove.

The level of detail that a SLA printer can produce is dependent on the laser spot size and resin properties. General guidelines for designing for SLA are as follows:

*Table 1 - Designing for SLA printing (Courtney Armstrong n.d.).*

Feature	Description
	<p>Supported walls: Walls that are connected to other structures on at least two sides have very little chance of warping. These should be designed at a minimum of 0.4 mm thick.</p>

	<p>Unsupported walls: Walls that are connected on less than two sides present a high chance for warping or detaching from the print. These walls must be at least 0.6 mm thick and should be designed with filleted bases reducing stress concentrations along the joint.</p>
	<p>Overhangs: Overhangs pose little threat unless the model is being printed without adequate internal and external support structures. Printing without supports often leads to warping of the print, but if printing without supports is necessary, any unsupported overhangs must be kept less than 1.0 mm in length at 90° and for slopping walls a minimum of 19° from level.</p>
	<p>Embossed details (including text): Any features on the model that are raised slightly above the surfaces around them must be at least 0.1 mm in height above the surface of the print to ensure visibility of the printed details.</p>
	<p>Engraved details (including text): Any features which are imprinted or recessed into the model are at risk of fusing with the rest of the model while printing if they are too small, therefore these details must be at least 0.4 mm wide and 0.4 mm in depth.</p>
	<p>Horizontal bridges: Bridges between two points on a model can be successfully printed, but the designer must keep in mind that wider bridges must be shorter (less than 21 mm) than thinner bridges. Wider bridges have a higher z-axis area of contact increasing the chance of print failure during peeling.</p>
	<p>Holes: Holes with a diameter less than 0.5 mm may close off during printing.</p>
	<p>Connections:</p> <ul style="list-style-type: none"> <li>• 0.5 mm clearance between moving parts.</li> <li>• 0.2 mm clearance for assembly connections.</li> <li>• 0.1 mm clearance will give a push or snug fit.</li> </ul>

## 2.2. Powder Bed Fusion

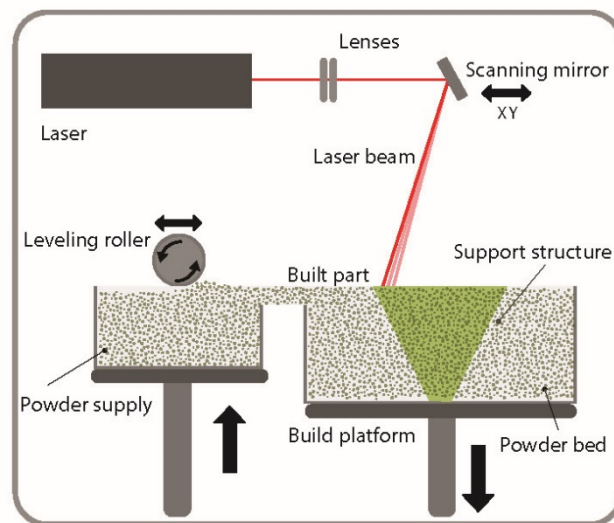
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### 2.2.1. Sintering Processes

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#### a) Selective Laser Sintering

Selective Laser Sintering (SLS) is a sintering process that begins by heating the material to a temperature below the melting point bonding together the powder that is been sintered. The layers of powder material are deposited onto a building platform in order to produce the physical model. The laser selectively sinters the powder and solidifies a cross section of the part (Redwood, Schöffner, and Garret 2017). After each cross section is scanned, the powder bed is lowered by one layer thickness, a new layer of material is spread on top, and the process is repeated until the part building is completed (Guo and Leu 2013) as illustrated in Figure 5.



*Figure 5 - SLS process scheme.*

SLS is used for producing functional prototypes and parts. The major advantage of laser sintering is the almost complete design freedom. Unlike other AM processes such as SLA and FDM, SLS does not require support structures. The excess un-sintered powder acts as a support for the part that is been produced, allowing for complex and intricate shapes to be manufactured with no additional support needed. In summary, SLS does not require support structures because the part been built is surrounded by un-sintered powder (Guo and Leu 2013). SLS produces in a wide range of materials with

good mechanical properties and complex geometries. However, the finished objects require more time to cool down hence the production time increases.

### **b) Direct Metal Laser Sintering**

Direct Metal Laser Sintering (DMLS) is a technology similar to SLS but instead produces metallic alloy parts by using a laser to sinter the metallic alloy powder near its melting point allowing the sintered powder to fuse. In this case, the gap between the processing temperature and melting temperature is less than in SLS systems due to the use of metallic powders. Unlike SLS, DMLS needs support structures to avoid distortions of the part. Due to the high temperatures involved in the process and the layer by layer nature of part construction, support structures are required to connect unsupported geometries to the building platform and act as a heat sink for excess thermal energy and also to support the weight of the metallic part been built (Redwood, Schöffler, and Garret 2017). The support structures are then removed in post processing stage.

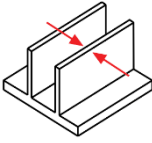
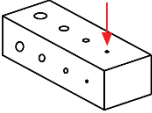
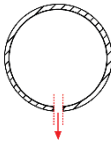
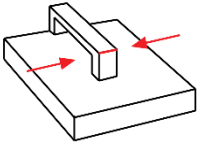
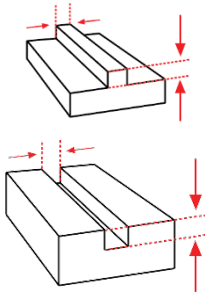
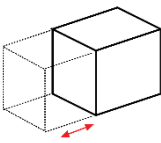
DMLS produces functional parts and tools for several demanding industries such as aerospace, automotive, medical, dental and jewelry. This process has the ability to produce fully dense parts with a high design freedom and complexity. It is possible to produce complex parts because there is no tooling, only in the post-processing support structures are removed the support structures. Additionally, the build parts have high specific strength and stiffness. Adversely, the surface finish quality depends on the grain size of the powder, and also the cost is high and the building size has limitations.

### **c) Geometric aspect**

SLS parts often suffer big distortion and warping. The orientation of the part is very important to avoid distortion of builded part. One geometric aspect to be considered when designing parts, is the volume of the part that should be reduced in order to avoid distortion. For the DMLS process, the support structures are really difficult to remove when compared to printed polymer parts. Generally, when more support structures are included in the design, more accurately the part will be, but higher cost, post processing time and difficulty in removing them (Redwood, Schöffler, and Garret 2017).

The detail level that a SLS printer can produce depend on the processing parameters of the laser and the material properties. General guidelines for designing for SLS are as follows. Regarding the DMLS process, since it is metal based, the general guidelines will be presented with the melting processes.

*Table 2 - Designing for SLS printing (Oceanz n.d.).*

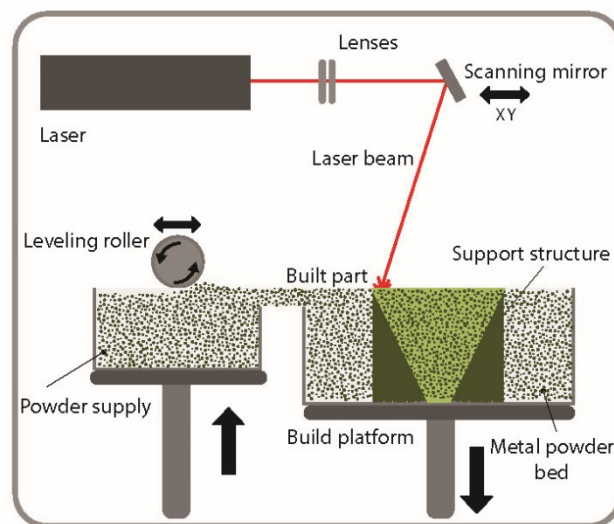
Feature	Description
	<p>Wall thickness: The minimum wall thickness to ensure a successful print varies between 0.7 mm (for PA12) up to 2.0 mm (for carbon filled polyamide).</p>
	<p>Hole size: All holes should be larger than 1.5 mm in diameter.</p>
	<p>Escape holes: To save weight (and sometimes costs) SLS parts are printed hollow. But in order to remove unsintered powder after production escape holes must be included. Escape holes must have a minimum of 3.5 mm in diameter.</p>
	<p>Feature size (pins, protruding features etc.): A minimum size of 0.8 mm is recommended.</p>
	<p>Embossed and engraved details: To ensure the visibility of the printed details, the following values are required:</p> <ul style="list-style-type: none"> <li>• Minimum depth of engraving 1 mm</li> <li>• Minimum height of embossing 1 mm</li> </ul>
	<p>Tolerances: Typical tolerances for SLS parts are within <math>\pm 0.3</math> mm or <math>\pm 0.05</math> mm/mm.</p>

## 2.2.2. Melting Processes

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### a) Selective Laser Melting

Selective Laser Melting (SLM) process is based on SLS process, but in this case uses a high-power laser beam to melt successive metallic powder layers. The laser will heat particles on a metallic powder bed until completely melted. The powder is delivered and spread over the plate by the levelling roller, similar to the previous powder processes. Laser scanning begins with predefined tracks after the powder has been spread over the plate. After the layer scanning concluded, building platform is lowered in the depth of a layer and new powder is spread over the previous layer (Zeng 2015). The building process is done in a chamber with an inert gas environment in order to avoid metal oxidation (Gao et al. 2015). The SLM scheme is illustrated in Figure 6. This process is repeated until full part is printed. SLM requires support structures during production for similar reasons such as the DMLS process, as the powder acts as a natural support in the building process. After production, parts may require surface finishing procedures such as milling in order to remove the support structures.



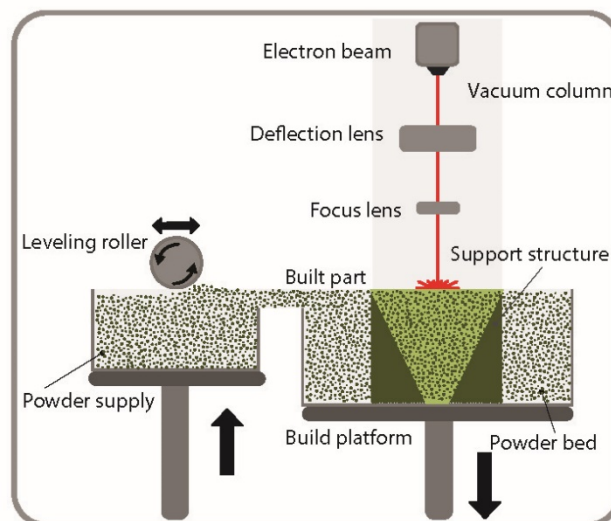
*Figure 6 - SLM process scheme.*

SLM is capable to produce functional metallic parts and tools. Typically, the systems requires large amount of energy which can be more difficult to control. This technology is also able of producing complex geometries. As DMLS, SLM have low structural properties, size limitations and the surface finish depends on the size and quality

of the powder grain. The difference between SLM and DMLS systems is that SLM achieves a full melt while DMLS only sinters the powders. This means that DMLS only works with alloys (nickel alloy, Ti6AlV4 alloy, etc.), whereas SLM does not operate with combination of different metals. For example, the building material could be either aluminium, or titanium, or copper, or stainless steel.

## b) Electron Beam Melting

In Electron Beam Melting (EBM) the machine delivers a layer of melted metal powder in a layer by layer fashion on the building platform, which is melted by the electron beam and then fused. The actual building process is done in a vacuum environment in order to avoid metal oxidation (Gao et al. 2015). Similarly to SLM and DMLS, EBM parts require support structures to support the building part and allow excess heat to transfer away from the melted powder. After part production, it is required a post-processing to remove support structures and the excess powder is removed and reused. Figure 7 represents a simple scheme of EBM process.



*Figure 7 - EBM process scheme.*

The fabricated parts are fully dense, free of voids, and extremely strong (Guo and Leu 2013). Since the building process occurs in a vacuum environment, despite the costs, this eliminates impurities. Besides these processing characteristics, it is able to process titanium which makes this technology the most adequate for the production of medical implants. Other sectors such as aerospace and automotive industries also turn to this



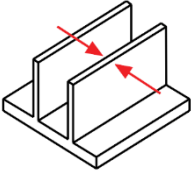
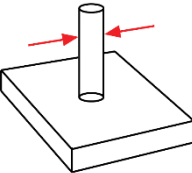
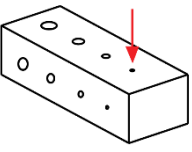
technology when titanium parts are required. It is able to print multiple components at the same time.

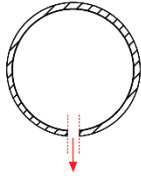
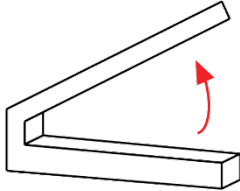
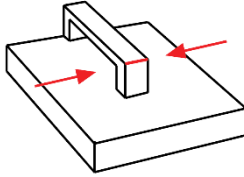
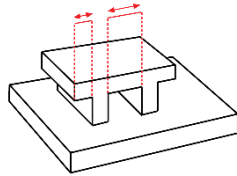
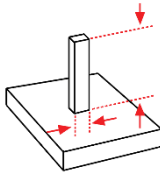
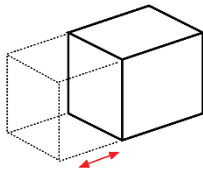
**c) Geometric aspects**

SLM parts suffers a residual stress or risk of failure or cracking can be caused by thermal gradients, but with the combinations of high temperature and suitable cooling the parts are more strong and durable. The rule is to avoid sloping walls, because for the case of lower building angles more support structure are needed.

The detail level that a DMLS, SLM and EBM printer can produce is dependent on the processing parameters of the laser or electron beam and the metallic properties. General guidelines for designing for melting processes are as follows:

*Table 3 - Designing for metal processes (Redwood n.d.).*

Feature	Description
	<p>Wall thickness: The minimum thickness to ensure a successful print is commonly 0.4 mm, depending on material, orientation and printer parameters.</p>
	<p>Pin diameter: The minimum reliable pin diameter is 1 mm.</p>
	<p>Hole size: Hole diameters between 0.5 mm and 6 mm can be printed reliably without supports. Support free building of hole diameters between 6 mm and 10 mm is orientation dependent. Above 10 mm, support structures are required.</p>

	<p>Escape holes: Holes are required on hollowed metal parts to remove unmelted powder. A bore hole diameter of 2-5 mm is recommended. Using multiple escape holes will greatly improve the ease of powder removal.</p>
	<p>Overhanging Surfaces: The minimum angle where support material is not required on an overhanging surface is 45° relative to the horizontal. It is possible to reduce this angle further by optimizing the laser parameters.</p>
	<p>Feature size (pins, protruding features etc.): A minimum size of 0.8 mm is recommended.</p>
	<p>Unsupported Edges: The maximum length of a cantilever-style overhanging surface is 0.5 mm. An overhanging horizontal surface supported on both ends can be 1 mm long. These rules will apply to embossed and engraved features with unsupported surfaces as well.</p>
	<p>Aspect Ratio: The maximum ratio between the vertical print height and the part section is 8:1 to ensure stability of the printed part on the build plate.</p>
	<p>Tolerances: Part tolerance in the print direction is <math>\pm 1</math> layer thickness. In the XY plane, the achievable tolerance is <math>\pm 0.127</math> mm.</p>

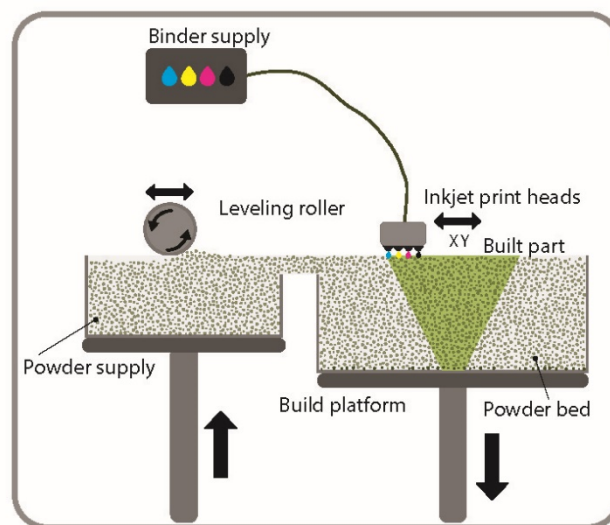
### 2.3. 3D Printing

3D printing includes the following techniques: binder jetting, that refers to indirect inkjet printing and material jetting, that describes inkjet printing and multi-jet modelling.

