FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

# Design for large-scale additive manufacturing

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**Abstract:** The use of three-dimensional printing use has been increasing due to the industry trend towards customizable products and small series. In addition, this technology meets the current demands in terms of sustainability, being able to use recyclable materials, and still producing little waste. One of the most fascinating aspects of 3D printing is figuring out how big parts can be printed, hence the term LFAM (Large Format Additive Manufacturing) was born. However, it has some difficulties that do not exist in traditional 3D printing of small parts. Even so, this branch of 3D printing has been experiencing high growth rates.

Given this context, the motivation for the topic emerged when Solidtech (a company specialized in additive manufacturing) offered the opportunity to develop the topic in their facilities, being able to work in an area of interest and on a topic that generated curiosity. With Solidtech, it was possible to systematically study some inherent difficulties of LFAM, using a robotic arm coupled with an extruder head for pellets (MEX process). Material shrinkage, construction paths, raster angles, path radius, surface finish, and adhesion to the construction platform, among others, were studied to enable printing parts with adequate properties.

Thus, the objective of this work was to establish a set of parameters for LFAM, especially in terms of the design and final quality of the printed parts. The work was divided into two steps: a first part, where materials, equipment, techniques and solutions used in this technology were investigated; and a second part, consisting in the experimental work, which involved carrying out several printing tests with different thermoplastic materials, to make parts with the best parameters.

The results obtained allowed to conclude that different materials (PP30GF, PETG, recycled PET, and some PLAs) can be used to print large format parts. The material is chosen according to the part requirements (cost, resistance, lightness, and finishing, among others). The data obtained allowed the creation of fundamental strategies (especially for the design) that relate the line thickness as a function of the extrusion and printing speeds, as well as identifying the different types of defects that can be obtained in the parts, their respective cause and solution. In addition, it was also possible to identify the limitations of the materials in terms of construction angles, speeds, layer heights (Lh), or others, which was fundamental to making the technical sheet of the material to build large parts.

This work allowed to conclude that design for additive manufacturing (DFAM) is critical when the objective is to manufacture large parts. This study demonstrated that sometimes it’s necessary to change the design of a part to be feasible to be built, but also that using the right material, equipment and parameters it is possible to make parts that would otherwise take much longer, or even be impossible to print.

**Keywords:** LFAM; DFAM; MEX; Polymers; Printing parameters; Defects; Large Format.

**Resumo:** A impressão 3D tem sido cada vez mais utilizada devido à tendência da indústria para produtos customizáveis e pequenas séries. Além disso esta tecnologia vai ao encontro das exigências da atualidade em termos de sustentabilidade, sendo capaz de utilizar materiais recicláveis e ainda ter pouco desperdício. Um dos aspetos mais fascinantes da impressão 3D é descobrir até que dimensão é possível imprimir, daí nasceu o termo LFAM (fabrico aditivo de grandes dimensões). No entanto aqui surgem dificuldades que não existem na impressão 3D "convencional", de pequenas peças. Mesmo assim este ramo da impressão 3D tem vindo a crescer a um bom ritmo.

Diante do referido contexto, a motivação pelo tema surgiu quando a Solidtech (empresa especializada no fabrico aditivo) ofereceu a oportunidade de aprofundar o tema nas suas instalações, podendo trabalhar numa área de interesse e num tema que despertou a curiosidade. Em conjunto com a Solidtech foi possível estudar e solucionar algumas dificuldades inerentes ao LFAM, usando um braço robótico acoplado a um extrusor para *pellets* (processo MEX). Questões como as contrações do material, trajetórias de construção, parâmetros do *raft* (camada de sacrifício), ângulos da trajetória, acabamentos de superfície, adesão à plataforma de construção, entre outros, foram estudados de forma a ser possível construir peças de grande formato.

Assim, o objetivo deste trabalho foi estabelecer um conjunto de parâmetros adequados para LFAM, especialmente em termos de design e qualidade final das peças impressas. O trabalho foi dividido em duas etapas: uma primeira parte, onde foram investigados materiais, equipamentos, técnicas e soluções utilizadas nesta tecnologia; e uma segunda parte, de trabalho experimental, que envolveu a realização de vários testes de impressão com diferentes materiais termoplásticos, para fazer peças com os melhores parâmetros possíveis.

Os resultados obtidos permitiram concluir que vários tipos de materiais (PP30GF, PETG, PET reciclado, e certos PLAs) podem ser utilizados para imprimir peças de grande formato, sendo o material escolhido de acordo com os requisitos da peça (custo, resistência, peso, acabamento, entre outros). Os dados obtidos permitiram criar estratégias fundamentais (especialmente para o design) que relacionam a espessura de linha em função das velocidades de extrusão e de impressão, bem como identificar os diferentes tipos de defeitos que podem ser obtidos nas peças, a sua respetiva causa e solução. Além disso, também foi possível identificar as limitações dos materiais em termos de ângulos de construção, velocidades, alturas de camada (Lh), temperaturas, entre outros, o que foi fundamental para fazer a ficha técnica do material para construção de peças de grande formato.

Este trabalho permitiu concluir que o design para fabrico aditivo (DFAM) é crítico quando o objetivo é fabricar peças de grande formato. Este estudo demonstrou que por vezes é necessário alterar o design de uma peça para ser viável a sua construção, mas também que com os materiais, equipamentos e parâmetros certos é possível fabricar peças que de outra forma demorariam muito mais tempo, ou que seriam até impossíveis de realizar.

**Palavras-chave:** LFAM; DFAM; MEX; Polímeros; Parâmetros de impressão; Defeitos; Grande Formato.

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*“My goal is not to be better than anyone else, but to be a better version of myself every day.”*

## Generated scientific disclosures

(1) BRITO, Henrique; ALVES, Jorge Lino. “Design for large scale additive manufacturing.” In: DOCTORAL CONGRESS IN ENGINEERING, 5th, 2023, Oporto, **Book of abstracts and invited lectures of the 5th Symposium on Mechanical Engineering,** Oporto, 2023: FEUP Editions, 2023.

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(3) BRITO, Henrique; ALVES, Jorge Lino. “A systematic study of Large Format Additive Manufacturing”. **Submitted to 2$^{nd}$ International Conference on Engineering Manufacture** in September 2023. Status: Waiting to be accepted.

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## Abbreviations

3D – Three Dimensional
3DP – Three Dimensional Printing
ABS – Acrylonitrile Butadiene Styrene
AM – Additive Manufacturing
ASTM – American Standard Test Method
BJT – Binder Jetting Technology
CAD – Computed Aided Design
CNC – Computer Numerical Control
DED – Directed Energy Deposition
DFAM – Design for Additive Manufacturing
DSLM – Direct Selective Laser Melting
EBAM – Electron Beam Additive Manufacturing
EBM – Electron Beam Melting
FDM – Fused Deposition Modeling
FFF – Fused Filament Fabrication
FRP – Fiber Reinforced Polymers
FRP – Fiber Reinforced Polymers
LFAM – Large Format Additive Manufacturing
LOM – Laminated Object Manufacturing
MEX – Material Extrusion
MFI – Melt Flow Index
MJT – Material Jetting
PA – Polyamide
PBF – Powder Bed Fusion
PC – Polycarbonate
PEEK – Polyetheretherketone
PEI – Polyetherimide
PEKK – Polyetherketoneketone
PET – Polyethylene Terephthalate
PETG – Polyethylene Terephthalate Glycol
PLA – Polylactic Acid
PP30GF – Polypropylene with 30% Glass Fibers
PPSU – Polyphenylsulfone
RPM – Rotations per minute
SHL – Sheet Lamination
SLA – Stereolithography
SLM – Selective Laser Melting
SLS – Selective Laser Sintering
STL – Standard Triangle (Tesselation) Language
UV – Ultra Violet
VPP – Vat Photopolymerisation

## List of symbols

D – Nozzle diameter [mm]
F – Load [N]
Lh – Layer height [mm]
Lt – Layer time [s]
Lw or w – Line or layer width [mm]
p – Cooling pressure [bar]
Td – Dehumidification temperature [°C]
Tg – Glass transition temperature [°C]
Tm – Melting/extrusion temperature [°C]
Tr – Room temperature [°C]
V – Robot printing speed [mm/s]
ρ – Density [kg/m$^3$]

# Chapter 1

# Introduction

The present work was written as part of the curriculum of the 2nd semester and last year of the Master in Mechanical Engineering at the Faculty of Engineering of University of Porto (FEUP).

This work was carried out during the whole semester at Solidtech, an additive manufacturing company dedicated to prototyping and product development.

## 1.1. Research context

Additive manufacturing (AM) is starting to become a common technology in nowadays society. Some decades ago, it was something never heard of. Today however, the technology is so spread out in the market and has so much information available, that everyone can have a small 3D printer at home.

Still, this is not the case for all the AM technologies. Large format additive manufacturing (LFAM) is a technology that only a few have tried and even fewer have succeeded. The costs and required knowledge to make the technology work properly are much bigger, hence the difficulties compared to the traditional 3D printing, which consists in the extrusion of plastic filament.

Although there are already some capable systems in the market, the difficulties involve several matters:

- Making the robotic arm movements and the extruder's material output work in syntony;
- Controlling the material shrinkage since the parts are much larger than in conventional FDM;
- Having good surface finishing, as the layer height is much higher than in conventional FDM systems;
- Selecting appropriate construction platforms to improve the finishing surfaces;
- Selecting appropriate materials since each manufacturer uses different additives/fillers which may or not behave well with this technology;
- Good adhesion, specially between the 1st layer and the construction platform;
- Reduce the moisture absorption for transparent materials;
- Among many others which will be explained further in the work.

LFAM has already a promising future since the environmental consciousness and rules are growing, in the sense of using recycled materials for several end-use applications instead of the typical non-recyclable ones.

DFAM takes a major role because in large format parts, the imperfections are more visible and some design problems are enhanced compared to the ones in small parts.

Besides the design, the paths, angles, speeds, temperature, and others, must be adjusted to create a good final surface.

## 1.2. Motivations

When the decision about this dissertation theme had to be made, some companies in the area of interest (molds, polymers, and 3D printing) were contacted.

The motivation for the theme “Design for LFAM” emerged when Armando Alves from Solidtech (a reference company in the area of rapid prototyping and product development) presented the opportunity to develop this work with the company. It immediately became an attractive option to go for because, on the one hand, it was a very trendy topic (several dissertations involve 3DP), but on the other hand, there are only a few publications and articles about LFAM.

Another motivation was that this technology might be the future AM trend, since it keeps up with the industry interest for exclusivity and bespoke parts, replacing large series productions for small ones. Also, it keeps up with one of the main concerns in today’s society, sustainability, as it’s able to use recycled materials and it makes little waste.

Besides that, the company also offers some other interesting non-related LFAM technologies (like SLA, SLS, FDM, etc.) which fill some personal curiosity.

## 1.3. Objectives

The main goal of this thesis is to develop LFAM knowledge, especially about product design, for the LFAM printing equipment, applying the results and conclusions of the conducted experiments.

To achieve that, this dissertation has the following topics as specific objectives:

- Characterization and selection of the printing materials;
- Study of the materials printing limitations (speeds, angles, etc.);
- Study of the printing defects, their causes and limitations;
- Elaborate the materials technical sheet for printing;
- Realization of the graphics for the line thickness as a function of the printing and extrusion speeds.

## 1.4. Methodology

To build up this thesis content, two concepts were used:

- Theoretical research for commonly used materials, equipment, techniques, and solutions;
- Practical work done in Solidtech which involved several experiments and analysis of the results, applying different solutions for the problems that were encountered. The experimental work took the majority of the time but it also provided most of the information to support and write this dissertation.

## 1.5. Outline of the dissertation

The chapters of this thesis are organized as shown below:

- Chapter 1: Introduction of the work;
- Chapter 2: Theoretical background review of the main topics related to the theme;
- Chapter 3: Methodology and materials used in this work to obtain the data;
- Chapter 4: Results obtained from the practical experiments and discussion;
- Chapter 5: Presentation of some case studies;
- Chapter 6: Conclusions and intended future work.

After the last chapter there will be the used references and appendices.

## Chapter 2

# State-of-the-art

This chapter provides a theoretical background on Additive Manufacturing (AM), the different existing technologies, and appropriate materials, focusing on the concepts related to the printing of large format parts. The importance of the design in this technology will then be explained in further detail.

## 2.1. Additive Manufacturing

3D Printing is the popular term used to refer to AM and what used to be called Rapid Prototyping. The term Rapid Prototyping was used widely to describe technologies that created real prototypes directly from a digital source. ASTM consensus standards now use the term Additive Manufacturing as do most standards entities worldwide.

This work is about the latter technologies, first developed for prototyping but now used for many more purposes, such as parts for small production series and some specific kinds of prosthetics [1].

The basic principle of this technology is that a digital model, previously created using a three-dimensional computer-aided design (3D CAD) system, can be physically created without any process planning [2, 1].

The key to how AM works is that parts are made by adding material in layers, in contrast to machining technology that removes or subtracts material from a block of raw material. In this process, each layer is a thin cross-section of the part created. The thinner the layer, the more detailed the part will be. The layer height will be key in the accuracy of the final part, influencing the mechanical properties, how quickly it will be made, how much post-processing will be required, the size required for the AM machine and the overall costs [3].

Saying that AM is only useful for making prototypes would be inaccurate and underestimate the technology [4]. This technology when used in conjunction with others to form process chains, can be used to significantly shorten product development times and costs. Recently some of these technologies were developed to the extent that the output is suitable for end use, meeting the current demands [5].

In a general manner, most AM processes include the following steps:

- **CAD drawing:** All parts must start from a digital model that fully describes the external shape;
- **STL conversion:** Most AM machines accept the STL file format (industry standard);
- **File transfer to the machine**: The file might need some manipulation so that it has the correct size, position, and orientation for the building;
- **Machine setup**: Related to the build parameters like the energy, layer height, speeds, and others;
- **Build:** There is not much to do at this stage, just some regular checking of the process to see if there aren’t any problems like running out of material, software glitches, and others;
- **Removal and clean-up:** Once the machine has finished the build, the parts must be removed and cleaned, if needed (the machine should be in a safe position and the part should not be handled if hot);

- **Post-processing:** Parts may require the removal of supports. They may also require sanding, priming and painting to give an acceptable surface texture and finish. Post-processing may be costly, laborious, and lengthy if the finishing requirements are demanding;
- **Application:** This may require them to be assembled with other mechanical or electronic components to form a final model or product [6].

Several significant limitations must be overcome for AM to gain widespread acceptance in conventional serial manufacturing. One of the foremost challenges is the scarcity of knowledge in this domain. The need to systematically document design rules, principles, best practices, and standards has been identified as a major hurdle hindering the broad adoption of this technology [7].

Furthermore, embracing AM still requires substantial capital investment and substantial financial commitment from organizations. Additionally, components manufactured using AM techniques are subject to limitations related to surface finish, often influenced by thermal considerations that, in turn, affect the mechanical properties of the final product. Surface quality is also intricately linked to factors such as the part's orientation during deposition and the thickness of each layer.

These challenges underscore the ongoing necessity for research, standardization, and the development of best practices to fully harness the potential of additive manufacturing for mass production [1].

### 2.1.1. Classification

There are numerous ways to classify AM technologies. A popular approach is to classify according to the baseline technology, like whether the process uses lasers, printer technology, extrusion technology, among others. Another approach is to collect processes together according to the type of raw material input [4].

According to the ISO/ASTM 52900 standards, AM processes fall into one of the seven categories shown in Table 1:

Table 1- AM technologies classification [7].

| Process category | Techonlogies | Material |
|---|---|---|
| Vat Photopolymerisation (VPP) | SLA | UV curable resin |
| Powder Bed Fusion (PBF) | DMLS, SLS, SLM, SHS, EBM | Metals, but also thermoplastics in SLS |
| Material Extrusion (MEX) | FDM, FFF, FGF | Thermoplastics, waxes |
| Material Jetiing (MJT) | MJT | UV curable resins, waxes |
| Binder Jetting (BJT) | 3DP | Composites, polymers, cermics, metals |
| Sheet Lamination (SHL) | LOM | Paper, metals, thermoplastics |
| Direted Energy Deposition (DED) | LMD, LENS, EBAM | Metals |

Figure 1 helps to distinguish the different process categories according to their main principles, considering only the ones that work with polymers, which will be the type of material used in this thesis.

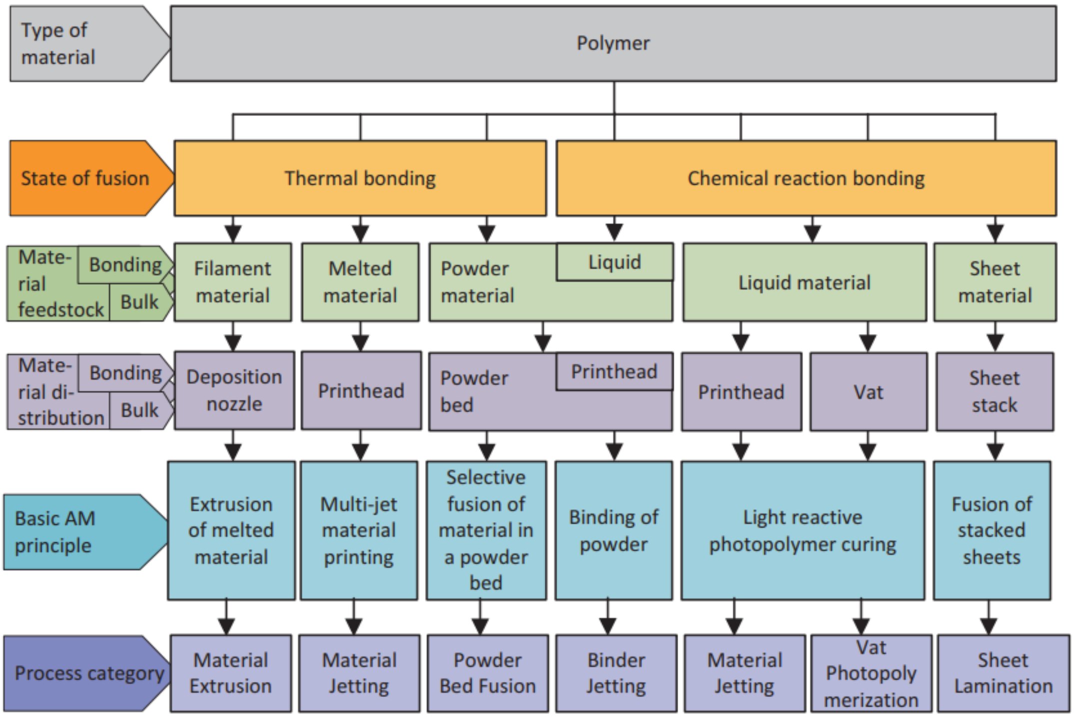


Figure 1- Characteristics for each AM category that works with polymers [6].

### 2.1.2. Benefits

Additive Manufacturing (AM) is a disruptive technology that is revolutionizing the way we approach product design and manufacturing. Among its major advantages is its exceptional speed. AM not only accelerates part fabrication but also propels the entire product development process forward through the integration of computer-aided design (CAD) software. This reliance on 3D CAD models as the starting point for AM eliminates concerns about data conversion or misinterpretation of design intent [2].

Another remarkable aspect of AM is its ability to streamline the manufacturing process. Unlike traditional manufacturing techniques, which entail multiple sequential stages to construct a part, AM accomplishes this feat in a single, continuous step regardless of the part's intricacy. In contrast, traditional manufacturing processes often witness an elongated production timeline as design complexity grows, leading to a greater number of stages. However, AM remains relatively resilient to minor design alterations that may emerge during the early phases of product development, resulting in consistent fabrication times [4].

Furthermore, AM has the potential to eliminate or simplify many of the multifaceted processes that typically characterize traditional manufacturing. This dual benefit, cost savings coupled with heightened design and production adaptability, underscores its significant value. In summary, AM's capacity to expedite the product development lifecycle, streamline manufacturing steps, and simplify overall production has firmly established it as an indispensable tool in modern design and manufacturing methodologies [6].

### 2.1.3. Materials

AM technology was originally developed around polymers, paper laminates, and waxes. Only later composites, metals, and ceramics were introduced [4, 6].

Depending on the used process, several materials can be used. Since only polymers will be used in this work, some of the most common ones for AM are shown in Table 2.

Table 2- Polymers used in AM [6].

| | |
|---|---|
| Amorphous | ABS<br>PC<br>PC/ABS blend<br>PLA<br>PEI<br>PS |
| Semi-crystaline | PA<br>PP<br>PEEK |
| Thermoset | Acrylics<br>Acrylates<br>Epoxies |

## 2.2. Material extrusion (MEX) technology

This technology involves extruding material that is in a semisolid state through a nozzle. The material must solidify completely while maintaining the deposited shape and bonding to previously extruded material to create a solid structure. The AM machine used for MEX must be capable of horizontal scanning, starting and stopping the material flow during scanning, and indexing or moving the part for the production of further layers [8].

Several key features are common to any MEX system. The first is the loading of the material, followed by its liquefaction and the application of pressure to move it through the nozzle. Extrusion occurs next, with the material plotted according to a predefined path and in a controlled manner. The material must then bond to itself or secondary build materials to form a coherent solid structure. Lastly, support structures may be included to enable complex geometrical features [6].

The majority of the large format AM equipment operates according to the MEX principles, however, there are already developed a few large format systems that use other AM technologies [5]. Those systems won´t be addressed in this thesis since the printing equipment that was used in this work was a MEX equipment.

### 2.2.1. Materials used in MEX

Material extrusion processes use different materials depending on the application and requirements [9]. The Table 3 shows the most common polymers used in this technology.

Table 3- Common thermoplastic polymers used in MEX [6].

| Material | Characteristics |
|---|---|
| ABS | Good quality engenieering thermoplastic |
| PC | Durable, stable, good for strong parts |
| PLA | Inexpensive, prints quickly |
| Nylon 6 and 12 | Good impact strenght and toughness |
| PPSF/PPSU | High strength and chemical resistance |
| PEI | High strengh to weight ratio |
| PEKK | Best strength characteristics of all MEX materials |

### 2.2.2. Processes

This topic addresses the different processes for MEX production:

- **FDM/ FFF**

By far the most common MEX AM technology is Fused Deposition Modeling (FDM), invented and developed in 1989 by Stratasys, USA. The simplicity and cost-competitive design of FDM machines were the reason for the huge success in the industry [10].

In this approach, a heating reservoir is used to liquefy the polymer that is fed into the system as a filament [11]. The filament is pushed into the reservoir by a pinch roller arrangement, and it is this pushing that generates the extrusion pressure (Figure 2). This process is also known as Fused Filament Fabrication (FFF). There are thousands of filaments available in the market for this technology, with different colors, diameters, and materials. PLA is the most common one [9].

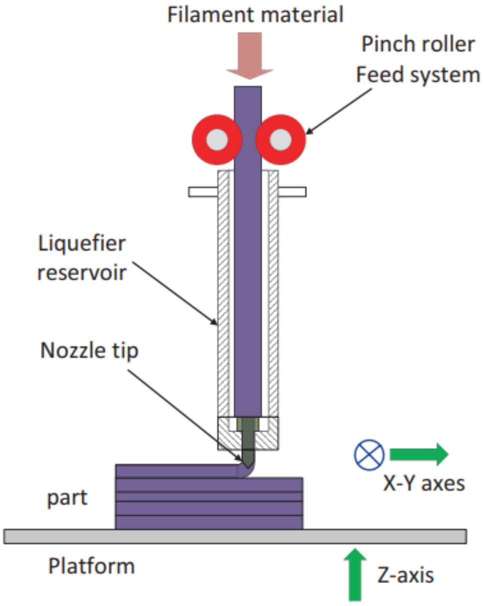


Figure 2- Fused deposition model process illustration [6].

Although this is not the most common process for large format AM, there are already in the market some printing systems that successfully print large parts using this process. *Wasp* is one of the most famous and established brands in this category [12].

- **FGF/FPF**

Although AM can be highly profitable, the current prices for commercial filament restrict the product applications.

Fused granular fabrication (FGF) or fused particle fabrication (FPF) has the main working principles as FFF but it can attenuate the material costs by printing products directly from polymer pellets. Besides that, it is the most common method used to print large format parts since large filaments are not easy (and cheap) to get [13].

Usually, FGF machines incorporate a screw and barrel like the ones used in injection molding [14, 15]. In contrast to filament extruders that operate along a linear path, pellet extruders employ a distinct screwing mechanism. This mechanism serves a dual purpose: melting the pelletized material and conveying it through a heated nozzle, often referred to as a die [16].

The process starts as plastic pellets that are introduced through a designated feeder inlet. Subsequently, these pellets navigate a barrel that features multiple sections, each meticulously heated. This controlled heating sequence induces the gradual liquefaction of the pellets, achieving the desired viscosity for processing [17]. Upon attaining the optimal molten state, the screw mechanism applies calibrated pressure. This heightened pressure propels the molten material through a specialized nozzle, meticulously layering it onto a designated platform [18]. The incremental deposition method culminates in the meticulous fabrication of parts, layer by layer. This process is represented in Figure 3.

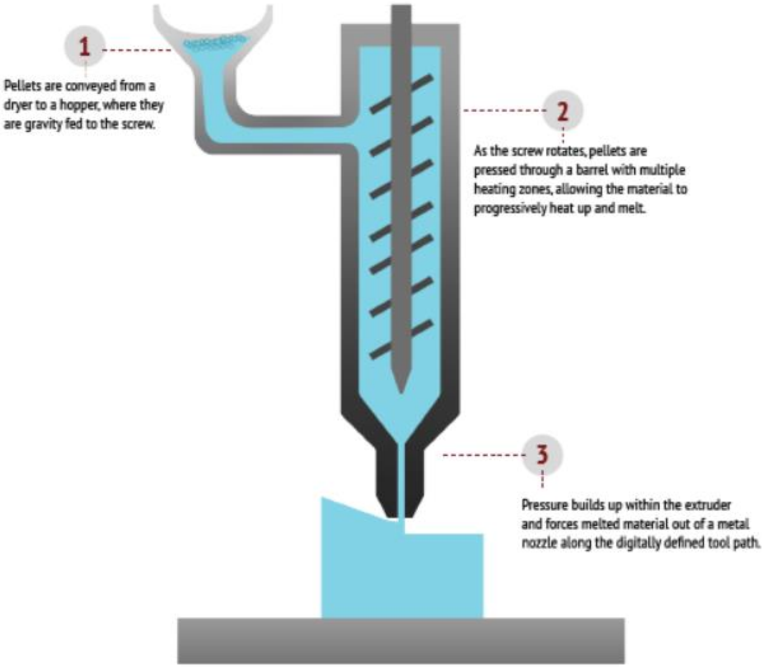


Figure 3- Fused granular fabrication process [15].

Although inherently more intricate than filament extrusion, this approach offers a trove of distinct advantages. Notably, the employment of plastic pellets translates to lower material costs, facilitated by their economical nature compared to pre-made filaments. Furthermore, the method significantly bolsters production speed, rendering it especially advantageous for large-scale industrial applications. Beyond these merits, the adoption of pellet-based extrusion broadens the array of available materials, underscoring its capacity for enhanced flexibility and adaptability within the manufacturing process [13].

## 2.3. Large Format Additive Manufacturing

Large Format Additive Manufacturing (LFAM) is a pioneering technique that harnesses the power of additive manufacturing technologies to create large parts. Industries like aerospace, automotive, naval, construction, and electronics, find LFAM to be an invaluable asset [19, 20, 21, 22]. When traditional manufacturing methods stumble due to scale or complexity, LFAM allows to bridge the gap [23].