### 2.3.1. Binder Jetting – Indirect Inkjet Printing

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Binder printing process creates parts with a binding agent. The liquid agent is deposited onto a bed of powder through a nozzle uniting the part, in a layer by layer fashion until the part is complete. When finished, the part is in a green state, then is removed from the building platform and cleaned and all the excess powder removed. Then needs to be infiltrated so that the part becomes more resistant and ready for use. This process does not require additional support structures since the excess of un-binded powder acts as support structure. Figure 8 illustrates the binder jetting process.



*Figure 8 - Binder jetting process scheme.*

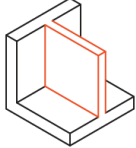
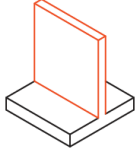
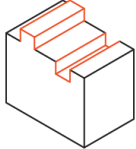
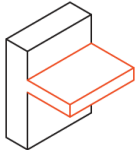
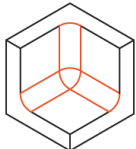
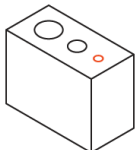
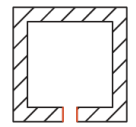
Architectural models and sculptures are the main application for indirect inkjet printing due to the ability to print in full colours and to produce highly complex geometries. It is a process that requires less energy, since no laser or electron beam is involved, but when compared to SLS nonetheless, the parts are not as strong and the surface finish tends to be grainy.

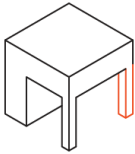
#### **a) Geometric aspects**

As mentioned before, parts after being printed are in a fragile green state, which adds restrictions to the designs that can be printed such as thin features that may break in the green state during handling. The part needs to be reinforced with extra structures

because when pressurized air is applied to remove the excess powder, the part can be damaged or even break. General guidelines for designing for binder jetting are as follows:

*Table 4 - Designing for binder jetting processes (Varotsis n.d.).*

<b>Feature</b>	<b>Description</b>
	<p>Wall thickness: The recommended minimum value for parts is 2.0 mm. This ensures that the part can be removed from the powder and handled in the green state without being damaged.</p>
	<p>Unsupported walls (including fins or ribs): These features are at a greater risk of being damaged during handling and should not be thinner than 3.0 mm.</p>
	<p>Embossed and engraved details: To ensure the visibility of the details, embossed and engraved details should be at least 0.5 mm below or above the surface.</p>
	<p>Unsupported edges: Although the powder surrounding the part offers support during building, unsupported edges are at a high risk of breaking during handling in the green state. Unsupported edges should be no longer than 20 mm.</p>
	<p>Fillets: All fillets should be a minimum of 1.0 mm in radius and used in all edges of the design where possible. This ensures that they the part will not be damaged in the green state.</p>
	<p>Hole size: For a hole to be successfully printed the minimum diameter should be no smaller than 1.5 mm.</p>
	<p>Escape holes: Binder Jetting is able to produce parts with hollow sections, but in order to remove the unbound powder after printing, escape holes must be included in the design. The holes must have a minimum of 5.0 mm in diameter and the use of at least 2 escape holes is recommended.</p>

	<p>Feature size: The main concern with minimum feature size is the potential for damage. Although the process is able of producing parts with very fine details, the main concern regards the handling of the part in the green state. Because of this, a minimum feature size of 2.0 mm is recommended.</p>
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### 2.3.2. Material Jetting

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#### a) Inkjet Printing

Similar to binder jet printing technology that transfers ink droplets from a fluid channel onto the powder substrate in a drop by drop fashion, material jetting processes directly deposit material droplets of wax or photopolymer resins onto a substrate in a drop on drop demand (Gao et al. 2015). In this case, due to the absence of powder on the building plate, material jetting requires support structures.

This technology is directed to production of full colour visual prototypes and medical models. Inkjet printing is slower than laser printing processes. Although it has the ability to produce a variety of material parts and colours in a single process, the ink is expensive.

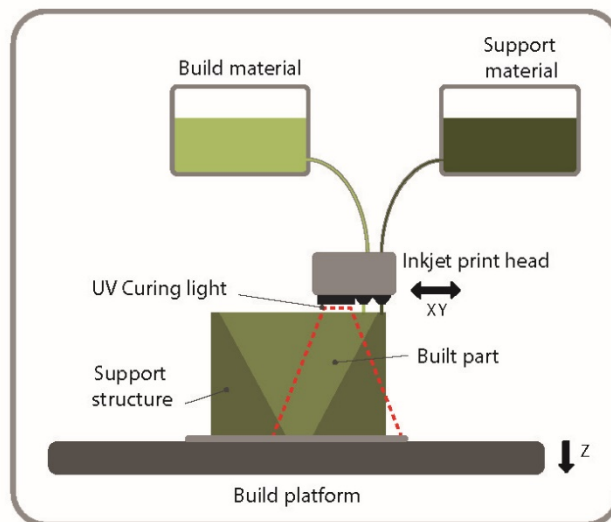


Figure 9 - Material jetting printing process scheme.

## **b) Multi-Jet Modelling**

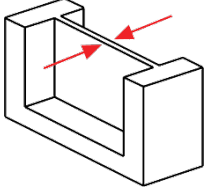
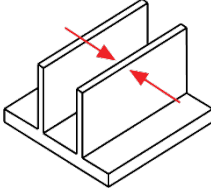
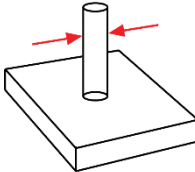
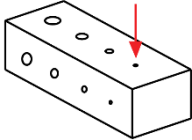
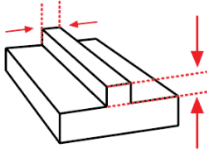
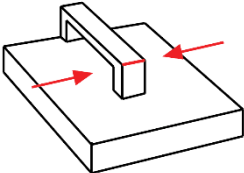
Multi-Jet Modelling (MJM) process has the same principle of inkjet printing, but in this case, it builds the part using multiple nozzles. The printing head generates jets of material which are oriented in a linear array. Each individual jet dispenses UV curable polymer or wax on demand. The MJM head shuttles back and forth to build every single layer, followed by a UV lamp flashing that cures the deposited polymer. In the case of wax, no UV lamp is required. When one layer is completed, the platform is descended by a layer thickness and the next layer is built upon the previous layer. This process is repeated until the entire part is built (Guo and Leu 2013). MJM requires support structures that are generated automatically and the support material is water washable making easy to remove from the final part.

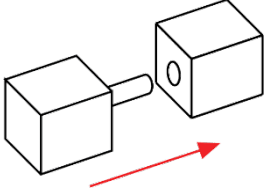
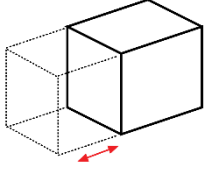
MJM is capable of producing realistic and dimensionally accurate prototypes with big details. This technology is effective and it has a fast building time but it also has a limited range of processing materials.

## **c) Geometric aspects**

Material Jetting is one of the most accurate 3D printing technologies, producing high detail parts with a very smooth surface. The lack of heat present during the Material Jetting process as well as the use of dissolvable support material allows for high level of design freedom, with few specific process design rules outside of minimum feature sizes (Redwood, Schöffner, and Garret 2017). Since the support material is removed manually or dissolved, hollow parts are one of geometrical limitation, because it is not possible to remove manually support structures or dissolve it entirely. General guidelines for designing for material jetting are as follows:

Table 5 - Designing for material jetting processes (Varotsis n.d.).

Feature	Description
	<p>Major support walls: The minimum thickness for major supported walls is 1 mm.</p>
	<p>All other walls: For all other walls the minimum thickness should be no less than 0.5 mm.</p>
	<p>Pin diameter: A minimum pin diameter of 0.5 mm is recommended.</p>
	<p>Hole size: For a hole to be successfully printed, the minimum diameter should be no smaller than 0.5 mm.</p>
	<p>Embossed and engraved details: To ensure the visibility of small details, the following rules are required:</p> <ul style="list-style-type: none"> <li>• Minimum depth of engraving 0.5 mm</li> <li>• Minimum height of embossing 0.5 mm</li> </ul>
	<p>Feature pins sizes and Protruding feature sizes: This process is capable of producing part details as low as 0.25 mm.</p>

	<p>Moving parts: Assembled parts, hinges and joints should have a 0.15 - 0.2 mm clearance around all sides. This clearance must also be accessible to allow for cleaning/removal of the support material that will be build within the gap.</p>
	<p>Tolerances: The parts range from from +/- 0.1mm to 0.3 mm depending on geometry and material.</p>

## 2.4. Sheet Lamination

Sheet Lamination, most commonly known as Laminated Object Manufacturing (LOM), is a process that relies on material in a sheet format (paper) to produce the part. A sheet of material is spread across a movable substrate, and a blade cuts it along the contours of the part's geometry determined by the CAD model. The layers bond when a hot roller compresses the sheet and activates a heat sensitive adhesive (Guo and Leu 2013). The process is repeated until the part is completely built (Figure 10). LOM does not require support structure as the material sheet provides support for the model. A blade cuts the desired pattern into the material and in-print the material that wasn't used so that it can be removed later.

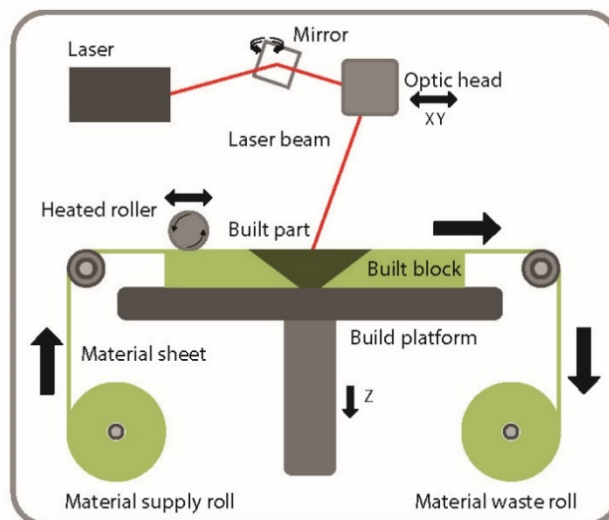


Figure 10 - LOM process scheme.



LOM has advantages as it has a high production speed due to the blade doesn't scan the whole cross-section, only the contour and it is a low-cost process with easy material handling. On the contrary, LOM is currently limited to the use of paper. The surface quality depends on the thickness of the sheet. It is difficult to achieve a good surface finish (Guo and Leu 2013).

#### **2.4.1. Geometric aspects**

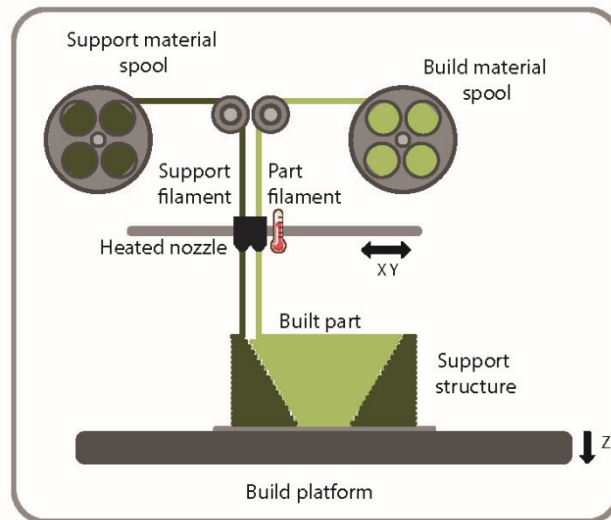
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For a design perspective, LOM It is not capable of producing hollow parts. The excess surrounding paper helps the building process as it acts as the support structure of the part being built. Current LOM systems capable of producing in full colours and are fully dense parts, but the parts can't be used in any functional prototype.

### **2.5. Material Extrusion – Fused Deposition Modelling**

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Fused Deposition Modelling (FDM) is a process mainly trademarked by Stratasys, the main producer of FDM systems. This process occurs as the material is drawn in a filament through a heated nozzle and as the material reaches near its melting point, the material is deposited in a layer by layer fashion in a pre-determined path onto the building platform, solidifying and providing foundation for the next layer, until the part is completely finished. Figure 11 illustrates the FDM process. The deposition head usually contains two nozzles for part material and support material due to the fact that the materials can be different. The FDM process often requires support structures. The support material can be removed manually, easily breakable or dissolved in a solvent solution.



*Figure 11 - FDM process scheme.*

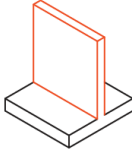
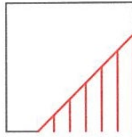
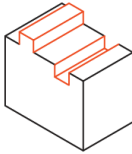
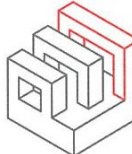
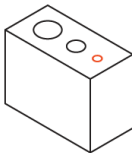
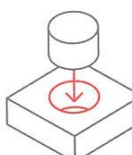

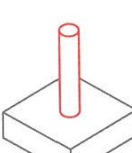
The FDM parts have good structural properties in the case of ABS which is an engineering polymer and an accessible material. It is a technology easy to use, clean and also multi-material printing. Within the FDM systems, currently the market supplies two types of systems, namely the high-cost system supplied by Stratasys and low-cost system supplied by other suppliers. The high-cost system present high dimensional accuracy when compared to low-cost systems. The nozzle radius affects the final quality of the part.

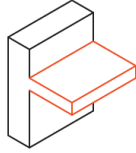
### **2.5.1. Geometric aspects**

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FDM requires support structures to anchor the part to the building platform. Studies confirm that the support structure is needed for overhangs above 45° degrees. When designing a part, it is important to consider the sloping walls, also the surface of the part that needs the support structure tend to be rougher. Therefore, is important to study the orientation that better suits the part. It is important that a designer understands the application of a part and how the direction will impact the performance (Redwood, Schöffner, and Garret 2017).