An exceptional merit of LFAM lies in its ability to drastically reduce both production costs and timeframes [24]. By eliminating the need for tooling and minimizing waste, LFAM significantly slashes the financial and temporal investments typically linked with manufacturing large parts [1]. Through the capability to fabricate molds, structural end parts, and non-structural end parts on-site, companies can reduce their dependence on external suppliers and simplify inventory management [1, 5, 20, 25]. This consolidation not only enhances operational efficiency but also holds the promise of substantial cost savings [26]. LFAM can also be used simultaneously with subtractive technologies, minimizing the use of the subtractive part. 3D-printed molds for the aerospace and naval industries are a perfect example of that. After the build, those are many times machined by CNC machines to fulfill the dimensional tolerances [27].

LFAM emerges as a catalyst for local production in an era where protracted global lead times have become a constant reality [24]. By empowering companies to establish localized manufacturing processes, this technology effectively curtails the need for intricate international transportation logistics. This agility in production addresses a critical concern in industries where time-sensitive deliveries are of major importance [28].

Sustainability takes center stage as LFAM embraces eco-conscious practices. By its reduced supply chain complexity and minimized transportation requirements, LFAM inherently contributes to a diminished carbon footprint. Yet, its environmental commitment extends further. LFAM enables a circular economy by facilitating the utilization of recycled materials in the 3D printing process, thereby exemplifying an approach to responsible production [5, 11, 29].

While the initial investment in LFAM technology might scare some people, its long-term economic benefits are compelling. The combination of reduced labor costs, streamlined inventory management, supply chain simplification, and potential environmental incentives positions LFAM as an economically viable choice in the realm of manufacturing [5, 13].

However, LFAM has its challenges, with the foremost among them being the precise and uniform adhesion of layers across large surfaces [18]. The larger parts introduce the specter of distortions, warping, delamination, residual stresses, and related issues that will jeopardize the quality and integrity of the final product [30, 31]. Indeed, problems encountered during the process can lead to costly print failures. What makes this challenging is that these failures may not become apparent until well into the printing process or even after the print has been completed.

Several complex phenomena occur simultaneously during LFAM which contribute to the mentioned problems:

- **Anisotropic Flow**: LFAM materials often exhibit anisotropic flow, which means that the flow of material isn't uniform in all directions. This can result in uneven layer adhesion and structural weaknesses in the final print;
- **Shrinkage**: As the printed material cools and solidifies, it may undergo shrinkage. If not properly accounted for in the design and printing parameters, this can lead to warping, deformation, or parts that don't fit together as intended;
- **Heat Transfer:** Controlling the heat transfer within the printing process is crucial. Inadequate cooling can lead to overheating, which may cause layer delamination or distortions in the part;
- **Viscoelasticity:** Materials used in LFAM have viscoelastic properties, meaning they exhibit both viscous (flow-like) and elastic (solid-like) behavior under stress. Understanding and managing these properties is essential to achieving accurate prints;
- **Polymer Crystallization** (Semi-Crystalline Polymers): Some LFAM materials, particularly semi-crystalline polymers, may undergo crystallization during the cooling process. This can influence material properties and dimensional stability [8];
- **Fusion Bonding:** Achieving strong fusion between layers is critical for print strength. Inadequate fusion can lead to weak bonding lines and structural instability in the final part [13].

To mitigate these challenges and reduce the risk of print failures, thorough material testing, process optimization, and design considerations are essential. This may involve adjusting printing parameters, using support structures, incorporating cooling strategies, and post-processing techniques [31].

Furthermore, monitoring and quality control during the printing process can help detect issues early on, minimizing wasted time and materials. Developing a deep understanding of the specific materials and printing techniques being used is crucial for successful LFAM production.

Concerning the layer adhesion, the goal is to get such a good chemical bonding between the layers that when performing an impact/mechanical resistance test, the part will never crack along the layers. To achieve that is necessary to deposit a layer on top of another in the process temperature window, which differs for each material. The cooling time (proportional to the layer time) must therefore be in syntony with that process temperature window because if it cools below the critical temperature before the subsequent layer has been deposited, no bond formation is achieved [32, 33].

The key factors influencing the cooling time in LFAM include:

- **Layer Height:** Choosing a smaller layer height can lead to thinner layers, reducing cooling time as there's less material to cool. However, this may extend the overall printing time;
- **Material:** The type of material used in LFAM greatly impacts cooling time. Different materials have different thermal conductivity and heat dissipation properties, which influence how quickly they cool and solidify after deposition;
- **Printing Strategy:** Related to the various process parameters that are defined before each construction, such as extrusion temperature, printing speed, and extrusion RPMs. Adjusting these parameters can impact significantly the cooling time;
- **Cooling Mechanisms**: These mechanisms can be adjusted to optimize cooling times for specific materials and geometries;
- **Geometry and Complexity:** The complexity of the object being printed, including its shape and overhangs, can affect cooling times. Complex geometries may require additional cooling time to prevent distortion or warping [16, 30].

Optimizing these parameters is critical to achieving high-quality LFAM parts. Experimentation and adjustment of these settings are often necessary to find the ideal balance between cooling time, print speed, and overall print quality for a given LFAM project [24].

While traditional additive manufacturing is good for crafting small components with meticulous detail, LFAM stands out as a promising field of research and development, prepared to revolutionize the landscape of large-scale parts. As the technology continues to evolve, anticipations run high for the upcoming innovations within the field, such as novel materials, refined software, and advanced production methodologies [23, 34].

### 2.3.1. LFAM Equipment

LFAM demands specialized equipment and materials. Given its involvement in the fabrication of large structures, the machinery utilized in LFAM typically exhibit both larger dimensions and higher robustness compared to conventional additive manufacturing systems [23].

That equipment includes:

- **Construction Platforms:** LFAM systems require significantly larger construction platforms compared to their conventional additive manufacturing counterparts. This characteristic enables the fabrication of larger parts with fewer seams or joints, ultimately enhancing the robustness and durability of the end product;

- **Material Feed Systems:** To ensure uniform material flow and layer thickness, LFAM systems may incorporate specialized material feed mechanisms. In certain systems, wide-diameter nozzles or extruders ensure even material deposition across the construction platform;
- **Cutting-edge Software:** Many LFAM systems integrate sophisticated software to optimize the printing process and secure precise layer adhesion. Employing real-time monitoring and feedback mechanisms allows dynamic adjustments to printing parameters, which helps minimize distortions and related concerns [30];
- **Robotic arm/structure:** MEX technology for LFAM requires a structure with a movement range big enough to reach the necessary height and length to build large parts;
- **Dehumidifier:** Just like filaments, the material pellets used in LFAM need to be thoroughly dehumidified before printing a part. The dehumidifier also needs to have considerable dimensions since the material output is much bigger than conventional AM;
- **Extruder:** The extruder is one of the most critical components in the equipment, because it needs to be able to withstand the large material debits;
- **Cooling system:** Some LFAM setups include cooling mechanisms like fans or compressed air systems to expedite the cooling process.

Nowadays there are only a few companies specialized in LFAM, however, each one uses different materials and equipment. Nagami, LaMaquina, Aectual, Loci Robotics, and Cead, are some of those companies.

Some of their printing solutions include different machine setups (dehumidifier, construction platform, and others) for the different projects. However, having several machines and setups requires considerable investment [35].

For example, some of them place a small dehumidifier right above the extruder head instead of being on the floor. This might reduce the chance of contamination and getting air bubbles in the printed part, however for large format parts that kind of dehumidifier might not be enough to keep up with the extruder's material output. The Figure 4 shows that setup.

Figure 4- OneMethods Nagami's different machine setups [36].

Another example is the robotic arm that is placed on guide rails which allow it to move and continue to print through long distances. Several companies, like *Caracol*, already offer this solution.

The Figure 5 shows the system used by Aectual.

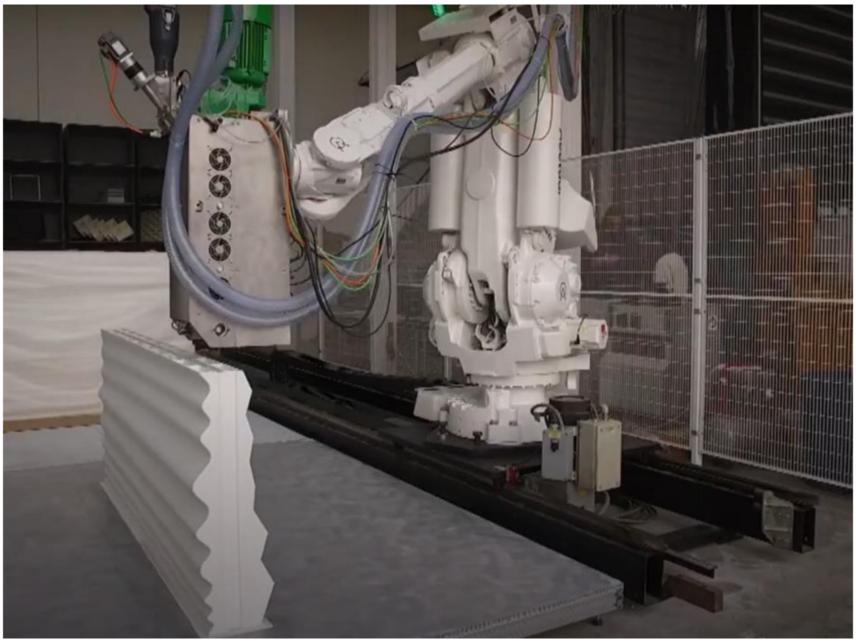


Figure 5- Aectual's machine setup [37].

### 2.3.2. Equipment for this work

The equipment used in this work follows the common AM process stages, with some slight adjustments for the LFAM technology:

- **CAD drawing:** although the used design software was mainly *Solidworks, Rhinoceros* was also used in a later work for generative design;
- **File conversion:** for the Kuka machine software the file must be transferred in SRC format, not STL;
- **File transfer to the machine:** this step was done using a pen drive, however, it can be made by other means;
- **Machine setup:** although some parameters were previously defined in the Caracol slicer software, others must be defined in the equipment itself (extrusion controller, robot controller and cooling system) [38];
- **Build:** at least the beginning of the build was monitored to see if adjustments were necessary to be done. Some periodic checks were also important to make sure that everything was running smoothly;
- **Removal and clean-up:** done carefully, especially for the part with staples or glue;
- **Post-processing:** some parts required the removal of rafts/brims, and some surface treatment, like sanding or polishing;
- **Application:** the parts were tested and inspected to see if they fulfilled the requirements [6].

Concerning the equipment hardware, it included a six-axis robotic arm from Kuka (Figure 7) coupled with an extruder head for pellets, from Caracol (Figure 9)[38].

All the equipment was installed in a closed room with controlled temperature (Figure 6).

The printing room was also equipped with anti-fire safety systems, which included automatic extinguishers and smoke extraction.

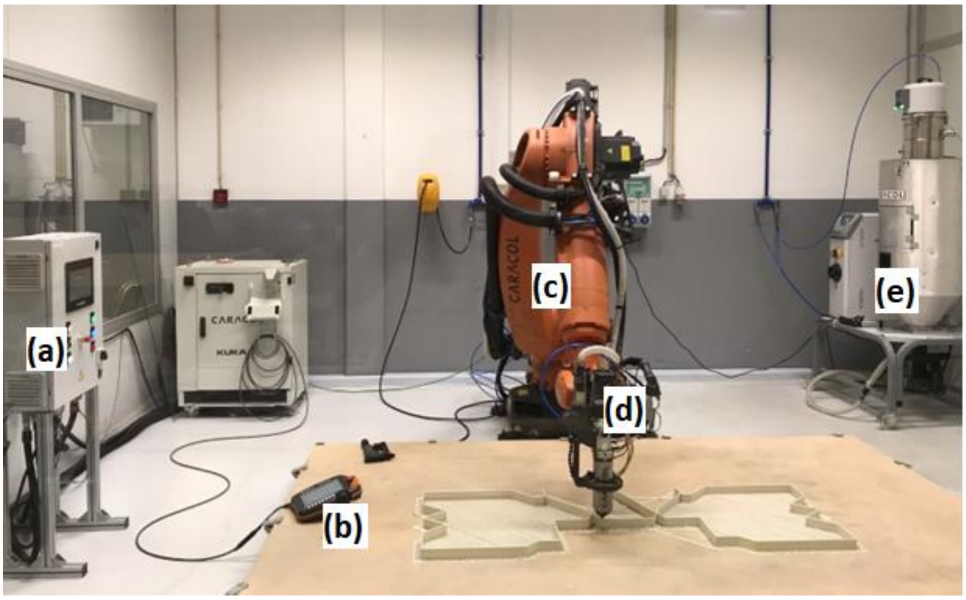


Figure 6- Printing room equipment: (a) Extruder controller; (b) Robotic arm controller; (c) Robotic arm; (d) Extruder head; (e) Dehumidifier.

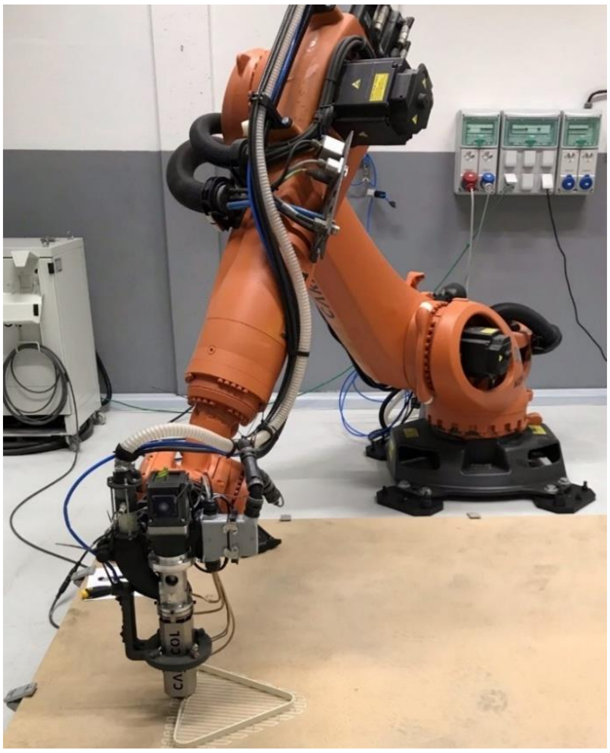
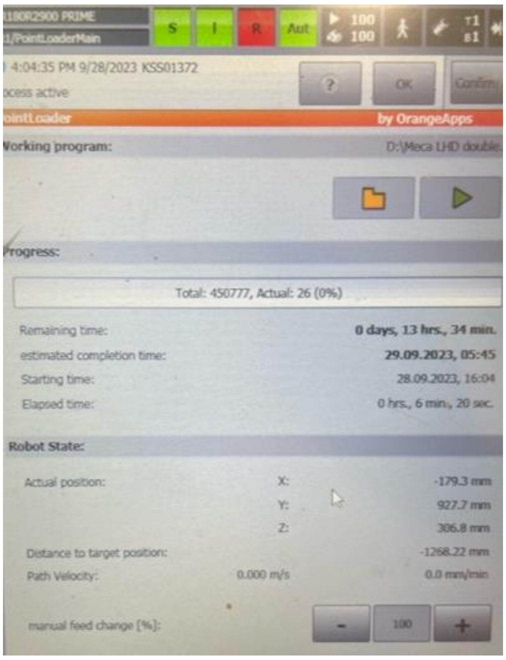


Figure 7- Robotic arm from Kuka.