Table 6 - Designing for material extrusion (Redwood, Schöffer, and Garret 2017).

Feature	Description
	<p>Wall thickness: as rule of thumb, its minimum value should be a multiple of the nozzle diameter. For example, if this such value is 0.4 mm, the recommended wall thickness is 0.8 mm.</p>
	<p>Overhangs: Material support is required for angles below 45°.</p>
	<p>Embossed and engraved details: dimensions should be not smaller than 0.6 mm (wide) x 2 mm (height).</p>
	<p>Bridges: to avoid sagging, the unsupported bridges span should be &lt; 10mm.</p>
	<p>Holes: to ensure accurate dimensions &lt; 2 mm, it should be performed after the printing process by drilling.</p>
	<p>Clearance: A spacing of 0.5 mm should be used when clearance is required.</p>
	<p>Feature size: its minim value should be 2 mm.</p>
	<p>Vertical pins: make them functional, their diameter should not be smaller than 3 mm.</p>



Unsupported edges: if longer than 3 mm, quality of the print is being compromised.

## 2.6. Process Overview

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The tables below present an overview of the described technologies in order to provide a better understanding of their advantages, disadvantages and geometric aspects Table 7 and their materials, support structures and applications Table 8.

To sum up, these different processes have some constraints yet to be determined and studied. There are still design guidelines to be defined. Therefore, this study is focused on identify and analyse the limitation found. FDM technology is the process in question. Since it is a low-cost process and there was availability to work with the necessary equipment, this study was developed in this apparatus. On the following chapter is described the methods and all the equipment used.

Table 7 - Advantages, Disadvantages and Geometric aspects of AM processes.

AM PROCESSES	ADVANTAGES	DISADVANTAGES	GEOMETRIC ASPECTS
<b>SLA</b> (Stereolithography)	High level of accuracy and detail, good finish, quick process, small and intricate models	Limited material use (Photo-resin), High cost of supplies, Often requires structures	Difficult to produce hollow parts
<b>MPSL</b> ( Mask projection Stereolithography)	Faster than SLA	Limited material use (Photo-resin)	Difficult to produce hollow parts
<b>SLS</b> (Selective Laser Sintering)	Functional parts with good mechanical properties, complex geometries	High power consumption	Distortion and warping of the parts
<b>DMLS</b> (Direct Metal Laser Sintering)	High accuracy and details	Size limitations, finish depends of powder grain size	Support material difficult to remove
<b>SLM</b> (Selective Laser Melting)	Complex geometries	Low structural properties, size limitations, finish depends of powder grain size	Hollow sections need to be carefully designed
<b>EBM</b> (Electron Beam Melting)	High accuracy and strong parts, design freedom	Expensive process	Sloping walls
<b>Indirect Inkjet Printing</b>	Wide range of colours	Porosities on the finished part	Parts are fragile
<b>Inkjet Printing</b>	Variety of material parts and colours in 1 process	Slower than laser printing process The ink is expensive	Hollow sections
<b>MJM</b> (Multi-Jet Modelling)	High accuracy, Smooth surface finish, High precision	Often requires support material, High cost	Hollow sections
<b>LOM</b> (Laminated Object Manufacturing)	Low process costs High fabrication speed	Highly dependent on resins and curing processes, difficulto achieve good surface finish	Hollow parts
<b>FDM</b> (Fused Deposition Modelling)	Simple to use, clean, multi-material printing, low-cost extrusion machines	Poor surface finish, build speed, Dimensional accuracy limitations, material density	Sloping walls

Table 8 - Material, Support material and Applications of AM processes.

AM PROCESSES	MATERIALS	SUPPORT MATERIALS	APPLICATIONS
<b>SLA</b> (Stereolithography)	Polymers (UV curable, Photopolymer resin)	It requires support structures Same material	Jewellery Investment casting Dental and medical applications
<b>MPSL</b> ( Mask projection Stereolithography)	Photopolymer resin	It requires support structures	Electrical, automotive parts
<b>SLS</b> (Selective Laser Sintering)	Polymers (Waxes, Thermoplastics), Metal Powder, Ceramic powder	No need for support structure	Functional prototypes
<b>DMLS</b> (Direct Metal Laser Sintering)	Metals	It requires support structures	Aerospace and Automotive, Dental and Medical
<b>SLM</b> (Selective Laser Melting)	Metals (Aluminium)	It requires support structures	Manufacture end parts
<b>EBM</b> (Electron Beam Melting)	Metals and Alloys (Titanium, Colbat, SS, Copper)	It requires support structures	Manufacture end parts, Aeorspace, Automotive
<b>Indirect Inkjet Printing</b>	Polymer powder, ceramic powder and metallic powder	No need for support structure	Architectural models
<b>Inkjet Printing</b>	Polymers (Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP)	It requires support structures	Full colour visual prototypes, Medical models
<b>MJM</b> (Multi-Jet Modelling)	Polymers (Polypropylene, HDPE, PS, PMMA, PC, ABS, HIPS, EDP)	It requires support structures	Realistic prototypes with great detail
<b>LOM</b> (Laminated Object Manufacturing)	Paper, Plastic, Laminated Metal	No need for support structure	Manufacture end parts
<b>FDM</b> (Fused Deposition Modelling)	Polymers (Waxes, Thermoplastics - ABS, PC)	It requires support structures	Non-functional prototypes

### 3. Experimental framework

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Bearing in mind the detailed description of the processes and their geometric considerations, one issue tends to stand out in the overall process, namely the use of support structures during the building process. The usage of support structures has its advantages during the production but then presents disadvantages during the post-processing of the final part. Recent works have focused on the possibility of reducing the amount of support structures during the building process. Optimization algorithms have been developed in order to minimize the amount of support material while still been capable of withstanding the structural load during production. In order to fully understand the geometric limitations for the need of support structures, a experimental set-up was prepared which focused on a specific process and geometric design which some may require support structures and others may not. After the production process, the physical models were geometrically evaluated and compared to the corresponding CAD models. With this experimental set-up, it is possible to determine the influence of using support structures during the building process.

#### 3.1. Selected designs for the experimental framework

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There are several aspects that influence the printing process. In some case studies, the orientation of the part has a big influence on the outcome of the printing. According to Ezair et al. (Ezair, Massarwi, and Elber 2015), the support structure volume can be optimized by changing the model orientation through an algorithm that computes a certain optimal orientation. Therefore the printing time is also optimized. Hu et al. (Hu, Jin, and Wang 2015) introduces tools to optimize the orientation and the study of several orientations of the same model in order to find a minimized orientation that avoids waste of material, energy and production cost. The support structure has likewise an incredible weight in 3D printing process. Huang et al. (Huang et al. 2009) developed a support structure generation algorithm in order to create sloping walls of support structures instead of normal straight walls, hence optimizing the fabrication process by reducing both the amount of support material and production time. Adama and Zimmer (Adam and Zimmer 2014), referes the importance of having design rules for the printing of physical models. Although, there is now the need to create more intricated and complex parts,

there are still few studies that are testing the constraints and limitations of printing models in certain technologies. In a design perspective, it is relevant to have this information and most case studies are focused on the optimization of the support structure volume according to the orientation of the model.

Considering the previous geometric considerations and the above concerns, it is obvious that physical models with sloping walls is a relevant issue, since sloping walls may be produced with or without support structures according to their angle from the base of the building plate.

Several aspects were taken into consideration, including the building dimensions of each printer, the height, the orientation and the shape. The models were decided to have a simple design, an inverted conic shape with a specific selection of angles and heights. It was important to have the predefined sloping walls to establish a design guideline. Due to the printer's building chamber, the height of the models were adjusted in order to fit within the building space of the 3D printer. As the angles of the sloping walls varied, so did the width of the models, requiring that the height be adjusted. The wall of the models have 1mm in thickness in order to reduce the weight upon the sloping wall reducing geometric distortion.

The CAD models are represented in Figure 12 with the pre-defined angles as mentioned. Five geometric models were considered in this study that consisted of an inverted cone shape with different sloping walls that vary from  $10^\circ$  to  $90^\circ$  degrees with an interval  $20^\circ$  degrees between angles.



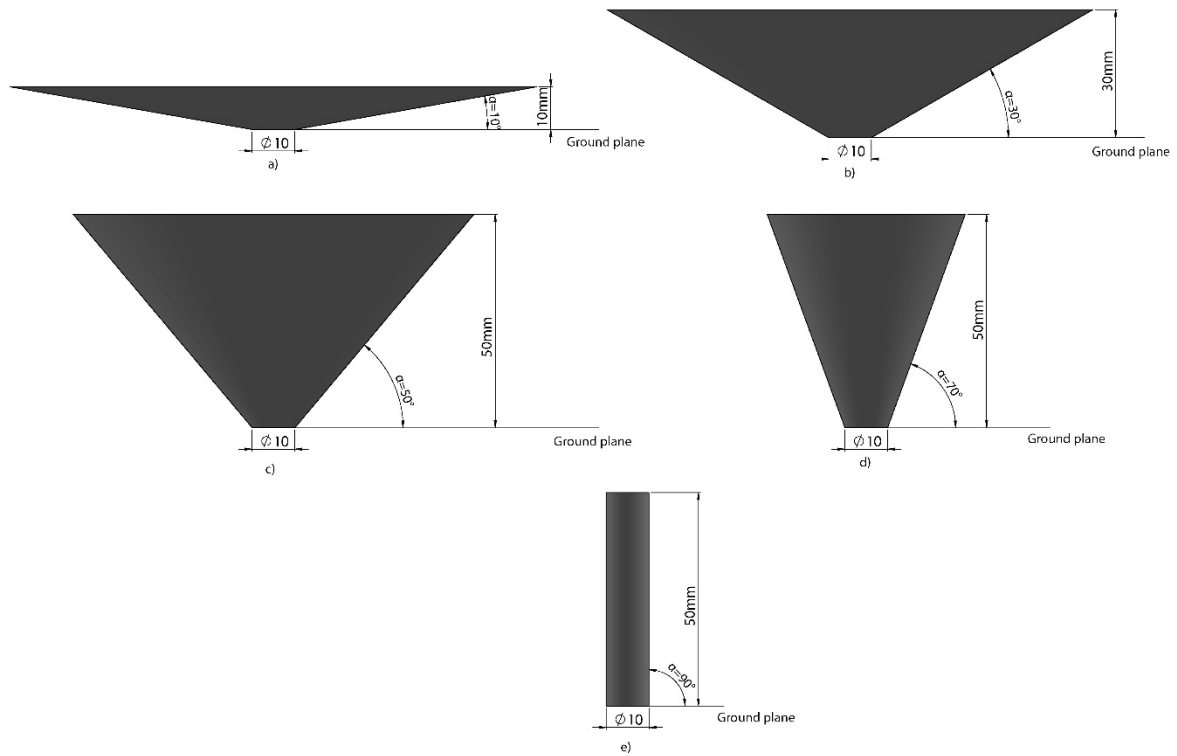


Figure 12 - CAD models for each considered printing angle  $\alpha$ : a)  $10^\circ$ , b)  $30^\circ$ , c)  $50^\circ$ , d)  $70^\circ$ , e)  $90^\circ$ .

### 3.2. FDM Equipment and Materials

The most adequate printing process for this study based on the availability of additive manufacturing systems and cost for both material and processing is the FDM systems. After performing this selection, the next step consisted in selecting a FDM printer to produce the physical models. Two FDM systems were selected for fabrication, namely a Mojo and a Hello Bee Prusa printer.

The Mojo printer by Stratasys (Figure 13) was supplied by a company Cadmold which showed availability in collaborating in this research. The Mojo printer (Figure 13) from Stratasys is a machine with a closed building chamber which allows it to have a controlled and constant building temperature inside the building chamber in order to avoid geometric distortions and/or warpage. The Mojo building size is 127 x 127 x 127 mm and prints the polymer material on a plastic non-reusable platform. The Print Wizard software allows to choose the scale and orientation that best fits the model. Before printing, the Mojo Control Panel gives information about the estimated printing

time, the part material and support material level to verify the amount of material needed to print the part (Figure 14).



Figure 13 - Mojo Printer from Stratasys (2008).

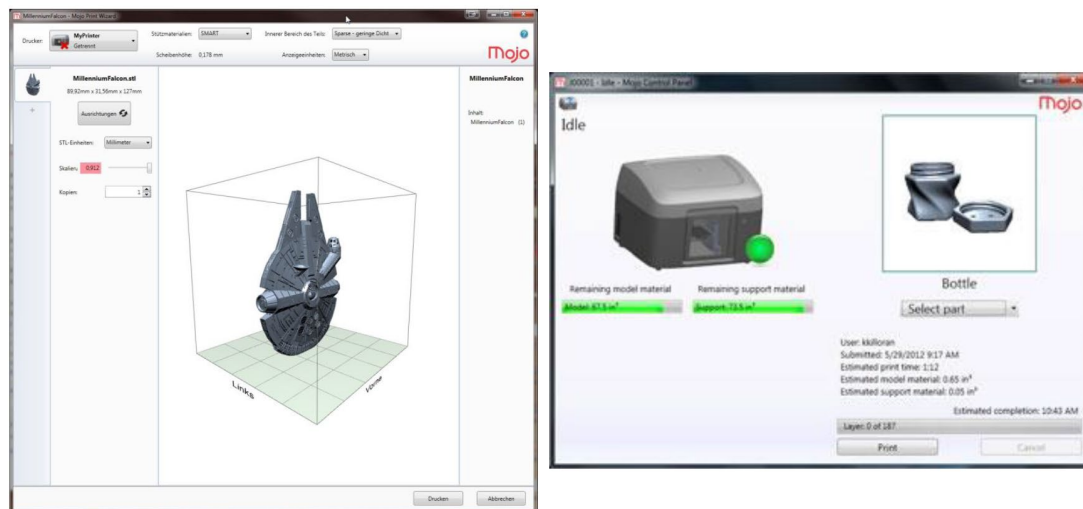
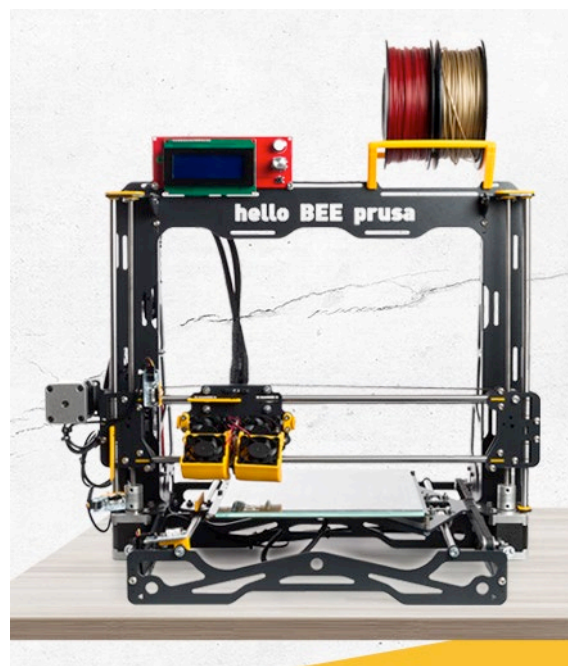


Figure 14 - Left Print Wizard software and Right Mojo Panel Control.