The *Kuka*'s controller allowed to move the robotic arm (in manual or automatic mode) and to start running printing files. It also allowed to adjust the printing speed while printing and to stop the program at any time, if needed (Figure 8).



180R2900 PRIME
1/PointLoaderMain
4:04:35 PM 9/28/2023 KSS01372
ocess active
ointLoader by OrangeApps
Working program: D:\Meca LHD double
Progress:
Total: 450777, Actual: 26 (0%)

| | |
|---|---|
| Remaining time: | 0 days, 13 hrs., 34 min. |
| estimated completion time: | 29.09.2023, 05:45 |
| Starting time: | 28.09.2023, 16:04 |
| Elapsed time: | 0 hrs., 6 min., 20 sec. |

Robot State:

| | | |
|---|---|---|
| Actual position: | X: | -179.3 mm |
| | Y: | 927.7 mm |
| | Z: | 306.8 mm |
| Distance to target position: | | -1268.22 mm |
| Path Velocity: | 0.000 m/s | 0.0 mm/min |

manual feed change [%]:

Figure 8 -Controller for the robotic arm.

Caracol implemented a vibratory motor in the feed cup to help the pellets to drain into the extruder screw. Before the screw entrance, there was a water-cooled ring which prevented the material from melting prematurely (Figure 9).

The extruder was also equipped with a channel of pressurized air to cool down the extruded material, distributed uniformly around the nozzle. The air pressure can be adjusted up to 6 bar.

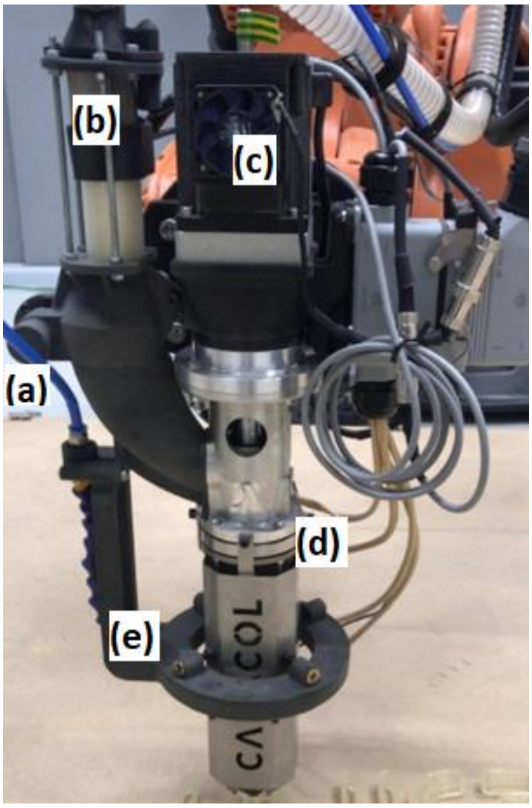


Figure 9- Extruder head from Caracol: (a) Vibratory motor; (b) Pellets feed; (c) Motor; (d) Water cooling ring; (e) Cooling air.

This extruder is relatively small for LFAM, having an extrusion rate of up to 3 kg/h, but there are extruders for LFAM capable of bigger extrusion rates, above 50 kg/h [32, 33, 38].

It was equipped with several heating cartridges which allowed the 20mm diameter screw to reach temperatures up to 400°C (Figure 10).

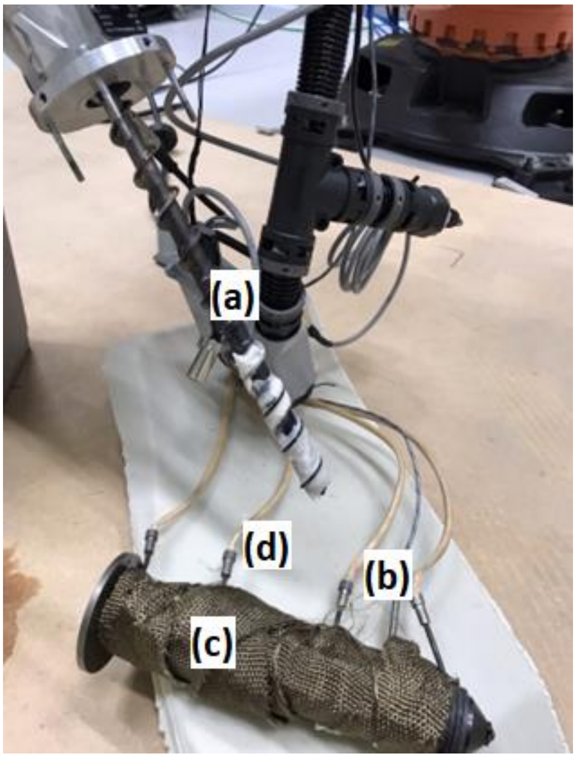


Figure 10- Extruder interior: (a) Screw; (b) Thermocouple; (c) Thermal wrap; (d) 4 Heating cartridges.

On the extruder controller, several parameters could be controlled: motor and its extrusion RPMs, temperature, material automatic feed, vibratory motor (ON or OFF), among other minor settings (Figure 11).

RPM Vel 130

Temp Set °C 250

Temp Real °C 24

Figure 11- Controller for the extruder.

Before the material got into the extruder, it was previously dehumidified in a *Piovan* silo. The dehumidification process is crucial to ensure good adhesion between layers and a uniform material extrusion flow (Figure 12). Before dehumidifying it is important to see in the material data sheet its glass transition temperature (Tg), so that the pellets don´t stick between them before getting into the extruder chamber.

Figure 12- Dehumidifier system from Piovan.

- Software:

To prepare the parts for printing, *Caracol* provided a slicer software, developed by the company, which allows to “slice” the parts and select/adjust the necessary printing parameters.

The part’s bottom surface should always be on the front plane (on *Solidworks*) to be correctly oriented when placing it in the software printing bed (Figure 13).

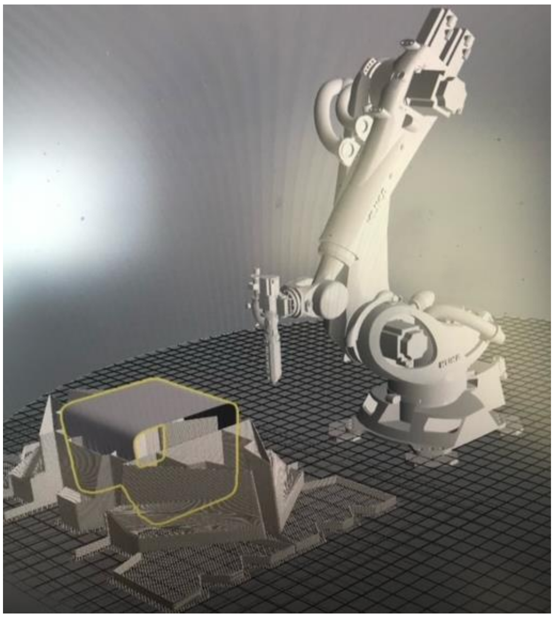


Figure 13- Slicer software´s printing bed.

### 2.3.3. Printing parameters for the used system

Before starting a construction, several printing options and parameters are selected, according to the project specifications and goals [17]. Not only on the slicer software, but also in the printing room some of those printing parameters must be selected to start the construction.

Software:

- **Layer height (Lh)**
- **Robot printing speed (V):** Although this value is established in the software it can be adjusted in the robot controller (by up to +50% and -100%);
- **Line width (Lw):** Although this value is imputed, it is just for the software to place the extruder nozzle in the correct path when building thick walls (which require several lines to achieve the final wall width). Its real value will depend on other parameters, mainly the speed and the extrusion RPMs;
- **Planar mode:** Can be planar, non-planar, or planar along a curve (the plane is always perpendicular to the “z” direction);
- **Slicing mode:** Can be normal or have spiralized contour. In the spiralized contour mode instead of the height increasing layer by layer (creating a seam line), it increases gradually;
- **Base travel speed:** This parameter doesn´t interfere with the looks or structural integrity of the part, but it does matter on the final production time, especially if there are many travels along the construction;
- **Seam position:** The point where the layer ends and the following one starts creates a noticeable seam line. The position of this seam line can be selected according to the user's interests;
- **Infill addition:** Not so used in LFAM, however it can be added. If added, the type and density of the infill must be selected;
- **Raft/brim addition:** For most of the parts, a raft or brim is necessary to create a good base to start the construction. For the raft case, its angle and density can be chosen. For the brim case, the number of lines can be chosen. Besides spending time and material, having a raft or brim requires post-processing, so it should not be used if it’s not necessary.

Printing room:

- **Nozzle diameter (D)**
- **Room temperature (Tr)**
- **Extrusion/Nozzle temperature (Tm)**
- **Extrusion/Screw speed (RPM)**
- **Cooling pressure (p):** This parameter is selected based on the material and layer time (Lt). More cooling pressure is necessary for smaller layer times.

### 2.3.4. Materials used in LFAM

The materials intended for LFAM must demonstrate resilience against the strains inherent in large-scale production. Correspondingly, the utilization of specific materials, often reinforced with elements such as glass fibers or carbon fibers, enhances the performance of LFAM-produced items [20, 39].

Diverse attributes, including strength, stiffness, UV resistance, flammability, flame retardancy, and lifespan, exhibit variations among different thermoplastics. Of particular interest are the enhanced possibilities offered by fiber-reinforced thermoplastics, opening up new avenues for innovation. The integration of thermoplastic composites into additive manufacturing presents a spectrum of compelling advantages.

At the forefront of these benefits is the material's exceptional ability to withstand corrosion and chemical degradation. This inherent resistance amplifies its suitability for use in demanding and corrosive environments. Additionally, the standout feature of thermoplastics lies in their recyclability, forming a fundamental pillar for cultivating more sustainable production practices. This potential for recycling not only aligns with the responsible manufacturing ethic but also plays a main role in waste reduction and minimizing the ecological impact as a whole [13, 29].

For LFAM extrusion processes the rheological behavior of materials is very important because it helps understanding if a material is suitable for the technology and what parameters should be used, such as the extrusion temperature and screw speed. The addition of carbon (CF) or glass (GF) fibers to polymers is also very important because it can influence the rheological properties and glass transition temperature (Tg) of the materials [5, 31]. In this matter, the melt flow index (MFI) is very important because it is an indicator of the viscosity of the material. The MFI interval for extrusion processes usually oscillates between 2 and 12 [11].

The list below shows some of the most used materials (often with fiber reinforcement):

- Recycled and non-recycled PET;
- Recycled and non-recycled PETG;
- PLA;
- ABS;
- Cellulose fiber reinforced PLA;
- Recycled and non-recycled PP [36, 38, 40].

As mentioned before, most of the time those materials are reinforced with carbon or glass fibers to improve their properties. The carbon fiber has better mechanical properties than the glass fiber. On the other hand, glass fiber is much less expensive and also a good thermal insulator, unlike carbon fiber [20].

There are as well some materials already in use, mainly sustainable ones, which are not so common in 3DP solutions:

- Cellulose acetate;
- High-fire clays (white clay);
- Bio PLA;
- Low-fire clays (red clay) [35, 29];
- Bio-based recycled PA (based on vegetable oils instead of fossil fuels) [34];
- PolyAl (which comes from recycled drink cartons) [40].

## 2.4. Design for additive manufacturing

The practice of designing products to reduce manufacturing and assembly difficulties and costs is known as Design for Manufacture and Assembly (DFM). However, Additive Manufacturing Technologies have provided designers with an opportunity to rethink DFM and take advantage of the unique capabilities of these technologies (known as Design for Additive Manufacturing or DFAM) [41]. This encourages designers to explore new design concepts that are manufacturable by the selected AM process [6].

DFM involves understanding the constraints imposed by manufacturing processes and designing products to minimize constraint violation. While AM technologies have lessened some of these difficulties, not all of them have been eliminated. The conventional DFM guidelines for part manufacturing are not relevant to AM, but the design-for-assembly guidelines remain relevant and maybe even more important [42].

One of the most exciting aspects of AM is the design freedom it enables [2]. The capabilities of AM technologies offer new opportunities for customization, significant improvements in product performance, multifunctionality, and lower overall manufacturing costs. These unique capabilities include shape complexity, hierarchical complexity, material complexity, and functional complexity (Figure 14). This means that virtually any shape can be built, hierarchical multi-scale structures can be designed and fabricated, material can be processed at one point or layer at a time, and fully functional assemblies and mechanisms can be fabricated directly using AM processes [6, 43].

| Unique capabilities | Potencial opportunities | Example consequences |
|---|---|---|
| Shape complexity | Complex geometry | Simplified supply chain<br>Reduced operations<br>Reduced inventory |
| Hierarchical complexity | Custom geometry | Personalization |
| Material complexity | Multi-materials | Multi-functionality<br>Embedded sensors or actuators |
| Functional complexity | No tooling | Short lead-times<br>Short time-to-market |

Figure 14- AM unique capabilities examples [6].