In the Mojo printer, the models were printed in ABS (Acrylonitrile butadiene styrene) material which is a thermoplastic polymer used for several engineering applications. It has good mechanical properties such as toughness and resistance to impact. According to Stratasys, 3D printed parts in this material are mechanically strong and stable over time. Because ABSplus works with soluble support materials, support removal is hands-free, and complex shapes and deep cavities require no extra effort. The

type of support material is SR-30 Soluble which is a synthetic thermoplastic polymer used in Stratasys equipment for support structures that is dissolved in a specific solvent solution.

The other FDM printer considered in this research was the Hello Bee Prusa printer (Figure 15) which is available in the Robotics Electrical Engineering Department at the School for Technology and Management from the Polytechnic Institute of Leiria. The Hello Bee Prusa printer has no chamber allowing the temperature of the environment to influence the outcome of the printing process because it is difficult to control the temperature of the environment and the air currents, resulting in warpage and distortion of the printed parts. This system allows to change detailed processing conditions, such as material type, layer height, deposition speed and material flow rate, even allowing to decide to add or not support structures during the building process. The maximum building size is 185 x 200 x 190 mm. In order to fabricate parts with the Prusa system, two softwares are required. The Slic3r is a G-code generating software that imports the STL model and processes the CAD data while Pronterface reads and processes the SLI file for printing controlling the machine during the building process. In Slic3r it is possible to change the orientation, define the materials and modify processing parameters (Figure 16).



*Figure 15 - Hello Bee Prusa (2015).*

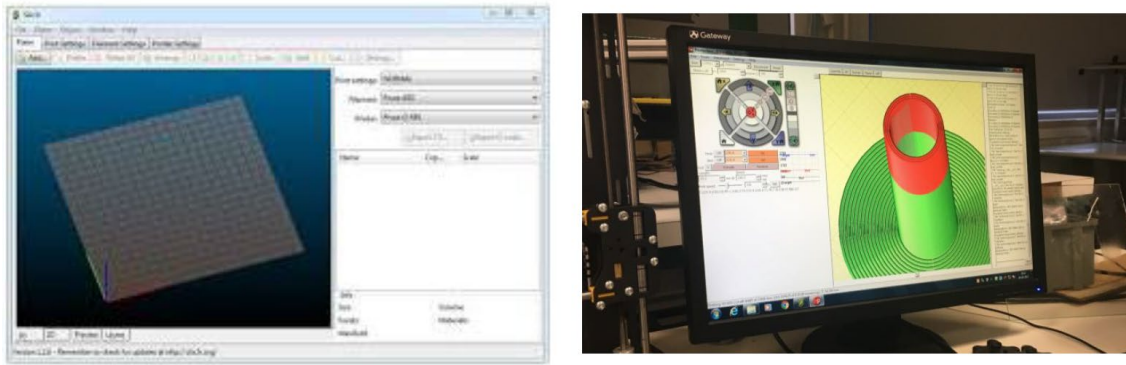


Figure 16 - On the left the Slic3r software while on the right the Pronterface software.

The Hello Bee Prusa uses ABS material to print the physical models but with this system, it is possible to either print the support material in ABS or PLA, which is a biodegradable material derived from renewable sources. In this case, the PLA material was selected for support material.

### 3.3. 3D Scanning System for Geometric Evaluation

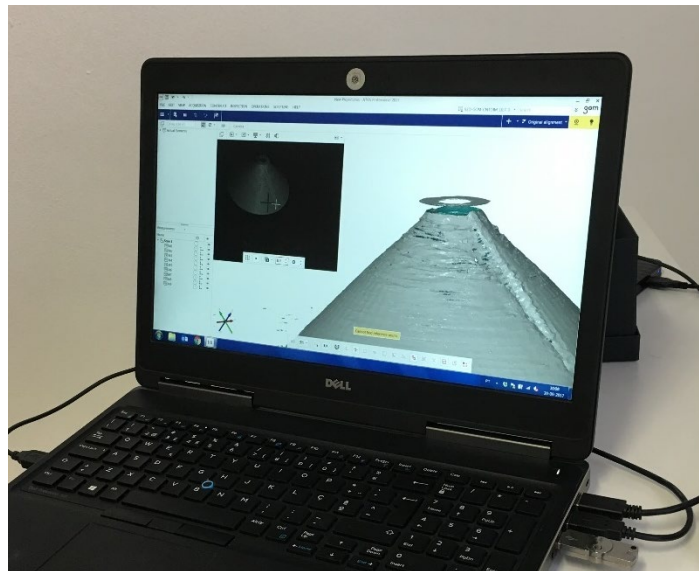
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In order to evaluate the geometric accuracy of the printed models, the models have to be scanned and converted into digital data. After obtaining the digital models of the physical models, it is then possible to compare the digital data to the original CAD model that was used initially for the building process. In order to perform this comparison, a 3D scanning system and a geometric evaluation software was used and provided by company S3D that showed their availability in collaborating in this research.



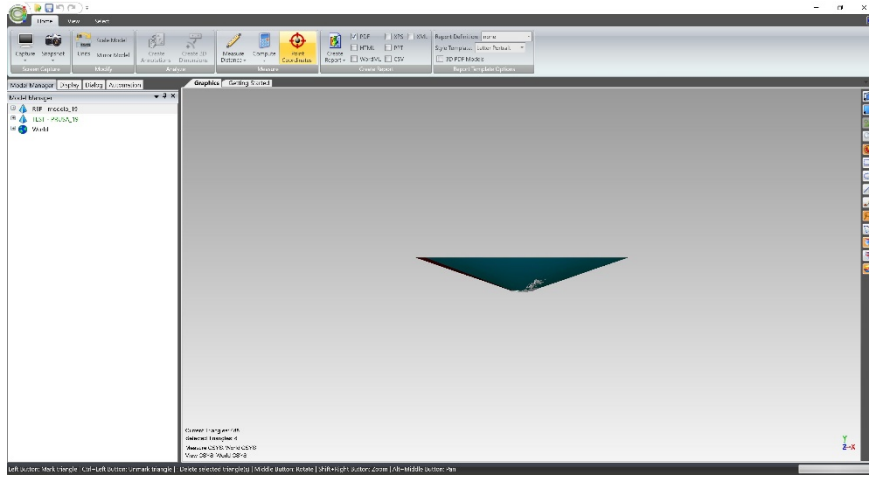
Figure 17 - ATOS Core 135.

The 3D scanning system that was used was the ATOS Core 135 (Figure 17) that is a structured blue light 3D scanning system with a maximum resolution of 0.05 mm. In order to ensure a good scanning performance, this device is composed by two cameras and a projector. This equipment uses a sensor that reproduces the part by measuring the model. The part is placed onto a whirling platform, that in this case was manually manipulated, even though, it could have been set with automatic settings. Since the models were fragile, for the safety of the models, the manual manipulation of the platform was selected. The GOM scanning software, represented in Figure 18, is where the scanned model is converted into digital data. The sensors work in a 170mm distance and it's measuring area is 135 x 100 mm.



*Figure 18 - GOM Scanning Software for the ATOS Hardware.*

The software used to compare the CAD model and the printed model was a demo version of Geomagic Qualify as represented on Figure 19.



*Figure 19 - Geomagic Qualify 2012 software.*

This software analyzes measurements from the digital data of a physical object with the CAD reference model and instantly draws a comparison between both models, which now includes support for both probe and scanner measurement workflows and multiple devices (“Geomagic Releases Geomagic Qualify 2012” n.d.).

## 4. Results and discussions

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Printing errors in 3D printing are common and might compromise the end result. The main reasons for them to occur are under-extrusion (the extruder does not print enough material), over extrusion (the printer extrudes too much material), overheating, layer separation, grinding filament, clogged extruder, vibrations, inconsistent extrusion, poor bridging and geometric inaccuracy. Such 3D printing errors are assessed by comparing the CAD models with the digital data from the 3D scan of the printed objects. In this chapter, the geometric accuracy of two distinct 3D printer models is evaluated in function of the slopping wall angle and being fabricated without support structures. The support structures were only fabricated when the system software didn't allow to fabricate the part without support structures. The main difference among all objects is the angle ( $\alpha$ ) between printed surface and the ground plane as illustrated in Figure 12.

The considered 3D geometries follow several design guidelines, such as the dimensions, orientation and shape. Both printers have a limited building platform which constrained the dimensions of the geometry of the printed object, namely the height. For example, if the models are printed upside down, i.e., inverted cone, the support material would be inside the printed geometry which would make its removal difficult. Moreover, printing a cone reduces the contact area of the object with the building platform, which might result in less damage to the object, and consequently might mitigate the printing error. Finally, the shape changes accordingly to an angle " $\alpha$ ". This allows to assess whether different slopping walls and their support structures have a significant impact on the final part. For easy reading, each study object is assigned to a letter as represented in Table 9. Therefore, the experimental procedure was carried out, for all objects and for both printers, as follows:

- Design of the 3D CAD models as illustrated in Figure 12 and Table 9;
- Printing of the physical models;
- Digital scanning of the printed models;
- Geometric evaluation of the physical models based on the comparison of the 3D scanned model with its original CAD design, in order to assess the printing error.

Table 9 - Assigned letter for each printing angle.

Model	Printing angle [°]
A	10°
B	30°
C	50°
D	70°
E	90°

In order to provide a guide to the designers, the required time to print each model in both printers and the total of layers needed is given in Table 10. This data has been estimated by the software of each printer. It was expected that the increasing of the total number of layers would also increase the printing time, regardless of angle “ $\alpha$ ”. This is not necessarily true. For example, considering the Prusa printer, a total number of layers of 156 for an angle  $\alpha = 30^\circ$ , lead to an estimated printing time of approximately 36 minutes. However, for the same printer, and considering only 33 layers for an angle  $\alpha = 10^\circ$ , the estimated time is over 2 hours. This means that not only the total number of layers has a significant impact on the printing time, but also the considered printing angle has an important role during production. Table 10 could be helpful tool to find the best compromise between printing angle and number of layers in order to reduce the printing time during production. It is possible to observe that as smaller the angle of the model, bigger distances will be covered by the extrusion head. It is not possible with the data collected in this work but will be interesting to analyse, concerning estimated time, the relationship between the distance travelled by the extrusion head and the number of layers deposited.

Table 10 - Time and number of layers for each model, considering both printers.

Stratasys - Mojo			Hello Bee - Prusa		
$\alpha$	Estimated time (s)	Estimated total of layers	$\alpha$	Estimated time (s)	Estimated total of layers
10°	2h55min	66	10°	2h17min21s	33
19°	4h24min	122	19°	21min34s	92
30°	4h57min	178	30°	36min15s	156
43°	55min	234	43°	13min07s	133
50°	1h10min	291	50°	15min54s	167
70°	46min	291	70°	8min40s	167
90°	23min	291	90°	3min15s	150



## **4.1. Production of the physical models**

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In order to proceed with the printing of each 3D object as illustrated in Figure 12, the CAD file for each model was imported into the printer software. In this context, each CAD model was printed twice, once printed using the Mojo (“Mojo Desktop 3D Printer for Professional Quality Models | Stratasy’s” n.d.) and another using the Prusa (“HELLO BEE PRUSA,” n.d.) for the quality comparative study assessment.

### **4.1.1. Production with the Mojo Printer**

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After a proper system calibration, the models A-E were printed with the Mojo printer. In particular for this printer, its software automatically assesses whether the considered model requires support structure or not. Additionally, its software also indicates and provides the necessary amount of support material for each model, in cm<sup>3</sup>. All the 3D CAD models were printed using this tool as illustrated in Figure 20. In Figure 20 it is possible to verify which of the models that required or not support structures during production. For example, it is clearly seen that, only models A and B needed support structures. On the other hand, models C to E did not require the use of support structures. As mentioned before, the decision of either object requiring or not the need for support structures was assessed by the printer software and proved upon the printing of each object.

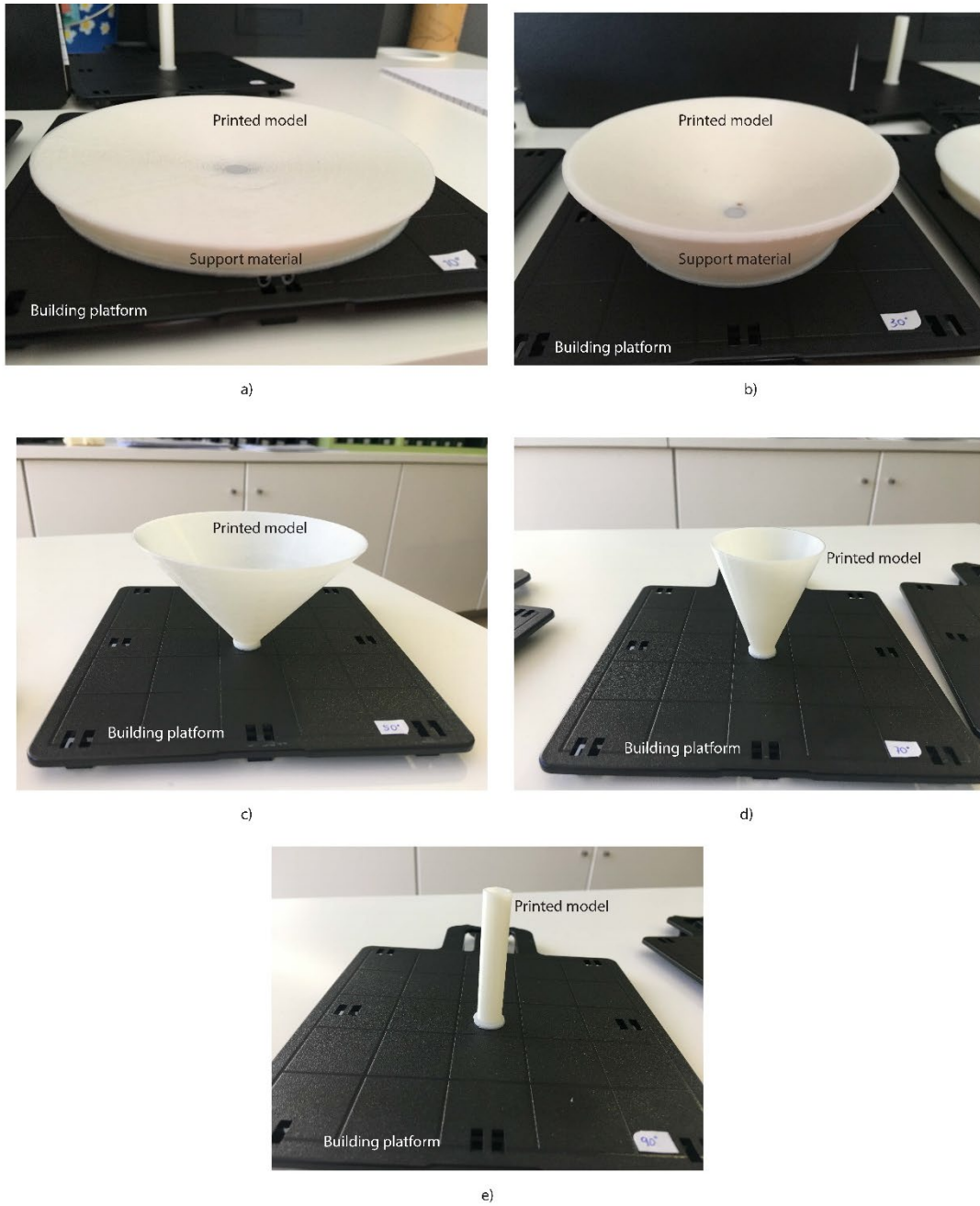


Figure 20 - Models Printed by Mojo: a)  $\alpha=10^\circ$ , b)  $\alpha=30^\circ$ , c)  $\alpha=50^\circ$ , d)  $\alpha=70^\circ$ , e)  $\alpha=90^\circ$ .

Additionally, in order to assess the exact angle that does not require support structure, a trial and error experiment was performed between the models B and C. First, a reference model with  $\alpha = 40^\circ$  was established, since the printing software indicates that for this angle support structure is still required. Consequently,  $\alpha$  was incremented degree a degree and simulated the printing of the model verifying and angle for which no support structures is required. The results of this study are summarised in Table 11. In this table

it can be seen that for  $\alpha \geq 43^\circ$  it is no longer required the need for structure. The model with angle  $\alpha = 43^\circ$  is illustrated in Figure 21.

*Table 11 - Support material evaluation for different angles.*

<b>Model</b>	<b><math>\alpha</math></b>	<b>Need support structure</b>
B	30°	Yes
	40°	Yes
	41°	Yes
	42°	Yes
	<b>43°</b>	<b>No</b>
C	50°	No



*Figure 21 - Printed model with  $\alpha=43^\circ$  by Mojo.*

#### 4.1.2. Hello Bee Prusa printer

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Similarly, to the procedure carried out with the Mojo printer, all CAD models from A to E were considered and printed with the Prusa printer. Before the printing the models, the Prusa has to be properly calibrated using its software. The printed objects are illustrated in Figure 22. It is possible to observe that only model A needed support structure. On the other hand, models B to E did not require support structures. In each case, similar to the previous case, the existence of supports structures was determined by the printer's software. However, the user can disable this software feature and choose not to consider support structures. Moreover, the model with  $\alpha=43^\circ$  determined in Mojo software was also printed in Prusa for comparative tests, model illustrated in Figure 23.

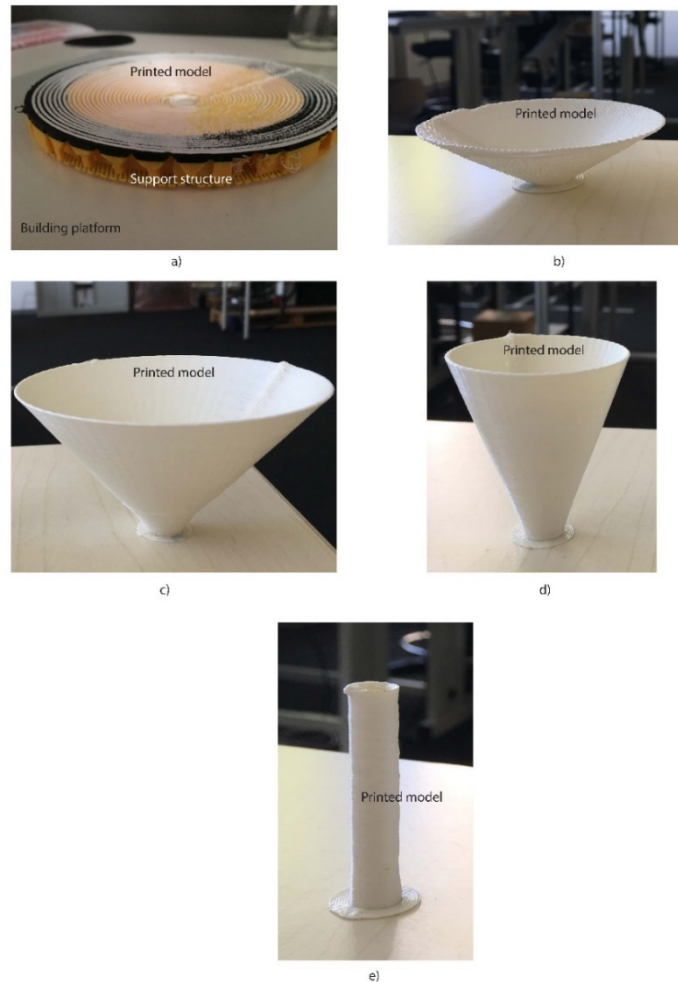


Figure 22 - Models Printed by Prusa: a)  $\alpha=10^\circ$ , b)  $\alpha=30^\circ$ , c)  $\alpha=50^\circ$ , d)  $\alpha=70^\circ$ , e)  $\alpha=90^\circ$ .

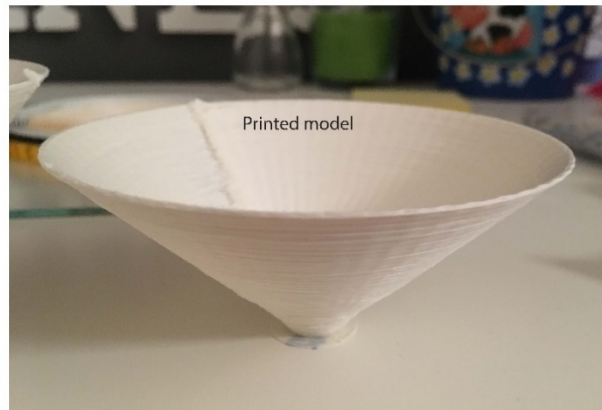
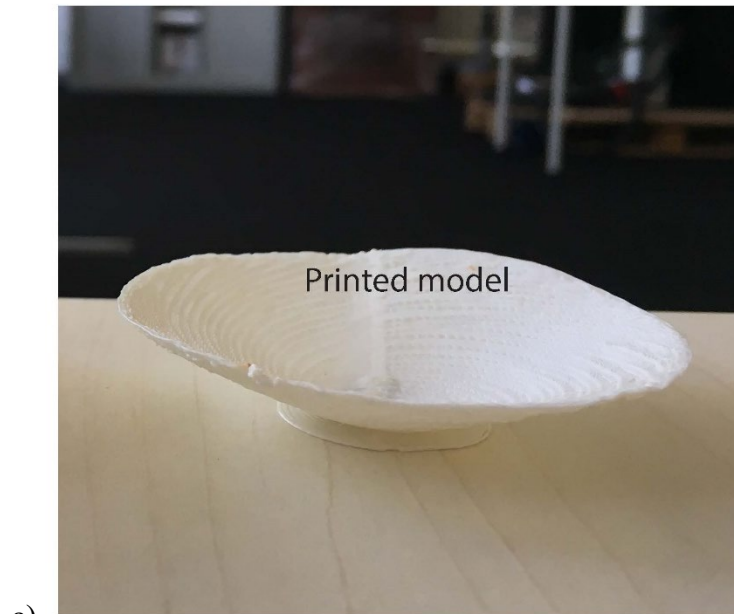


Figure 23 - Model with  $\alpha=43^\circ$  printed in Prusa.

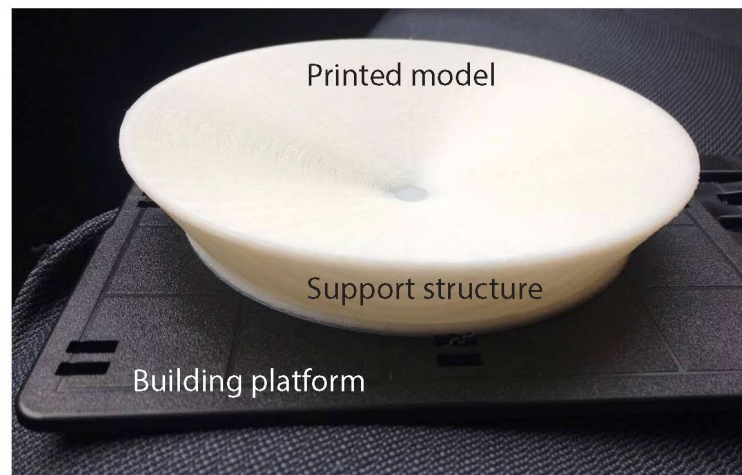
Similar to the previous case, simulating the printing of models with different sloping wall angles was also carried out in order to determine for which no support structures were required. Since model A needed support structure and the model B did not, as verified in Figure 22, several models with angles between both angles were simulated in the software as illustrated in Table 11. The model with  $\alpha=20^\circ$  was established as a starting point, since this object did not need support structures. Then the angle  $\alpha$  decreased degree by degree until the printed model requires support structures. It is verified that models with an angle of  $\alpha \geq 19^\circ$  do not require support structures. For a comparative study with the model with angle  $\alpha=19^\circ$ , the same model was printed using the Mojo printer. In Figure 24 it is possible to observe that for angle, the printed object requires support structures when considering the Mojo printer. This means that not only  $\alpha$  has an important role in the need for support structures, but also the printer technology has a significant impact in this feature.

Table 12 - Support material evaluation for different angles.

Model	$\alpha$	Need support structure
A	$10^\circ$	Yes
	$11^\circ$	Yes
	$12^\circ$	Yes
	...	Yes
	$19^\circ$	No
	$20^\circ$	No
B	$30^\circ$	No



a)



b)

*Figure 24 - Model  $\alpha=19^\circ$  for a) Prusa b) Mojo.*

In the previous angular analysis for both printers, some problems were detected while printing some of the CAD models, particularly with the Prusa printer. As the angle of the models decreases, the percentage of adhesion between layers also decreases. This is explained by the weight of the considered filament, which is not enough to ensure a relatively good printing. This happened in both model B and the established model with an angle of  $\alpha=19^\circ$ . Figure 25 and Figure 26 illustrates the damaged physical models caused by this phenomena. Therefore, in order to prevent this to happen, the height of both models were modified. In this case, the height was reduce to 20 mm in model B (the models was designed with 30mm) and in 15 mm model with angle of  $\alpha=19^\circ$  (the models was designed with 20mm).



*Figure 25 - Damaged model with  $\alpha=19^\circ$  printed in Prusa.*



*Figure 26 - Printing process of model B.*

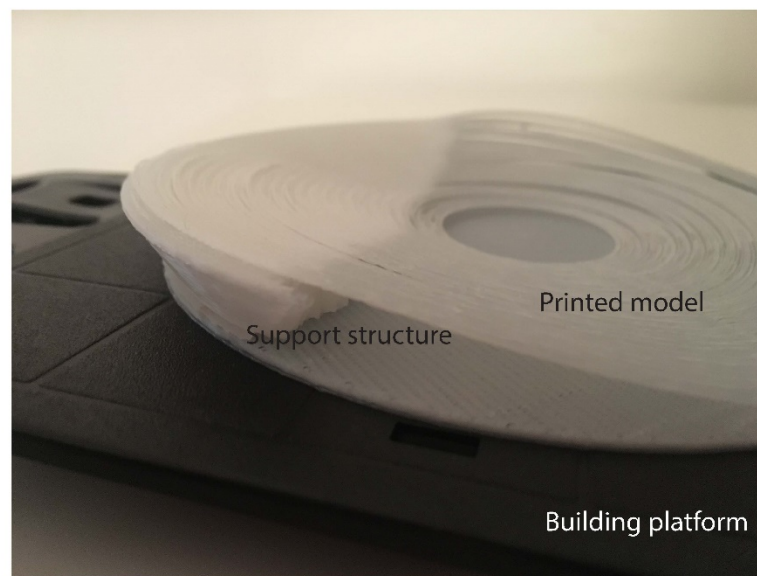
### **4.1.3. Support material removal**

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The removal of support structures is required for the models with angles of  $\alpha = 10^\circ$  and  $\alpha = 10^\circ/19^\circ/30^\circ$ , for the Prusa and Mojo printers, respectively. The process of support structure removal is different between both printers.

In the case of the Mojo models, they were dissolved in a special solvent solution that only dissolves the support structure material. The support material removal in model B ( $\alpha = 30^\circ$ ) and the model with angle  $\alpha = 19^\circ$  went perfectly normal removing completely

the support material leaving only the physical model intact. On the other hand, while removing the support material on model A ( $\alpha = 10^\circ$ ) the slopping walls were loose as illustrated in Figure 27, in other words, the layers weren't properly attached. If the support material was completely removed the model would've collapsed. This indicates that printing such object with that angle is not possible in the Mojo printer, unless by increasing the thickness of the slopping wall and increasing layer adhesion guaranteeing geometrical stability.



*Figure 27 - Model A printed in Mojo.*

Considering the Prusa models, the process of support structure removal is done manually. For example, it was impossible to remove the support structure from the glass platform in model A, consequently remaining attached to the building platform with the support material as illustrated in Figure 28. Clearly, if the support structure was eventually removed, the model would've collapsed because the layer is standing on the support material and not part material itself. When there is no layer below to print on, support is added. This allows features to be printed that would otherwise not be possible. While the filament is extruded, it needs to bond and solidify with the previously printed layers to form a solid, cohesive part (Redwood, Schöffner, and Garret 2017). But when the support is removed from below of the part's layer and it does not have sufficient layer adhesion with the other part's layers below and above, the model collapses. Therefore, both models A were excluded from the scanning process as illustrated in Table 13.



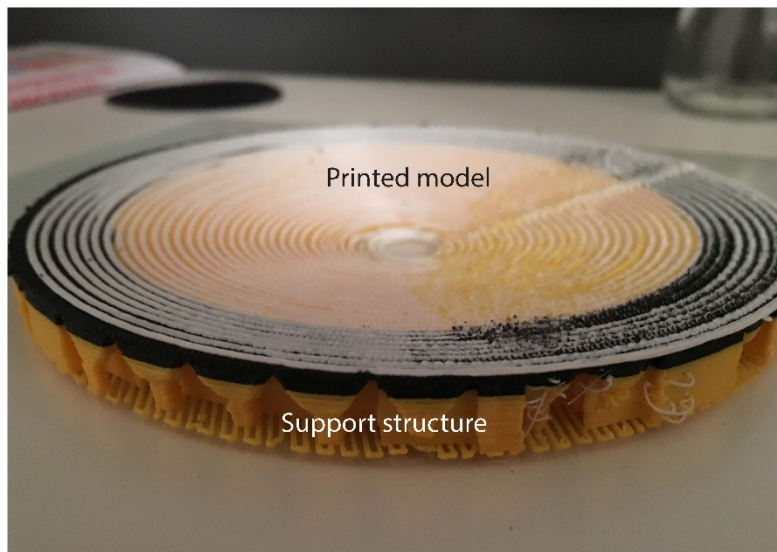


Figure 28 - Model A printed in Prusa.