Translating designs originally intended for traditional manufacturing methods directly into the realm of 3D printing is not a straightforward transposition. The distinctive capabilities inherent in 3D printing introduce novel possibilities that deviate from conventional practices [41]. Take, for instance, the seamless integration of multiple components within a singular design, a feat unattainable through traditional means reliant on manual assembly. By circumventing the necessity for joints established through riveting or welding, the ultimate output not only boasts elevated structural integrity but also yields substantial time economies [44].

Given the disparities in these design principles, a comprehensive adjustment in design approach becomes imperative to effectively fit additive manufacturing.

Case studies serve to meticulously evaluate the technical and commercial feasibility of implementing Large Format Additive Manufacturing [45]. At the core of these ventures lie the foundational concepts of design and printing strategies [13, 17].

AM processes can also help organizations integrated product development teams reduce the amount of time that they spend resolving constraints and conflicts. With AM, designers don´t have as many manufacturing constraints as in conventional subtractive manufacturing processes [6].

LFAM also offers the possibility of printing the part slightly oversized, to then machining the surfaces according to tight dimensional tolerances [27]. This allows to build parts with very restrictive designs [24].

### 2.4.1. Design guidelines for LFAM

When designing a part for LFAM some key points should be kept in mind:

- It´s important to know the **size of the print bed** and the maximum **range of the robotic arm** in all directions (x,y,z) [44];
- Do not forget the **maximum object size that can be transported** inside the facilities;

- To overcome the previous restrictions, the **part can be sectioned into several elements** and assembled afterward. That should be individually assessed for each project because it might create problems with the design and mechanical properties of the final part;
- The **layer width should be established in the beginning** so that it matches the required visual shape of the part (a higher Lh will create a more pronounced staircase effect) [18, 33];
- It's important to know if the **part was made in surface or solid mode** of the 3D modeling software. If it's in surface mode, the part walls will be printed in the center of the surfaces, splitting the Lw equally for both sides. If it's in solid mode, the part walls will be printed from the surface to the inside. This is very important to get the right dimensions when printing;
- **Straight segments should be split into several ones if their length is very big**, to avoid warpages. A big line width also helps to minimize this problem [44];
- The geometries should have few and **small overhangs**;
- To **design supports easy to take off**, minimizing the surface finishing needs;
- A **toolpath planning** should be made when creating the part's geometry [25, 43].

When slicing and preparing a part to be printed, some aspects should also be considered to ensure it doesn´t affect the final design of the part:

- Decide if the **path will be a closed or open loop**. Remember that having an open loop will more than likely create travel paths (can be avoided with start-stop extrusion systems);
- It should be decided if the part will be made in a **spiralized contour** (gradually moving up, in the z direction) or **layer by layer** (only moving up always at the end of the layer). Usually, the second option leaves a visual mark which is the seam;
- The printing path will never have perfectly sharp corners**. Corners should have a radius that is half of the layer width**;
- Complementing the previous topic, **slower speeds should be used to reduce the roundness of the corners** (increasing the precision);
- The **part orientation** when slicing should be the one that minimizes the surface's slope;
- For angled top parts, it should be decided if the layers will be made by **horizontal layering** (creating a staircase effect) or by **non-planar layering** (tilting the extruder) [33, 42, 46].

# Chapter 3

# Materials and methods

In this chapter, the methodological procedures and materials used to carry out this master's dissertation work will be presented. Different materials, tests and construction platforms were used to see how much they influence the design requirements, as represented in Figure 15.

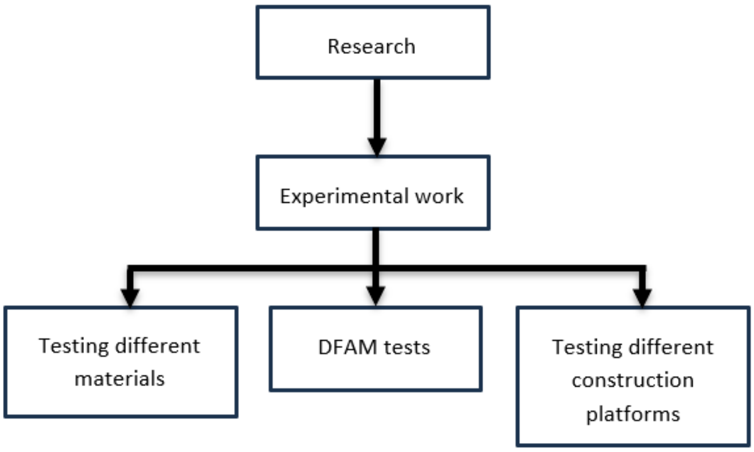


Figure 15- Scheme of the applied methodology.

## 3.1. Materials tested

Along this work, several materials were tested to create a list of the acceptable ones to print. That allowed to discover materials with different characteristics, like density, mechanical resistance or surface finishing. This way, for a certain project, the printing material can be chosen based on the part requirements. Table 4 shows all the materials that were tested.

Table 4- List of tested materials.

| **Material** | **Supplier** | **Reference** |
|---|---|---|
| PP30%GF (polypropylene with 30% glass fiber) | Caracol | PP-GF30 |
| PETG (polyethylene terephthalate glycol) | SK Chemicals | Skygreen S2008 |
| PLA+PSAC (polylactic acid + polysaccharides) | Nurel | Inzea F38 |
| PLA (polylactic acid) | NatureWorks | Inzeo 3D700 |
| PLA | Natureworks | Ingeo 2003D |
| Bio PA (polyamide) | Nurel | Recomyde B30 P4 G30 |
| PLA with cellulose fibers | UPM Biocomposites | UPM Formi 3D20/19 |
| Recycled PET (polyethylene terephthalate) | SK Chemicals | Ecotria R100 |

### 3.1.1. Clean-up procedure for changing material

Each time a different material was used or tested, a thorough cleanup of the whole system (elements (c), (d) and (e) of figure 6) was needed to eliminate all the remnants of the previous material and don´t contaminate the new material that will be used.

For that, a vacuum cleaner was used to take all the material inside the silo (Figure 16), hoses, venturi connections, filters, and extruder cup. In case there was a lot of dust in the system a cloth was also used to clean the interior surfaces. In the end, compressed air was always used to ensure that all the particles got out.

Figure 16- Clean up procedure using the vacuum cleaner.

All the material collected by the vacuum cleaner was then put inside a bag and zip-tied so that it could be used later without any contamination problems.

It was also very important to purge the extruder chamber with specific purging material. This material expands when heated, expelling what´s inside the chamber. To do that a quantity of approximately 2x the chamber volume was extruded (Figure 17).

Figure 17- Purge of material.

## 3.2. DFAM tests

The first experimental study consisted of performing several tests to register the line width (w) value. To do that a part with 3 sides was conceived (Figure 18).

When printing, each side had a different printing speed value (100%, 75% and 50% of the input speed), manually controlled, which required the operator to be there during the whole test. The printing speed transitions were always made in the corners so that it didn’t interfere with the measurement zone.

This allowed to build graphs of the line width as a function of the printing speed and extrusion RPMs, for each material. The graphs were different for each nozzle diameter and each layer height.

Further ahead, more tests were made to register the acceptable angles, printing speeds and layer heights, for the different materials.

Besides the tests, some case studies were also made alongside this work. The case studies were very useful for this thesis because they allowed to register the parameters and to take photos of different parts, complementing the information for the different materials technical sheet and the table of the common defects.

### 3.2.1. Raft/brim procedure

Before starting a construction, a raft or brim was selected, depending on the part requirements. For aesthetic parts, the brim is more suitable because it doesn´t ruin the first layer. For materials likely to have big warps a raft is better because it can hold the part to the platform more effectively.

To secure the raft/brim to the construction platform staples or screws were used, doing this while the material was still hot and soft. The screws and staples were placed mainly in the corners because that is where the part is likely to have big warps, lifting from the platform;

To attenuate the construction platform depressions, the first layer was done at a slower speed (usually 50%). To provide good adhesion between the raft/brim and the first layer, that layer was always done without cooling;

### 3.2.2. Data collection procedure

- Line width

It's important to mention that although "w" is mentioned as the line width, what is measured is actually the wall width, which has a small error associated. To simplify the process and since "w" in the software refers to the line width, the terminology was adopted.

When performing the experimental tests all the used parameters were registered in an Excel sheet. After the tests had been finished and the constructions cooled down, the final line width was measured using a caliper from Mitutoyo with a resolution of ±0,02 mm (Figure 18).

Figure 18- Caliper from Mitutoyo.

For each wall, the line width was always measured 5 times, on the central zone of each surface (red zones in Figure 19) being the average value used to build the graphs.

Figure 19- Part created in the experimental tests and its measurement zones.

Measurements of the line width were not taken when the surfaces were noticeably not acceptable (“zigzag” or melted layers, for example). The Figure 20 shows an example of that.

Figure 20- Example of a not acceptable surface.

- Layer heights (Lh) and printing speeds (V)

Concerning these parameters, 2 parts with different geometries were conceived to register the maximum acceptable layer height and printing speed, for a specific material.

The first designed part had only straight lines, with the surface slope slowly increasing along the Z direction (Figure 21). This allowed to check the maximum slope angle for a certain Lh. The sharp corners of the part also allowed checking the acceptable printing speed for that geometry.

Figure 21- Test parts made with the same material, for different layer heights.

The second part had a more organic shape, with the surface slope slowly increasing along the Z direction as well (Figure 22). Once again this allowed to check the maximum slope angle for a certain Lh.

Figure 22- Organic test part with fallen layers due to the Lh being too big.

The different geometries of the test parts also allowed to test the material's behavior, for straight and curved surfaces.

Since there was not enough time to perform these tests on all the materials and respective layer heights, other projects done along this work (Chapter 5) allowed to complement this information, registering once again the acceptable printing parameters.

## 3.3. Construction platforms

There are many materials possible to use as a construction platform (or printing bed as commonly known). In this work two different ones were used, MDF and glass. Those materials were used because they were easy to get and had appropriate characteristics for building the parts on top of them. Each one had its advantages.

- **Medium-density fiberboard wood (MDF)**

This type of construction platform was the one provided by *Caracol*, mainly because it’s cheap and it allows to secure the part to the platform by several methods (staples, screws, or glue). It might be the one used most by the industry because it handles well most of the materials. The Figure 23 shows the surface of the 6 $m^2$ MDF plate.

Figure 23- MDF platform.

- **Glass**

This construction platform was used mostly for parts that are intended to be visible from both sides (Figure 24). 3DP adhesive/glue was also added to the glass to improve the adhesion with the part, however for large format parts (with consequently bigger warps) it is insufficient to maintain full contact between the two. The Figure 25 shows the glue that was used.

Figure 24- Glass platform.

Figure 25- Adhesive spray for 3DP.

### 3.3.1. Construction platform calibration procedure

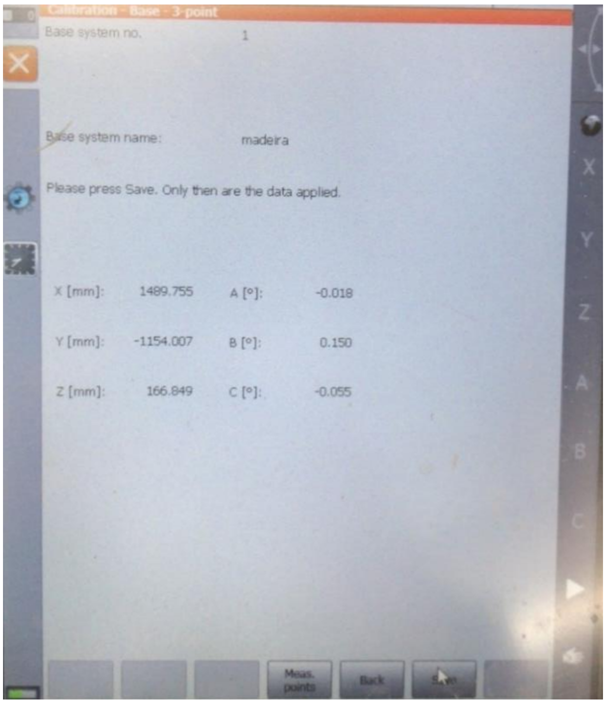
The calibration procedure was necessary each time the construction platform was moved or changed to another.

This procedure has 2 steps. The first one implies calibrating the robotic arm so that it knows where the construction platform plane is (z=0). This is done through the robot controller, pressing the button sequence: Main menu; Start-up; Calibrate; Base; 3-point.

A previously calibrated 1mm thickness metal sheet is necessary to put between the nozzle and the construction platform. The calibration requires 3 different points (defining a plane), all three 3 taken with the nozzle contacting the metal sheet (Figure 26).

Figure 26- Metal sheet used to calibrate.

In the end, the calibration must be saved by pressing the button “save” and the calibration values registered, to later insert them in the construction software. The Figure 27 shows that procedure on the controller.



Calibration - Base - 3-point

Base system no. 1

Base system name: madeira

Please press Save. Only then are the data applied.

| | | | |
|---|---|---|---|
| X [mm]: | 1489.755 | A [°]: | -0.018 |
| Y [mm]: | -1154.007 | B [°]: | 0.150 |
| Z [mm]: | 166.849 | C [°]: | -0.055 |

Figure 27- Robotic arm controller menu to finalize the calibration procedure.

# Chapter 4

# Results and discussion

In this chapter the results obtained throughout this work will be presented, organized into four sections: information collected for each material, problems (defects) detected and the respective solutions, analysis and comparison of the different construction platforms.

The last section demonstrates some of the results presented in the previous sections.

## 4.1. Results for each material

All the materials had their results registered, allowing them to be classified as suitable materials for the AM equipment or not. For the approved materials, a printing datasheet was made to put the information that is necessary for someone to know, when using that material. The sheet will be very useful in the future to know exactly what parameters should be used when printing large format parts, for each material.