Table 13 - Applicable models for scanning process.

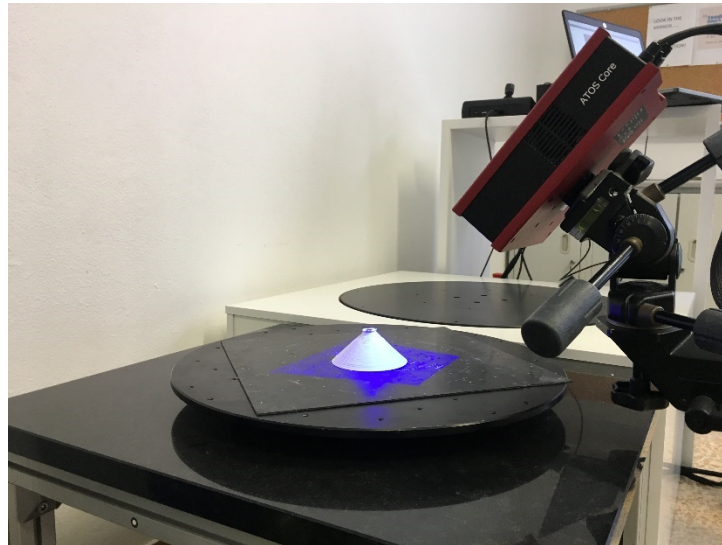
Model	$\alpha$	Ready for scan	
		MOJO	PRUSA
A	10°	No	No
-	19°	Yes	Yes
B	30°	Yes	Yes
-	43°	Yes	Yes
C	50	Yes	Yes
D	70°	Yes	Yes
E	90°	Yes	Yes

## 4.2. Digital Scanning of the Physical Models

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In order to assess the geometric 3D printing error of the models printed by both printers, the selected models from Table 13 were scanned and compared to their respective original CAD file. For this analysis a ATOS Core 135 3D scanner device was used. This specific scanner was selected by the S3D company as the best option due to its capability in scanning relatively small components and details as described previously (“ATOS Core | GOM” n.d.). The scanning process was carried out as follows: the object being scanned is first placed in the middle of the scanning platform and then the scanning

beam was pointed directly to the physical model in order to promote an alignment calibration. This step is illustrated in Figure 29.



*Figure 29 - Scanning process of the models.*

After conducting an initial scan on one of the Mojo's models, it was been verified that the scanning performance was significantly affected by the printing material. The ABS used for Mojo printer was too gleaming for the scan to fully detect the physical model. In order to overcome this problem, before performing the scans, the physical models were sprayed and coated with a specific powder, namely MR® 2000 Anti-Reflex L, to improve the scanning performance for all models. The coating process is illustrated in Figure 30. From Figure 31, it is possible to observe the difference of the scanning result of the model without coating as shown in Figure 31.a), which has a significant less quality of data, in comparison to the coated model as shown in Figure 31.b). The digital scanning of the model shown in Figure 31.a) presents an enormous lack of digital data (white regions) on the surface of the model which corresponds to uncaptured data from the physical model.

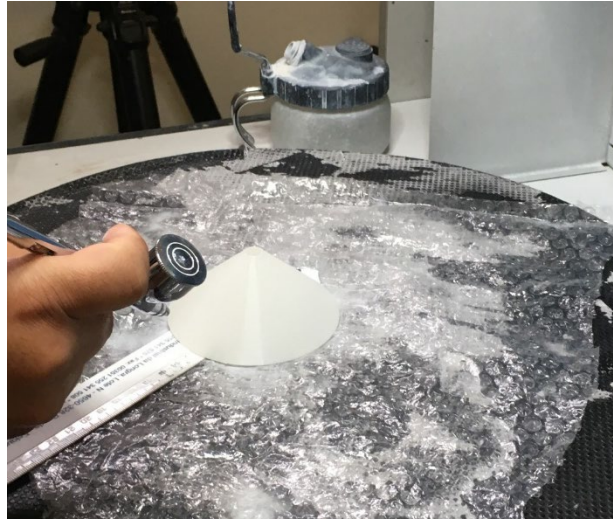


Figure 30 - Coating process.

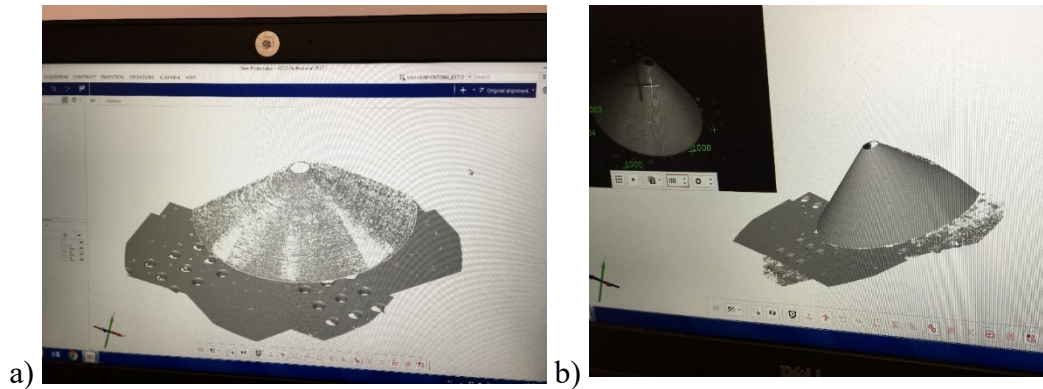


Figure 31 - Scanning performance assessment considering  $\alpha=43^\circ$  and the Mojo printer: a) without powder, b) with powder.

After performing all the digital scans of the physical models, with the aid of the ATOS Professional software that controls the ATOS scanner, the digital data was cleaned in order to remove unwanted data such as the scanning platform and then a STL file was generated for the next step which consists on the geometric evaluation.

### 4.3. Geometric Evaluation of the physical models

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After creating the STL files of each physical model, the next step consists in the geometric evaluation, determination of the printer error, between the scanned data from the physical models and the original CAD data that was used for the fabrication of the physical models on the printers. This process was performed with a demo version of Geomagic Qualify software. This software overlaps the 3D scanned model with the original CAD file, as illustrated in Figure 32, which allows the user to perform a 3D

geometric evaluation by comparing both digital models and determining the printer error. Figure 32 illustrates a colour plot with negative and positive values between the reference model (CAD model) and testing model (scanned model). The negative values corresponds to digital points from the digital point cloud that are inside the reference model and the positive values corresponds to digital points that are outside the reference model. For instance, the outer seam that results from the layer changing of the 3D printing process is an outward defect in comparison to the CAD model, thus resulting in positive values, as illustrated in yellow in the colour plot. This figure also illustrates that the scanned model has a very good agreement to the CAD model, as illustrated in green in the colour plot.

After analysing all the 3D geometric evaluations of all the models, the results turned to be inconclusive. Therefore, a 2D geometric evaluation was performed. Similar to the previous case, both digital models were imported, then a set of several planes with a spacing of 5mm was defined, and then the 2D geometric evaluation was performed on these planes. In this case, the results are evaluated in sections and in function of height. An example of 2D geometric evaluation is given in Figure 33 for the Mojo model with a sloping angle of  $\alpha = 43^\circ$  at a height of 5 mm. From Figure 33, it is possible to observe that the printed object presents in some areas some excess of material and in other areas a lot of missing material, thus demonstrating that some flaws occurred during the printing process. Figure 33 also illustrates that only the exterior boundary of the physical models was scanned. The points correspond to the digital scanned model and the two circular rings correspond to the CAD model, namely the exterior and interior of the CAD model.

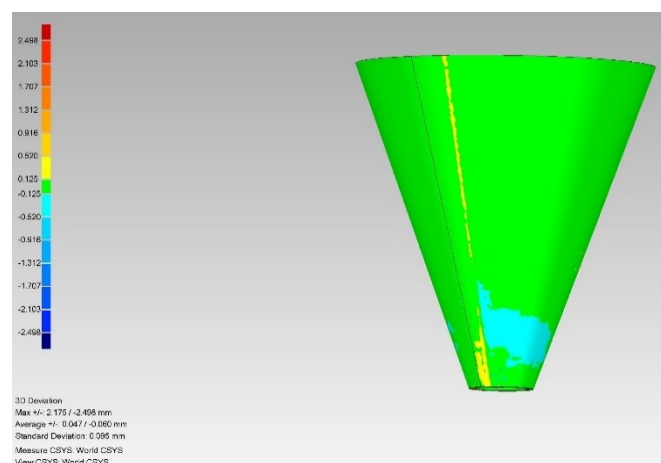


Figure 32 - Overlapping of the CAD file with its respective STL file for model D printed in the Mojo printer.

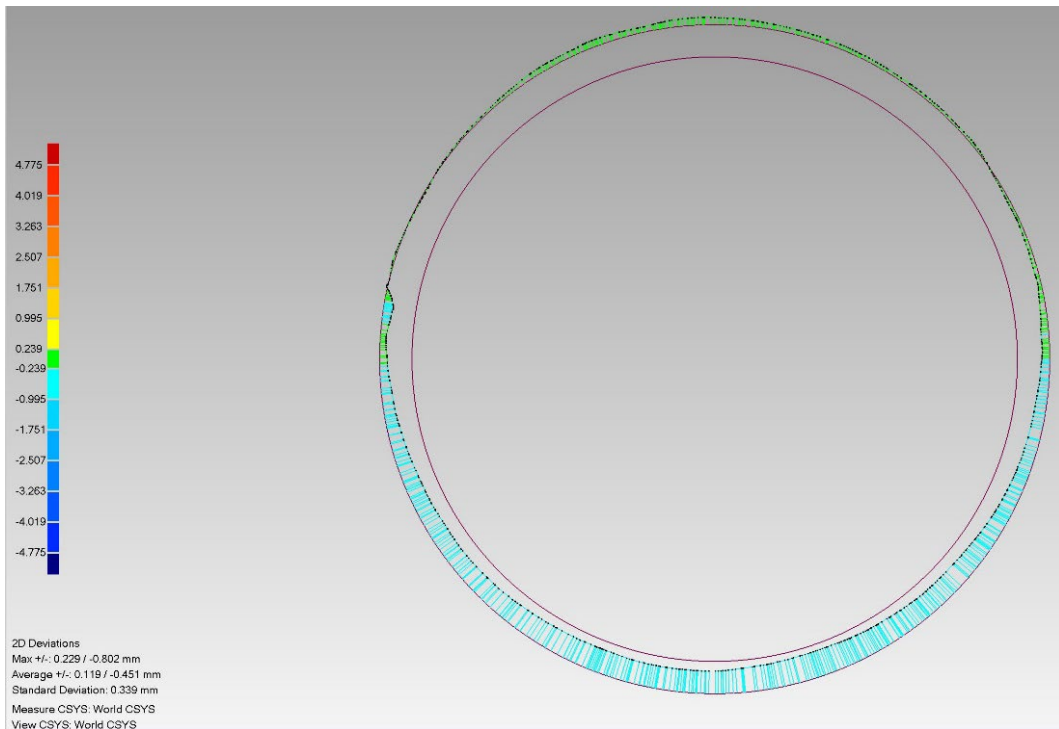


Figure 33 - Cutting section from the overlapping of the CAD file with its respective STL file for  $\alpha=43^\circ$  and height=5mm, printed in Mojo printer.

In order to proceed with an extensive analysis of the printing error versus printer manufacturer,  $\alpha$  and cutting section height, it was established the outer excess material, inner excess material and lack of material, as illustrated in Figure 34. Therefore, a scanned object can either have a positive or negative deviation from the reference CAD model, as mentioned before.

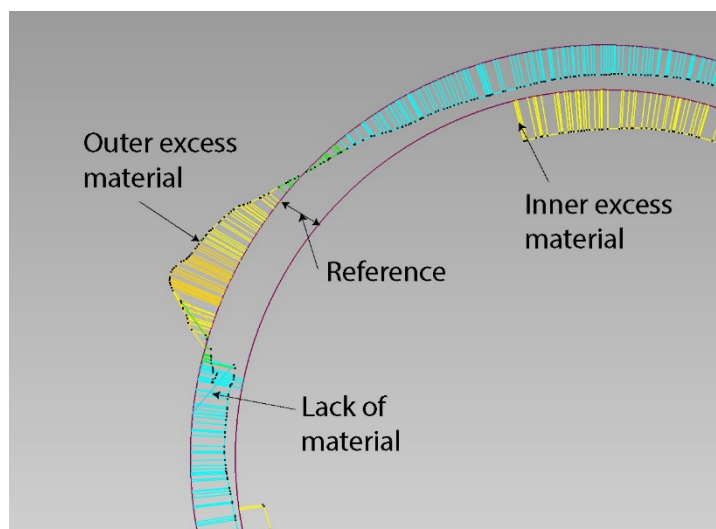


Figure 34 - Illustration of the printing flaws for model C from the Prusa printer at height=5mm.

Summary of the deviation results for all models in function of the height of the cutting section varying from 5 to 45 mm is given in Table 14 and Table 15, for both the Mojo and Prusa printers, respectively. Overall deviation refers to the mean value of the average excess material column values with the average lack of material column values. In both tables, the printed object with slopping wall angle of  $\alpha=19^\circ$  was not considered. The main reason is due to the fact that the printing object was so damaged that the software could not find any resemblance between the original CAD file with the scanned digital model, as illustrated in Figure 35. This only happened when considering the Prusa printer as the printed object wasn't printed successfully containing too many physical errors, for this reason it has been decided to remove it from the Mojo's summary results, as well.

Table 14 - Geomagic data from models printed in MOJO.

		ERROR						
		Maximum value		Average			Standard Deviation (mm)	
$\alpha$ (°)	Height (mm)	Excess material (mm)	Lack of material (mm)	Excess material (mm)	Lack of material (mm)	Overall (mm)		Average
30°	5	1.433	-1.325	0.21	-0.33	-0.027	0.331	0.329
	10	1.023	-1.346	0.223	-0.273		0.324	
	15	0.877	-1.447	0.23	-0.323		0.381	
	20	1.366	-1.377	0.231	-0.245		0.321	
	25	0.676	-1.458	0.214	-0.209		0.286	
43°	5	0.229	-0.802	0.119	-0.451	-0.144	0.339	0.319
	10	1.301	-1.243	0.124	-0.387		0.308	
	15	0.852	-0.694	0.123	-0.367		0.294	
	20	0.847	-0.724	0.131	-0.384		0.311	
	25	0.611	-0.737	0.115	-0.388		0.311	
	30	0.197	-0.782	0.128	-0.424		0.33	
	35	0.224	-0.872	0.099	-0.447		0.341	

Continuation of the previous table:

		ERROR						
		Maximum value		Average			Standard Deviation (mm)	
$\alpha$ (°)	Height (mm)	Excess material (mm)	Lack of material (mm)	Excess material (mm)	Lack of material (mm)	Overall (mm)		Average
50°	5	0.071	-0.114	0.042	-0.106	-0.001	0.085	0.057
	10	0.086	-0.101	0.045	-0.041		0.095	
	15	0.089	-0.13	0.036	-0.022		0.07	
	20	0.114	-0.122	0.033	-0.02		0.037	
	25	0.105	-0.14	0.033	-0.019		0.033	
	30	0.149	-0.128	0.034	-0.023		0.04	
	35	0.124	-0.135	0.035	-0.032		0.057	
	40	0.091	-0.118	0.031	-0.033		0.046	
	45	0.129	-0.145	0.033	-0.05		0.053	
70°	5	0.513	-0.9	0.153	-0.116	0.005	0.105	0.050
	10	0.167	-0.249	0.0822	-0.112		0.057	
	15	0.105	-0.188	0.03	-0.044		0.042	
	20	0.183	-0.263	0.05	-0.038		0.051	
	25	0.145	-0.063	0.05	-0.027		0.045	
	30	0.202	-0.065	0.045	-0.022		0.043	
	35	0.665	-0.07	0.035	-0.017		0.04	
	40	0.183	-0.038	0.025	-0.012		0.028	
	45	0.212	-0.092	0.03	-0.02		0.035	
90°	5	0.071	-0.114	0.032	-0.067	-0.012	0.035	0.039
	10	1.348	-0.101	0.034	-0.064		0.036	
	15	1.333	-0.13	0.034	-0.066		0.038	
	20	0.247	-0.122	0.048	-0.06		0.037	
	25	0.217	-0.14	0.041	-0.063		0.041	
	30	0.274	-0.128	0.044	-0.061		0.041	
	35	1.254	-0.135	0.038	-0.066		0.042	
	40	0.139	-0.118	0.04	-0.069		0.038	
	45	0.939	-0.145	0.061	-0.08		0.045	

Table 15 - Geomagic data from models printed in PRUSA.

		ERROR						
		Maximum value		Average			Standard Deviation (mm)	
$\alpha$ (°)	Heights (mm)	Excess material (mm)	Lack of material (mm)	Excess material (mm)	Lack of material (mm)	Overall (mm)		Average
30°	5	1.436	-1.436	0.243	-0.224	-0.131	0.269	0.372
	10	1.115	-1.115	0.208	-0.485		0.337	
	15	1.223	-1.223	0.354	-0.879		0.511	
43°	5	1.354	-1.354	0.925	-0.513	-0.026	0.592	0.369
	10	1.304	-1.304	0.417	-0.461		0.419	
	15	0.955	-0.955	0.23	-0.492		0.441	
	20	1.256	-1.256	0.231	-0.397		0.406	
	25	0.567	-0.567	0.204	-0.295		0.362	
	30	0.355	-0.355	0.087	-0.159		0.156	
	35	0.4	-0.4	0.081	-0.219		0.204	
50°	5	1.279	-1.399	0.616	-0.483	-0.029	0.586	0.294
	10	1.402	-1.518	0.509	-0.655		0.491	
	15	0.678	-1.516	0.164	-0.537		0.464	
	20	1.095	-1.409	0.195	-0.347		0.374	
	25	0.7	-1.427	0.123	-0.16		0.194	
	30	1.178	-1.135	0.143	-0.113		0.172	
	35	0.603	-1.079	0.077	-0.087		0.121	
	40	0.465	-0.927	0.085	-0.069		0.118	
	45	0.553	-1.095	0.131	-0.106		0.13	
70°	5	0.943	-0.341	0.261	-0.339	-0.147	0.322	0.341
	10	0.945	-0.332	0.353	-0.383		0.277	
	15	0.951	-0.339	0	-0.405		0.278	
	20	0.951	-0.342	0.07	-0.478		0.345	
	25	0.943	-0.342	0.106	-0.487		0.366	
	30	0.948	-0.34	0.134	-0.475		0.362	
	35	0.946	-0.341	0.13	-0.475		0.367	
	40	0.946	-0.341	0.156	-0.478		0.38	
	45	0.95	-0.34	0.142	-0.472		0.368	



Continuation of the previous table:

		ERROR						
		Maximum value		Average			Standard Deviation (mm)	
$\alpha$ (°)	Heights (mm)	Excess material (mm)	Lack of material (mm)	Excess material (mm)	Lack of material (mm)	Overall (mm)		Average
90°	5	0.34	-0.341	0.22	-0.154	0.0000 6	0.182	0.166
	10	0.307	-0.332	0.231	-0.176		0.211	
	15	0.299	-0.339	0.197	-0.16		0.19	
	20	0.25	-0.342	0.129	-0.18		0.145	
	25	0.333	-0.342	0.199	-0.19		0.181	
	30	0.325	-0.34	0.143	-0.155		0.14	
	35	0.202	-0.341	0.093	-0.129		0.122	
	40	0.271	-0.341	0.156	-0.143		0.174	
	45	0.166	-0.34	0.085	-0.167		0.147	

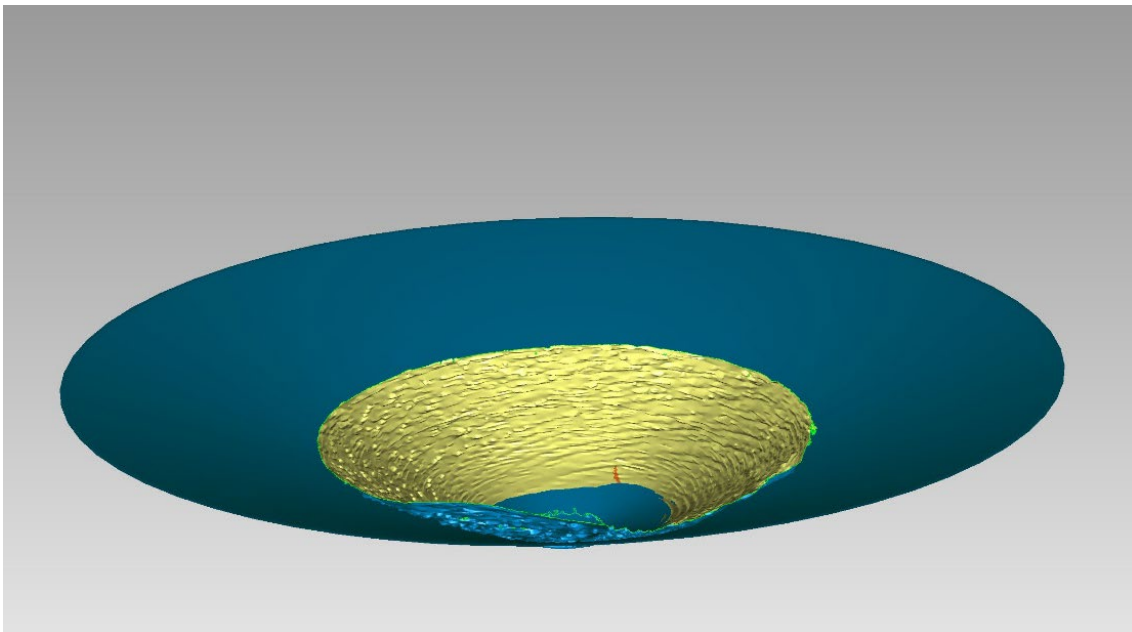
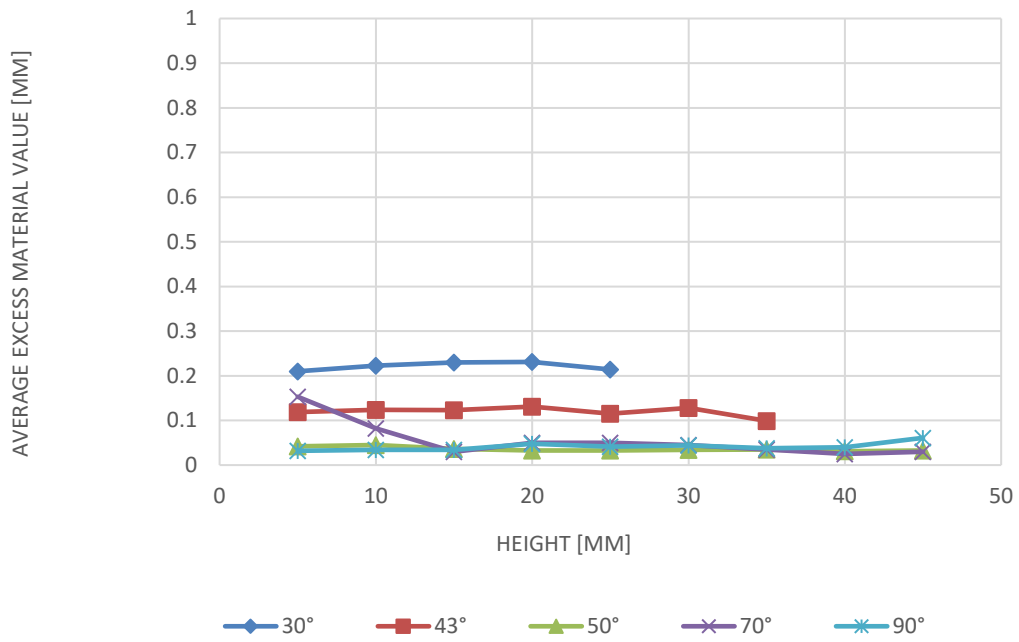


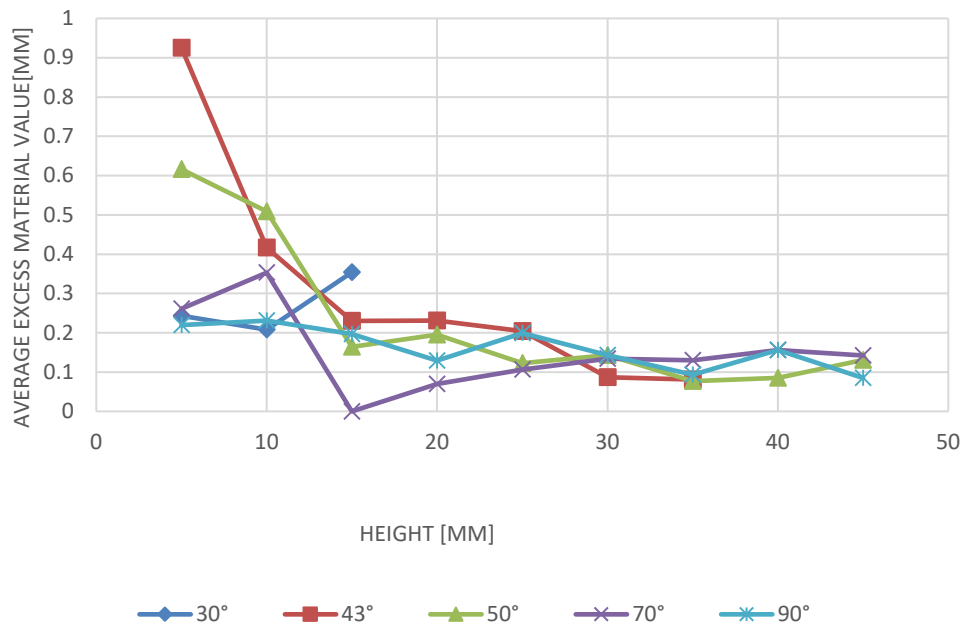
Figure 35 - Overlapping of the scanned model with CAD file in Geomagic software.

In order to facilitate the understanding of the printing error in terms of  $\alpha$ , height and printer, the information represented in Table 14 and Table 15 have been plotted into 3 charts for each printer. These charts show the relation between the planes with  $\alpha$ , considering as metrics the average excess/lack material values and the overall deviation.

In this context, by comparing both Figure 36.a) and Figure 36.b), it is clearly seen that the average excess material value is less significant in the models printed in the Mojo printer, when comparing, under the same conditions, to the models printed using the Prusa printer. Moreover, it is also verified that the Mojo printer ensures almost the same excess material value regardless the section plane (height) for any given angle  $\alpha$ . In other words, the excess material value only changes with angle  $\alpha$ , demonstrating that the angle  $\alpha$  has an important impact on the 3D printers. A different behaviour in terms of excess material value in the models printed using Prusa is verified. This is, such printer malfunction is only significant for models with height  $< 15$  mm. In all these section planes below the threshold, the excess material reduces with the increasing of angle  $\alpha$ . For example, two section planes at height = 5mm for different angle  $\alpha$  values of  $90^\circ$  and  $43^\circ$ , the first one has much lower excess material value (0.22 mm) than the former (0.925 mm), demonstrating that the height of the slopping walls during construction has a significant influence on the dimensional accuracy of the final part. Similar results were obtained when assessing the lack of material value for different angle  $\alpha$  and height, for both printers. In the Mojo case, Figure 37.a), varying angle  $\alpha$  introduces an offset on the average lack of material value regardless of the section plane height. It is also noted that such offset is more significant for models with  $\alpha < 43^\circ$ . Under the same conditions, the Prusa models present higher values of lack of material when compared with the Mojo models. In this particular case, it is not possible to establish any relation between angle  $\alpha$  and section plane height for a performance metric indicator.