Those printing data sheets include some of the material properties, its printing parameters, important precautions and cares.

Some materials also have attached the graphs of the line width. Only a few were made because creating accurate graphs requires several tests and time.

All the results presented here were based on the different tested geometries, and also on some case studies made for certain materials.

Approved materials:

- PP30%GF

This material delivered good results, being easy to print and adequate for a variety of parts and applications. Its mechanical properties are very good, especially the impact resistance. It also provides the parts good mechanical resistance without the necessity of having very thick walls, which would increase the weight substantially. This material is therefore indicated for structural applications. The Figure 28 shows a perfect example of that.

Figure 28- Support structure of a dashboard counter mold made from PP30%GF.

The Table 5 shows some data that was collected during the tests, and which will be important to put in the material datasheet. Although the dehumidification parameters and melting temperature were provided by the supplier technical sheet, the extrusion temperature had to be adjusted for the equipment.

Table 5- Printing parameters of the PP30%GF.

| | |
|---|---|
| Dehumidification temperature (Td) and time (t) | 80°C during 2h |
| Extrusion temperature (Tm) interval | 230-250°C |
| Acceptable speed (V) interval | 20-90mm/s |
| Nozzle diameters (D) and acceptable layer heights (Lh) | For a D=3mm: 0,5mm ≤ Lh ≤ 1,5mm<br>For a D=5mm: 1,5mm ≤ Lh ≤ 2,5mm |
| Nozzle diameters (D) and acceptable line widths (Lw) | For a D=3mm: 3,5mm ≤ Lw ≤ 5,5mm<br>For a D=5mm: 5,5mm ≤ Lw ≤ 7,5mm |

Observations: Due to the big contractions of PP, the first layer tends to detach from the construction platform at the corners/edges, especially when the part has long and straight walls.

To counteract this effect, staples should be used in the corners, and in the case of a raft, on both sides of the part. The raft/brim should be dense and made at low speeds, without cooling, to promote maximum adherence.

If the straight walls are very long, it is advisable to use DFAM knowledge to, for example, divide the straight segment into 2, which minimizes the contractions.

For this material it’s always recommended to use cooling after the first layer, being the air pressure adjusted in function of the layer time.

Graphs: For this material, it was possible to elaborate 2 graphs. The first one for a Lh=1mm (Figure 29) and the second one for a Lh=1,5mm (Figure 30), both for a 3mm nozzle.

The results allowed to conclude that for a certain extrusion RPM, the Lw follows a tendency line which is inversely proportionally to the printing speed. The higher the extrusions RPMS the less precise the tendency lines are.

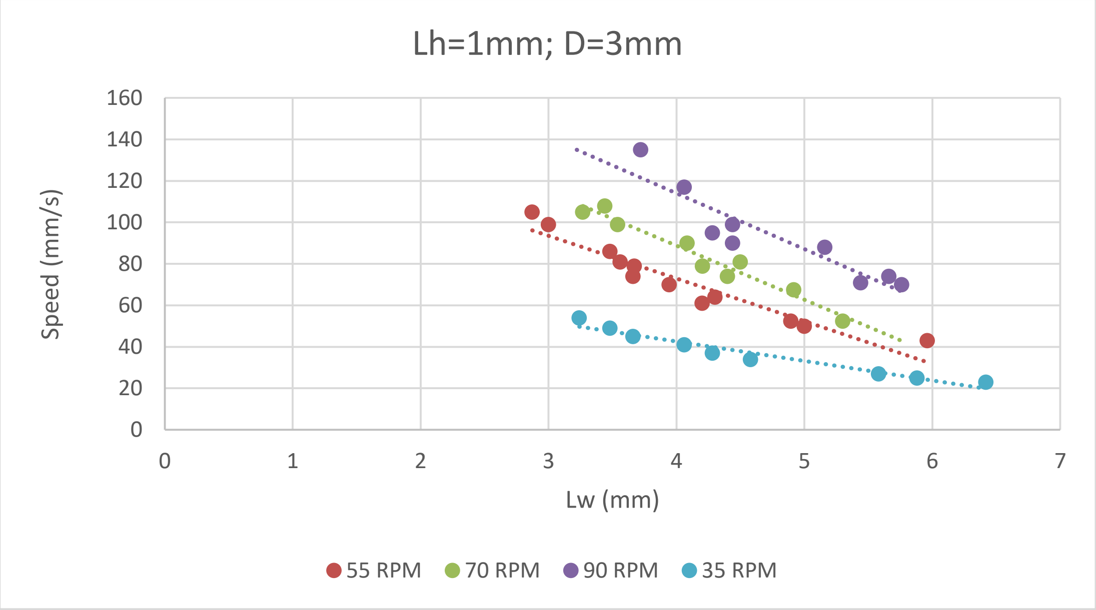


Figure 29- Line width as a function of the robot speed and extruder RPMs, for the PP30%GF.

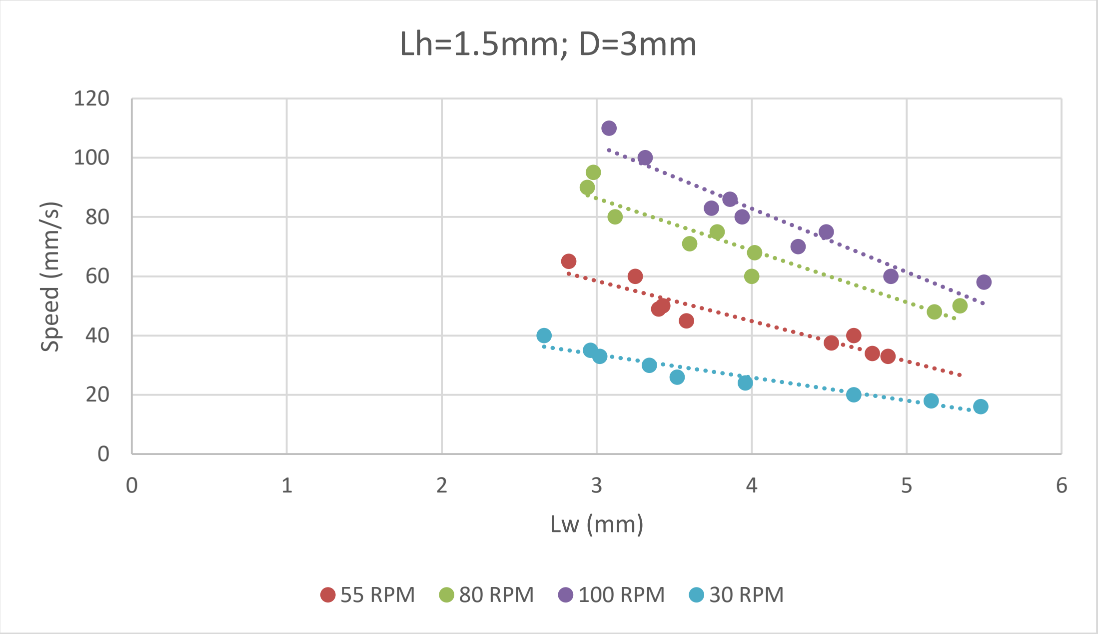


Figure 30- Line width as a function of the robot speed and extruder RPMs, for the PP30%GF.

- PETG (Skygreen S2008)

This material was, alongside PP30%GF, a very successful material for the printing of large format parts. This material presented excellent surface finishing and very good characteristics for strong aesthetic parts.

Its transparency allows it to play with light's reflection on decorative parts. An interesting aspect of this material is that the bigger the Lh the more transparent the part becomes, resembling glass (Figure 31).

Besides that, this material withstands big slope angles (>45°) which enables building parts with unique geometries.

Figure 31- Transparent part made from PETG.

In Table 6, the processing parameters of the PETG by 3D printing are presented.

Table 6- Printing parameters of the PETG.

| | |
|---|---|
| Dehumidification temperature (Td) and time (t) | 65°C during 4h |
| Extrusion temperature (Tm) interval | 250-270°C |
| Acceptable speed (V) interval | 15-35mm/s |
| Nozzle diameters (D) and acceptable layer heights (Lh) | For a D=3mm: 1mm ≤ Lh ≤ 2mm<br>For a D=5mm: 2mm ≤ Lh ≤ 3mm |
| Nozzle diameters (D) and acceptable line widths (Lw) | For a D=3mm: 3,5mm ≤ Lw ≤ 6,5mm<br>For a D=5mm: 4,5mm ≤ Lw ≤ 7,5mm |

Observations: Besides being transparent, this polymer is very hygroscopic, which requires a good dehumidification of the material and a deep cleaning of the feeding system, as any air bubble or contamination is easily visible in the final product.

It's also recommended to purge a generous quantity of material before starting a construction so that any pellet left inside the tubes and extruder chamber doesn´t ruin the part.

Making generous rafts/brims it's also an advantage because it allows to check if the material is ready to start the construction.

This material tends to crack when printing thin walls. To eliminate this problem, the walls should be thicker and cooling should not be used (only for Lt < 30s).

Graphs: For this material, it was possible to elaborate 2 graphs (Figures 32 and 33), however, they are both very incomplete due to not having enough data. This made it impossible to create accurate RPM tendency lines.

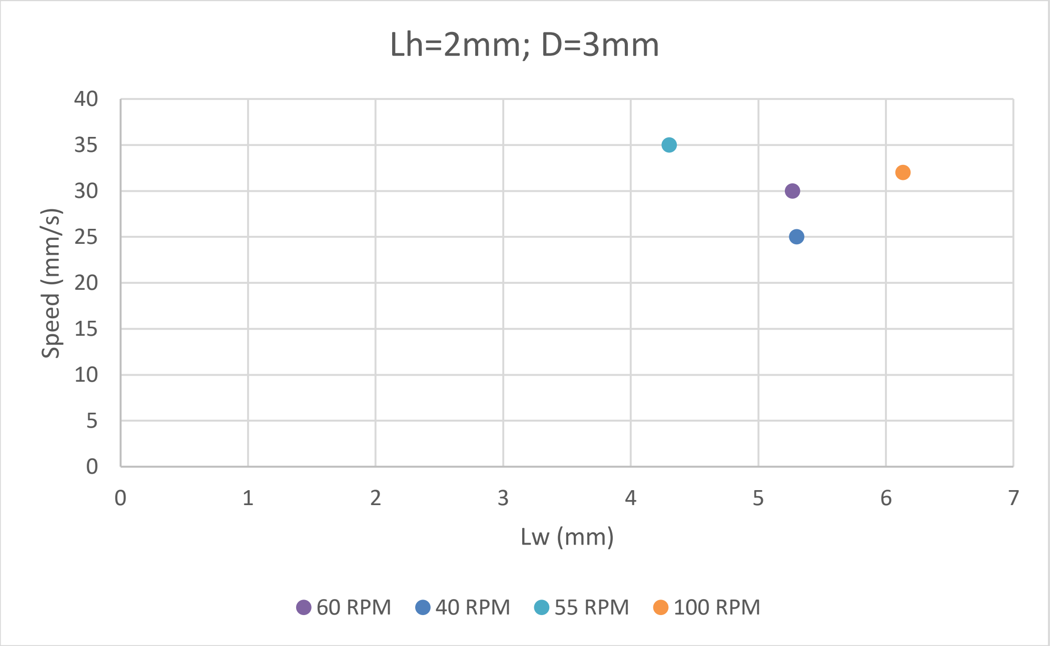


Figure 32- Line width as a function of the robot speed and extruder RPMs, for the PETG.

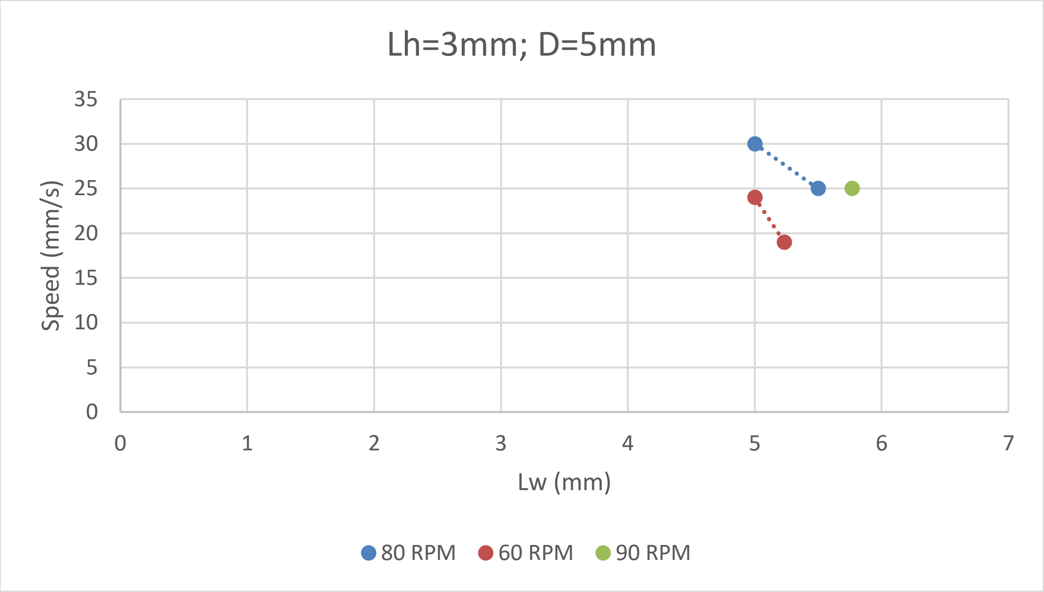


Figure 33- Line width as a function of the robot speed and extruder RPMs, for the PETG.

- PLA (Ingeo 2003D)

Few tests were made with this material because there was only a small quantity of it to test (10Kg), so it was not possible to collect significant data.

Still, this material presented good results. It proved to be very appropriate for aesthetic parts that require a very smooth surface finish. The material is translucent (visible in Figure 34) which makes it ideal for decorative parts and small objects that require the transmission of light.

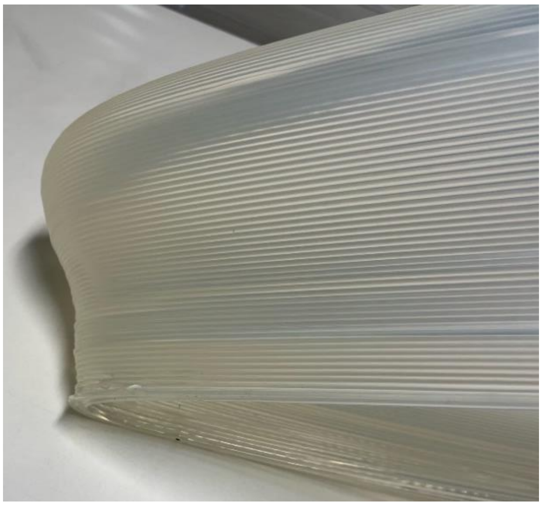


Figure 34- Translucent part made from PLA.

In Table 7, the processing parameters of the PLA by 3D printing are presented.

Table 7- Printing parameters of the PLA.

| | |
|---|---|
| Dehumidification temperature (Td) and time (t) | 90°C during 2h |
| Extrusion temperature (Tm) interval | 190-210°C |
| Acceptable speed (V) interval | 15-50mm/s |
| Nozzle diameters (D) and acceptable layer heights (Lh) | For a D=3mm: 1mm ≤ Lh ≤ 2mm |
| Nozzle diameters (D) and acceptable line widths (Lw) | For a D=3mm: 3,2mm ≤ Lw ≤ 7,2mm |

Graphs: For this material, it was possible to elaborate_a graph (Figure 35), however, it has scarce data due to the few tests done.

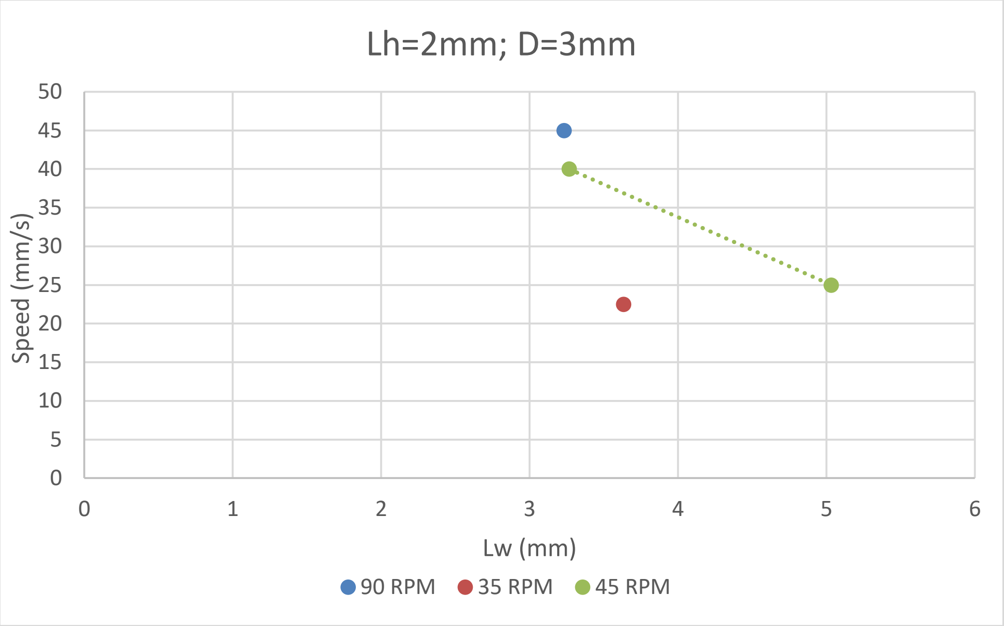


Figure 35- Line width as a function of the robot speed and extruder RPMs, for the PLA.

- PLA with cellulose fibers (UPM 3D20/19)

This material proved to be appropriate for the AM equipment, however, there was only a sample of 10kg to test, so it was not possible to collect enough data concerning the printing parameters.

Since it almost didn´t have any warpages, makes it suitable to print parts with long and straight surfaces.

Its touch feel resembles wood, which allied to its good mechanical properties makes it suitable for the printing of furniture, for example. The Figure 36 shows a part made with this material, with a 400mm height.

Figure 36- Part made from PLA with cellulose fibers.

In Table 8, the processing parameters of the PLA with cellulose fibers by 3D printing are presented.

Table 8- Printing parameters of the PLA with cellulose fibers.

| | |
|---|---|
| Dehumidification temperature (Td) and time (t) | 80ºC during 3h |
| Extrusion temperature (Tm) interval | 140-180ºC |
| Acceptable speed (V) interval | Only 30mm/s was tested |
| Nozzle diameters (D) and acceptable layer heights (Lh) | Not enough data |
| Nozzle diameters (D) and acceptable line widths (Lw) | Not enough data |

Observations: For this material, it is crucial to make a deep clean of the whole feeding system because it melts at a low temperature. Any pellet left inside the system won´t probably melt at this temperature, jamming the extruder screw and ruining the part.

It's recommended to make line widths (Lw) close to the nozzle diameter (D), otherwise, it tends to accumulate material around the nozzle, which eventually falls, creating defects on the part.

- Recycled PET with PETG (SK ecotria R100)

Recycled PET allowed to have adequate results when using the right parameters, otherwise, it shows inconsistencies in its extrusion due to the recycled material not being all the same. That makes it difficult to have a homogeneous extrusion.

The pellets have different colors, which are reflected in the printed part, showing some variability in the color (Figure 37) and in the layer width.

The different tests showed that this material behaves better with big layer heights (Lh) and straight surfaces, without many corners or sharp turns.

Perturbances such as the raft tend to propagate through the part.

Figure 37- Color heterogeneity on the surface of a recycled PET part.

In Table 9, the processing parameters of the PET by 3D printing are presented.

Table 9- Printing parameters of the recycled PET.

| | |
|---|---|
| Dehumidification temperature (Td) and time (t) | 150ºC during 6h |
| Extrusion temperature (Tm) interval | 260-280ºC |
| Acceptable speed (V) interval | Only tested up to 40mm/s |
| Nozzle diameters (D) and acceptable layer heights (Lh) | For a D=3mm: 1mm ≤ Lh ≤ 2,5mm<br>For a D=5mm: Not enough data |
| Nozzle diameters (D) and acceptable line widths (Lw) | Not enough data |

Observations: Rafts and staples should always be avoided with this material since it propagates the perturbances over the part’s surface.

Preferably secure the part with screws instead of staples.

This polymer requires a good dehumidification of the material since it is very hygroscopic.

Low printing speeds (<35mm/s) should be used to avoid sudden changes in the direction.

Using big layer heights is beneficial because it keeps the line width more constant.

Failed materials:

- Bio PA (Recomyde B30 P4 G30)

This material proved not to be suitable for the AM equipment. Its extrusion was not consistent, creating lines with a line width (Lw) that was not constant. This might be because of the material’s MFI, however, that parameter was not provided in the material’s technical data sheet. Although it wasn´t made, a MFI test could clarify this situation.

The parts have very bad adhesion between layers (Figure 38) and are also very fragile, breaking very easily.

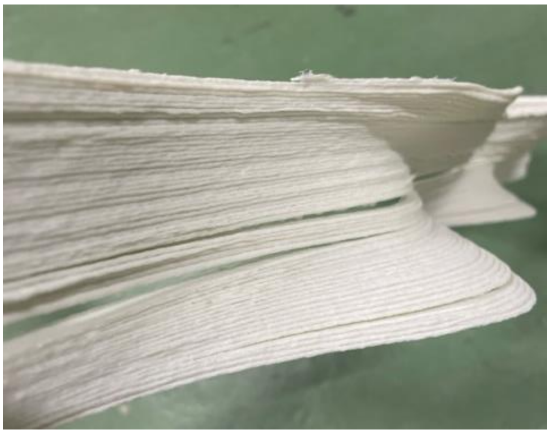


Figure 38- Part made from Bio PA.

- PLA+PSAC (Inzea F38)

This material proved to be very difficult to use, as it has a very viscoelastic behavior in which it does not come out of the nozzle at a constant flow.

Any perturbance such as the raft or the staples, for example, creates a wavy pattern that not only spreads over the surface but also intensifies reaching a height where the lines are made “dot to dot” (Figure 39).

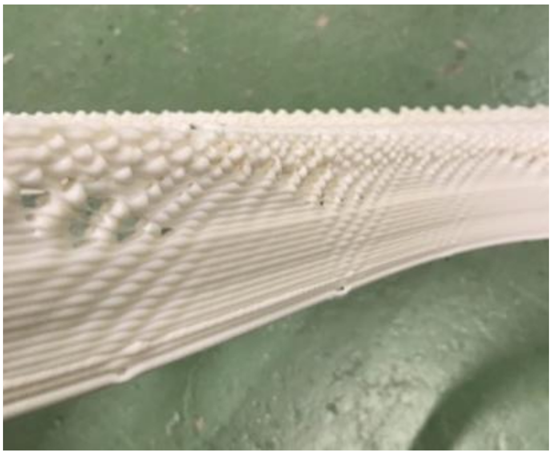


Figure 39- Wavy pattern created by the material.

To obtain decent results the part can´t have curves or corners, and neither use a raft (Figure 40). This made the material unfeasible to use.

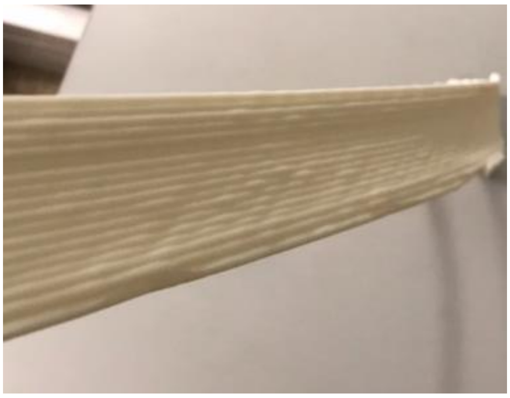


Figure 40- Straight surface made from PLA+PSAC.

- PLA (Ingeo 3D700)

This material proved to be very difficult to use because it has a very low Tg. At a temperature of 45°C it starts to get tacky which allows it to stick to the walls of the silo (partially because the silo can´t maintain such a small temperature, so it uses intervals of temperature variation).

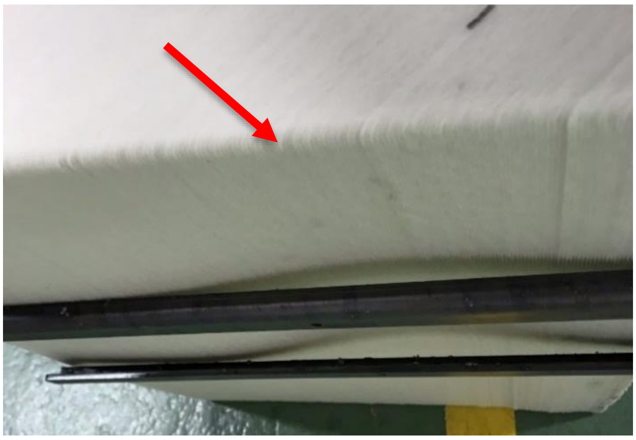
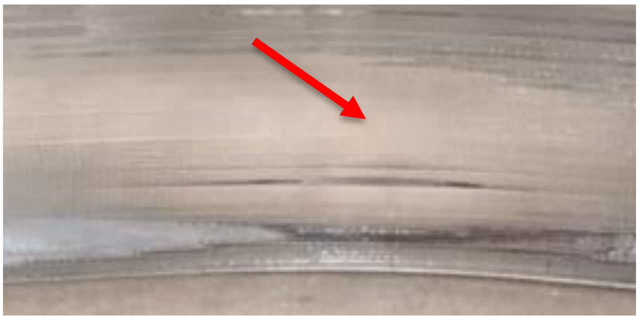
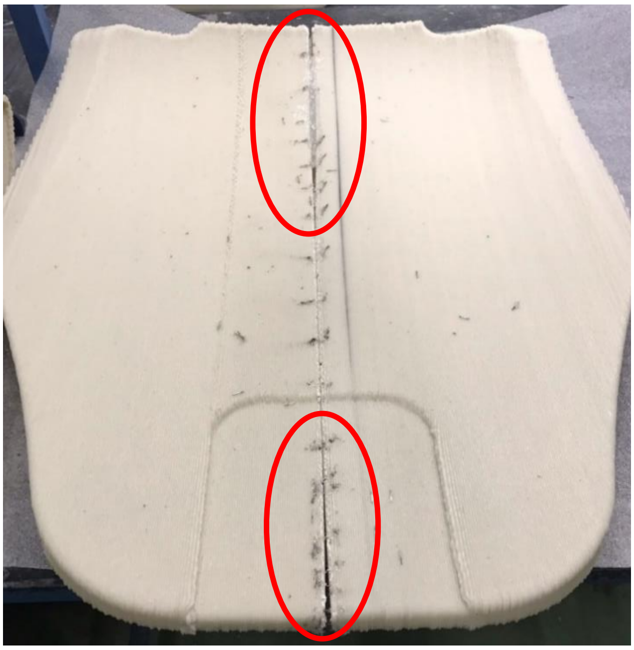
Even more serious is the fact that it gets stuck in the extruder screw (red zone in Figure 41), preventing it from rotating and subjecting the motor to a breakdown. Due to the screw's temperature gradually rising by heat conduction and due to the low Tg of the material, it creates a zone where the material sticks to the screw but at the same time doesn´t melt.

Figure 41- Pellets stuck in the extruder chamber.