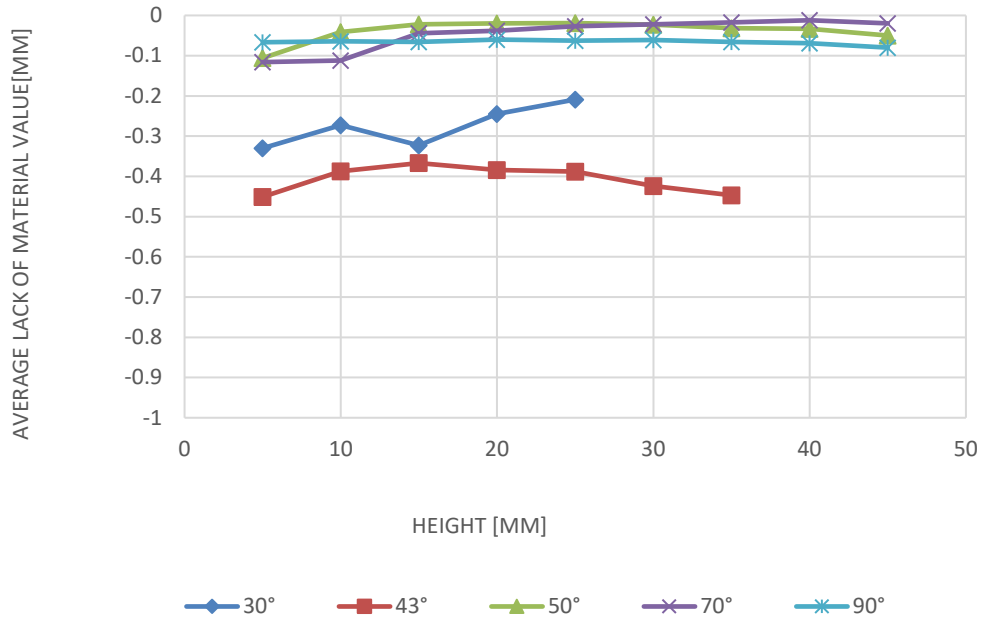


a)

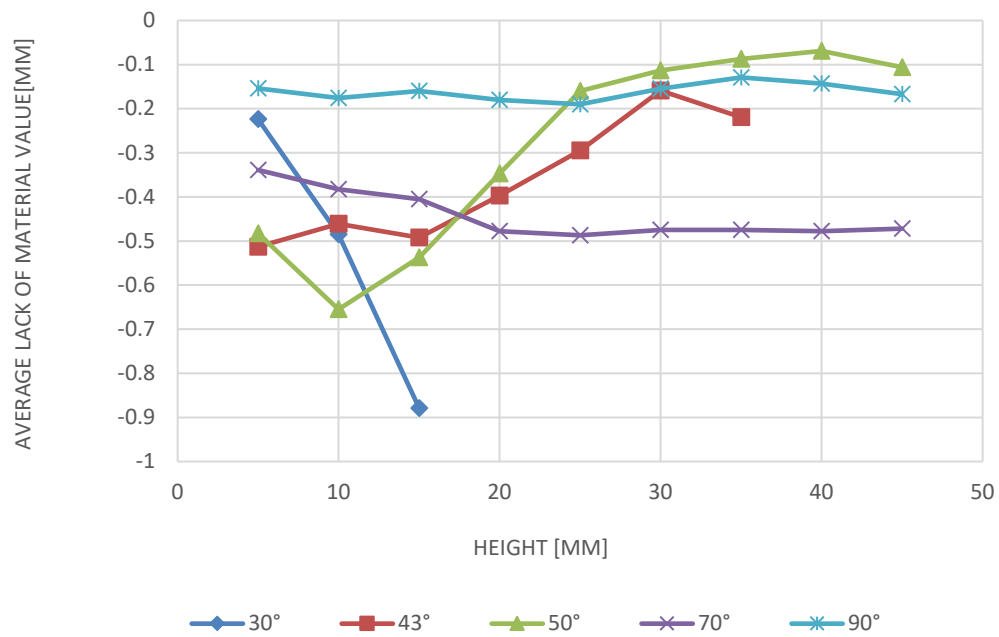


b)

Figure 36 - Average excess material error value versus  $\alpha$  and height, for models printed in: a) Mojo b) Prusa printers.



a)

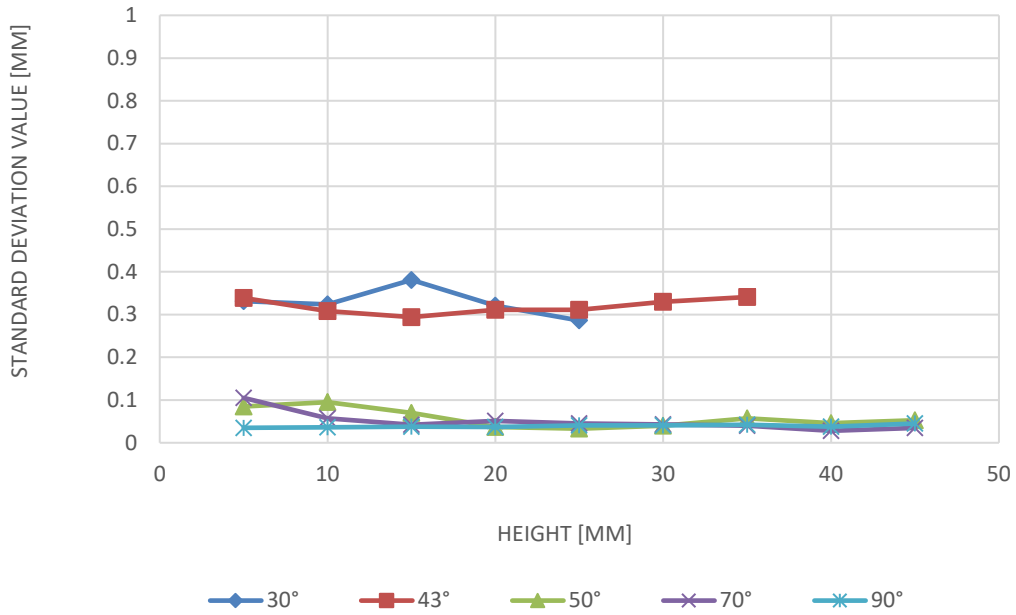


b)

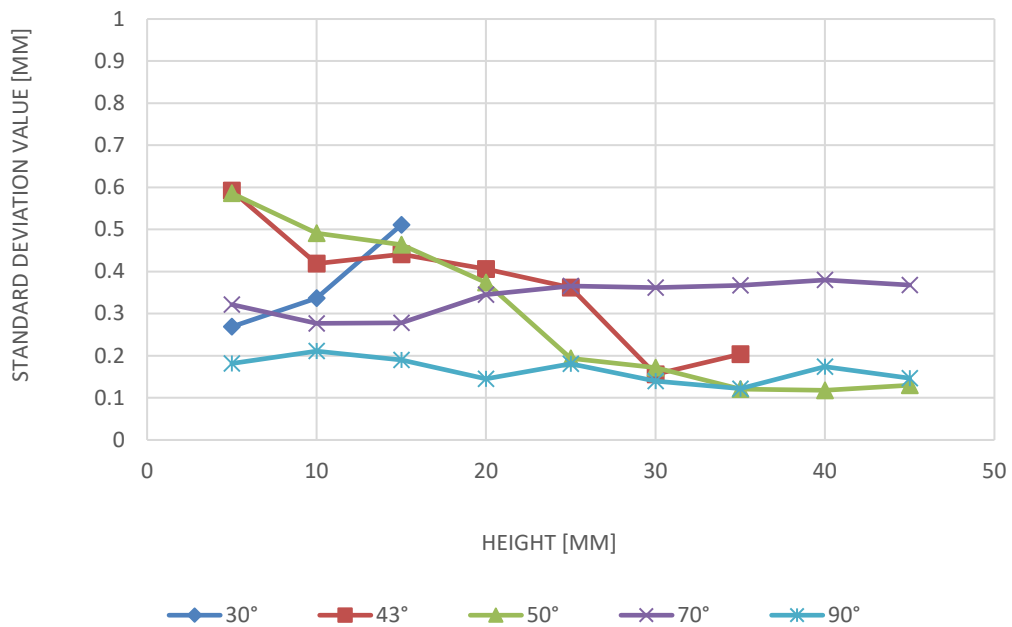
Figure 37 - Average lack of material error value versus  $\alpha$  and height, for models printed in: a) Mojo b) Prusa printers.

In this work, to quantify the amount of variation for both excess / lack of printing material in each model in function of sloping wall angle  $\alpha$ , the standard deviation is also considered. The obtained results for this 3D printing metric performance indicator are shown in Figure 38.a) and Figure 38.b), for the Mojo and Prusa printers, respectively. In summary, the standard deviation characteristic curve changes with angle  $\alpha$  and with the section plane height in the same way the excess / lack of material also do. Generally, the

standard deviation is higher for the models printed by the Prusa printer than the ones printed in the Mojo printer. In fact, this due the seam's layers imperfections of the Prusa's models, which are more bulkier when compared to the same models printed using the Mojo printer. This clearly seen by analysing Figure 39.



a)



b)

Figure 38 - Standard deviation value versus  $\alpha$  and height, for models printed in: a) Mojo b) Prusa printers.

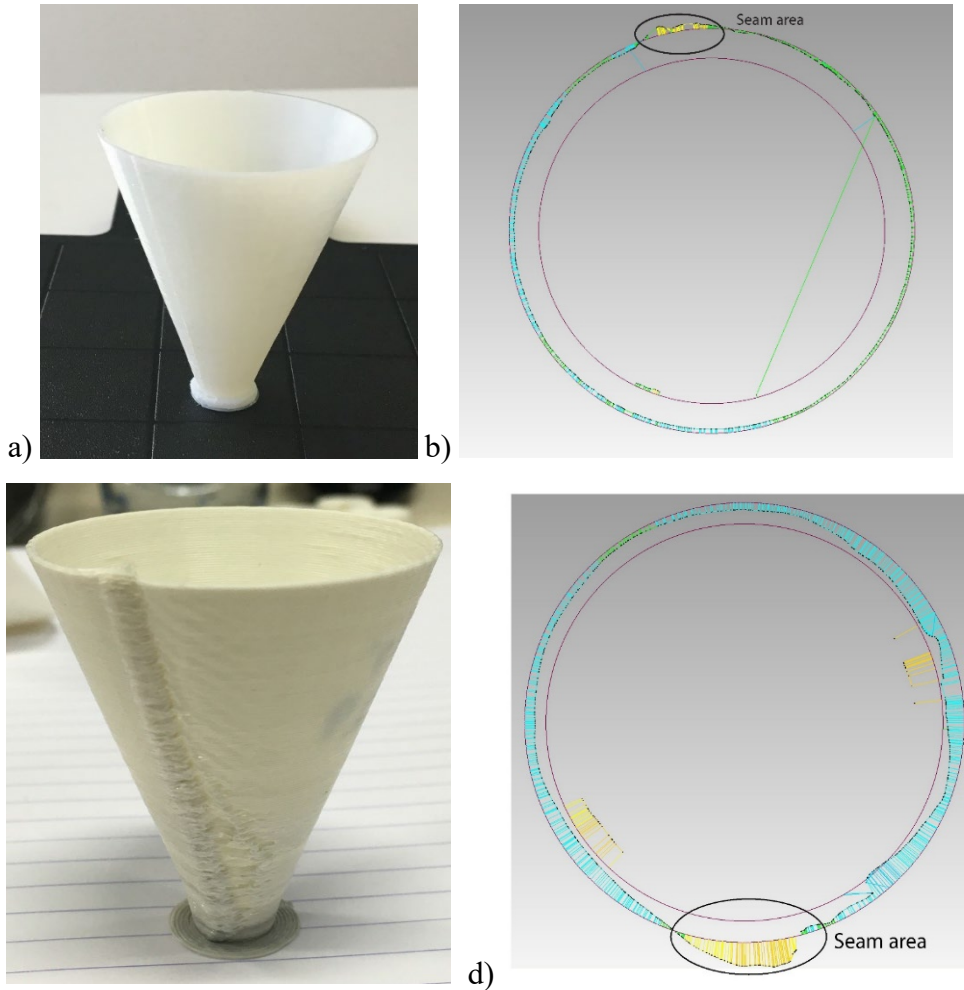


Figure 39 - Seam example of an  $\alpha=70^\circ$  model: a) 3D model using Mojo b) cutting section of Mojo model c) 3D model using Prusa d) cutting section of Prusa model.

The mathematical formulation of the average standard deviation curve versus angle  $\alpha$  has been obtained from a curve fitting from the data presented in Table 14 and Table 15, as represented in Figure 40. The average standard deviation equations for both the Mojo and Prusa printers are given in Equations (1) and (2), respectively:

$$SD(\alpha)_{Mojo} = 0.0001\alpha^2 - 0.0206\alpha + 0.8589 \quad (1)$$

$$SD(\alpha)_{Prusa} = -6 \times 10^{-5}\alpha^2 + 0.0047\alpha + 0.274 \quad (2)$$

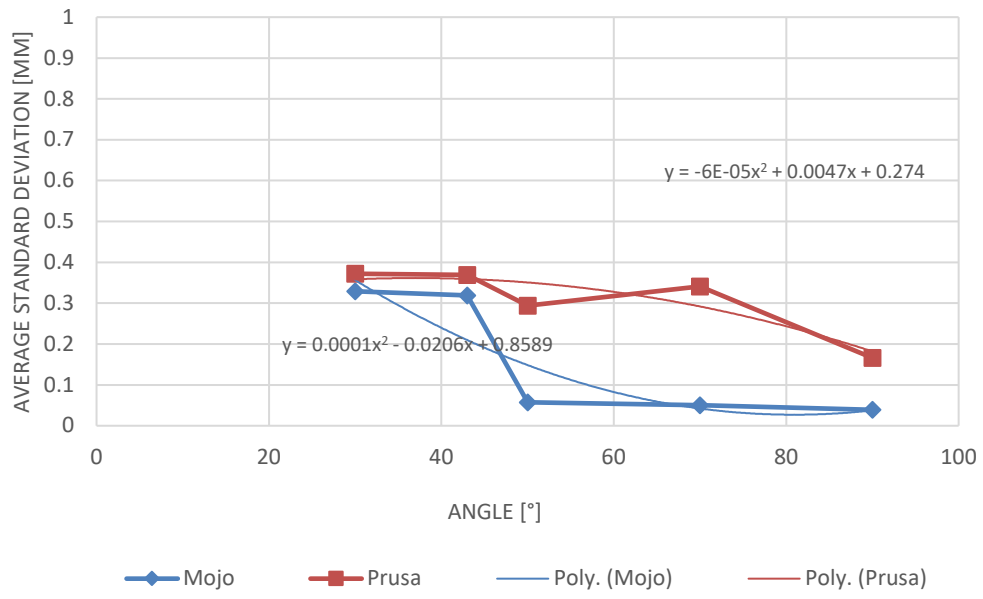


Figure 40 - Average standard deviation versus  $\alpha$  and both printers.





## 5. Conclusion

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This research details an experimental trial on FDM printed models with different slopping walls with angles without the existence of supports structures, in order to create some design guidelines. Established models were printed in two different printers, under the same processing technology, to compare results. The main conclusion of the work were:

- a) Slopping walls need support structures to be printed successfully.
- b) When angle  $\alpha$  decreases, the model becomes more fragile. As angle  $\alpha$  is decreasing, the layers have very little amount of previous layer below to print upon. In other words, the new layer has little amount of material for a proper adhesion between layers, meaning that the models being built need support structures.
- c) Support structure removal can damage the model creating a rough surface. In some cases the model can collapse. The model with  $\alpha=10^\circ$  the object collapsed while the support structure was being removed.
- d) Dimensional accuracy. When the filament is extruded, the nozzle temperature can vary which causes the layers to distort leading to slightly contract or deform.
- e) Deviation errors. When comparing the models to the original CAD file, it is clearly that Mojo prints a more accurate model than the Prusa printer, even with some deviations. Even though its overall accuracy is significantly more affected for  $\alpha < 43^\circ$ . For other angles, its standard deviation is below 0.05 mm. This is, for example, enough for non-functional prototypes. Particularly in this printer, it has been concluded that its printing effecting imperfection is approximately the same regardless the cutting section height. This is,  $\alpha$  is the dominant parameter in the feasibility of the printing object.



## 6. Further work

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After concluding this work, it is easy to identify some research possibilities to identify limitations and constraints not just for the FDM process but also for other technologies. Several are the suggestions for further works based on the results of this work:

- Analyze, considering estimated building time, the relationship between the distance travelled by the extrusion head and the number of layers deposited.
- Study the same printing material for different machines and how it can compromise the final result of the printing part.
- Study the patterns of the support structures in different machines and optimize this pattern in order to reduce the amount of support material without compromising the outcome.
- Study design guidelines regarding the thickness of the wall when submitted a geometrical shape.



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