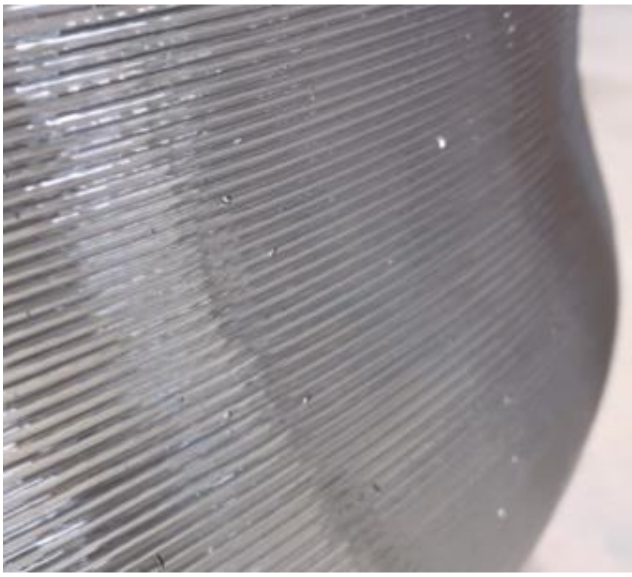
## 4.2. Defects

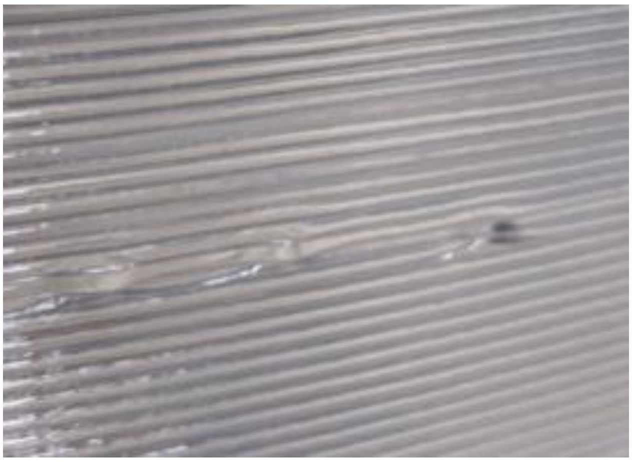
Along this work, several defects occurred when printing the parts in different materials and different circumstances. To overcome those problems many solutions were implemented, which solved or at least attenuated them. Although the majority of the defects can occur in any material, some of them only occur for a specific material. The Table 10 shows that information.

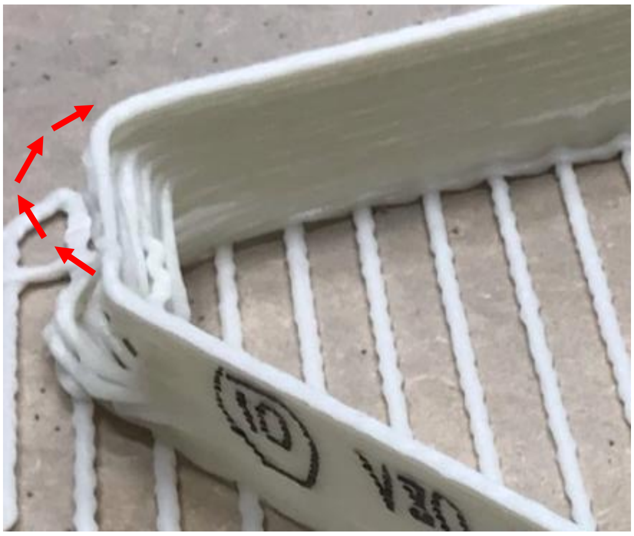
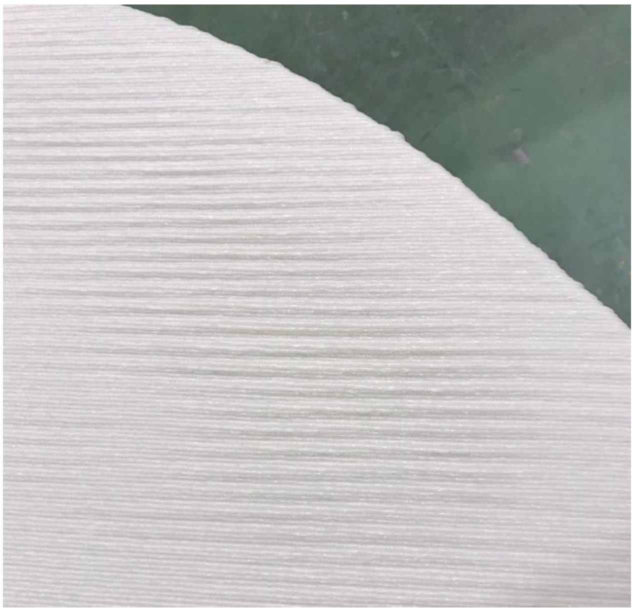
Table 10- Critical defects that occurred during the parts construction and the adopted solutions.

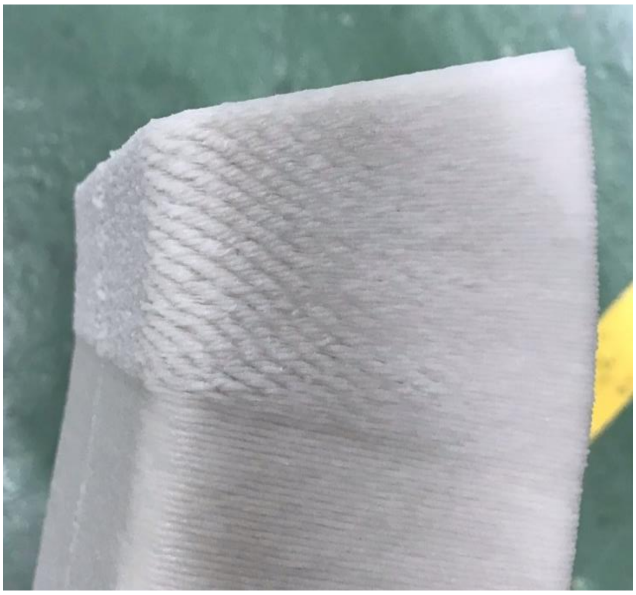
| Defect | Example image | Cause | Solution |
|---|---|---|---|
| Side and top warps |   | Shrinkage of the material | Use interior supports/ reinforcements;<br>Make the straight parts shorter or curved;<br>Use double walls; |
| Lower warps |  | Shrinkage of the material | Make denser rafts/brims;<br>Increase the extrusion RPMs in rafts/brims;<br>Put more staples or screws, especially on the corners;<br>Make the straight parts shorter or curved; |

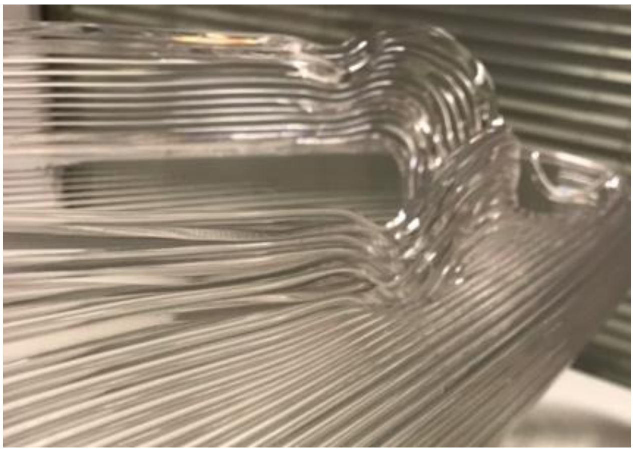
|  |  |  |  |
|---|---|---|---|
|  |  |  |  |
| Periodic defect | <br> | The robot gradually reduces and increases the speed, especially in tighter corners | Reduce the speed |
| Gaps between layers |  | Insufficient adhesion between layers | Reduce the speed and/or to reduce the Lh |

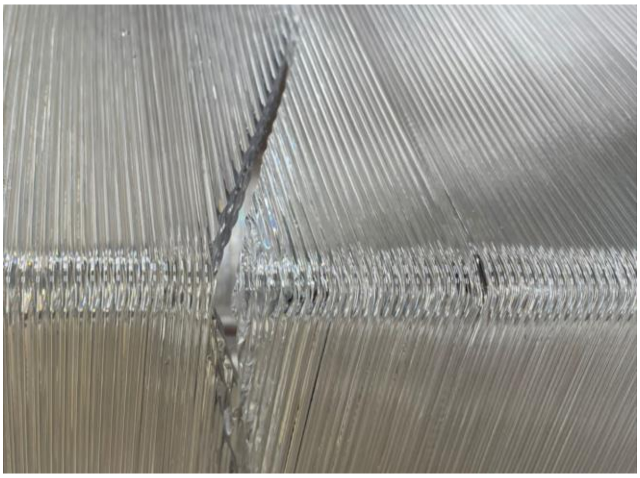
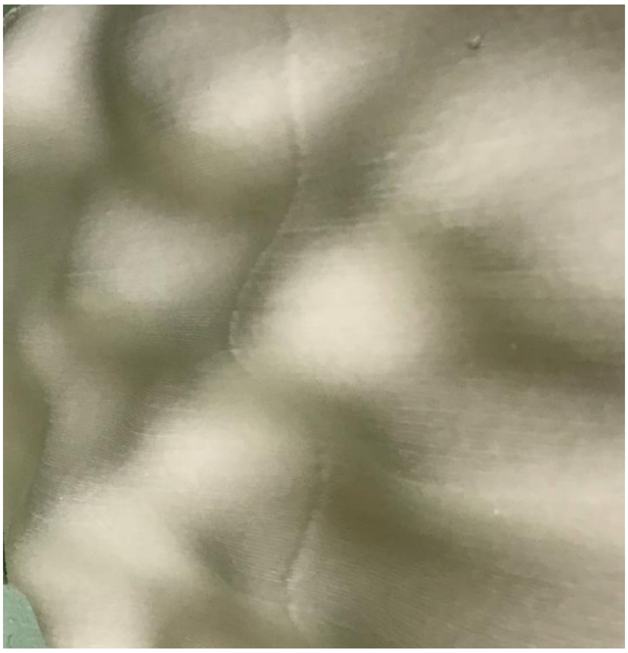
| | | | |
|---|---|---|---|
| |  | | |
| Zigzag line |  | Too much extrusion RPMs for the speed | Increase the speed or reduce the extrusion RPMs |
| Air bubbles<br>(specific for transparent materials, like the used PETG) |  | Moisture in the material | Dehumidify the material for a longer time;<br>Purge a considerable amount of material; |

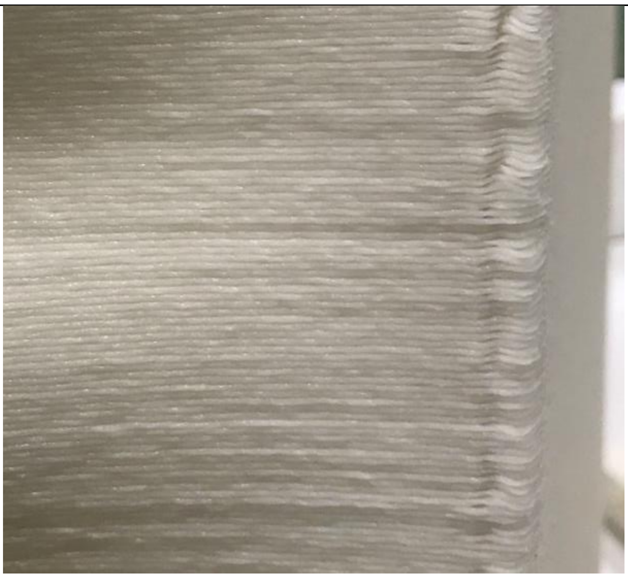
| | | | |
|---|---|---|---|
| |  | | |
| Material contamination | <br><br> | Remnants of previous materials in the system | Clean the whole system thoroughly;<br>Purge a lot of material; |

| | | | |
|---|---|---|---|
| Shortcuts in corners/curves |  | The curve is too tight for the extrusion parameters | Reduce the speed and/or reduce the Lh |
| Melted layers |  <br> | Excess heat | Increase the air pressure and/or reduce the speed |

| | | | |
|---|---|---|---|
| Compressed layers |  | Non-parallel layers | Optimize the extrusion parameters (does not eliminate the defect, but attenuates it) |
| Burnt material<br>(The visual aspect is like the contamination one, but the cause is different) | <br> | Nozzle leaks burnt/degraded material through the thread<br>(Check the bottom picture) | Change/ rectify the nozzle |

| | | | |
|---|---|---|---|
| Fallen layers | <br> | Overlap too small | Reduce the Lh and/or to decrease the wall slope |

| | | | |
|---|---|---|---|
| Unattached surfaces |  | Too small contact area or too much distance between surfaces | Increase the contact area;<br>Decrease the distance between surfaces;<br>Increase the extrusion RPMs (bigger line width); |
| Cracks |  | Material thermal stresses | Increase the room temperature;<br>Use double lines;<br>Remove carefully from the platform; |
| Seam line |  | Transition path when the robot moves up to start another layer | “Hide” the seam line in a strategic area (corners or interior zones for example);<br>Use the spiralized mode; |

|  |  |  |  |
|---|---|---|---|
|  |  |  |  |

Note: All the images presented in this table are zoomed in to point the defect, showing relatively small areas of the parts, with lengths between 200mm and 400mm.

## 4.3. Comparison among the different construction platforms

After printing several parts in each construction platform, a table with their different characteristics (Table 11) was built to help understand what is the most suitable platform for a certain project, since each one has its advantages and disadvantages.

Table 11- Characteristics of the different platforms.

| **MDF** | **Glass** |
|---|---|
| • It affects the bottom section of the part with little parts of wood;<br>• The staples require considerable time to take off when used in big quantities;<br>• Allows to use staples or other means to secure the part to the construction platform (wood glue for example);<br>• Indicated for large format parts that are likely to have big warps;<br>• The MDF surface is irregular, so the first layer of the part is irregular as well. | • Both sides of the parts look good, although the surface of the first layer is always a bit crushed;<br>• Since no staples are used here it requires less operator time;<br>• Besides an appropriate glue (3DP adhesive for example) there is no other way to secure the part to the construction platform;<br>• Indicated for aesthetic parts and materials with few warps;<br>• The glass surface is completely flat so the first layer of the part is also flat. |

The Figure 42 shows the same part, made with the same material, on the 2 different construction platforms. As expected the 2 construction platforms delivered very different results.

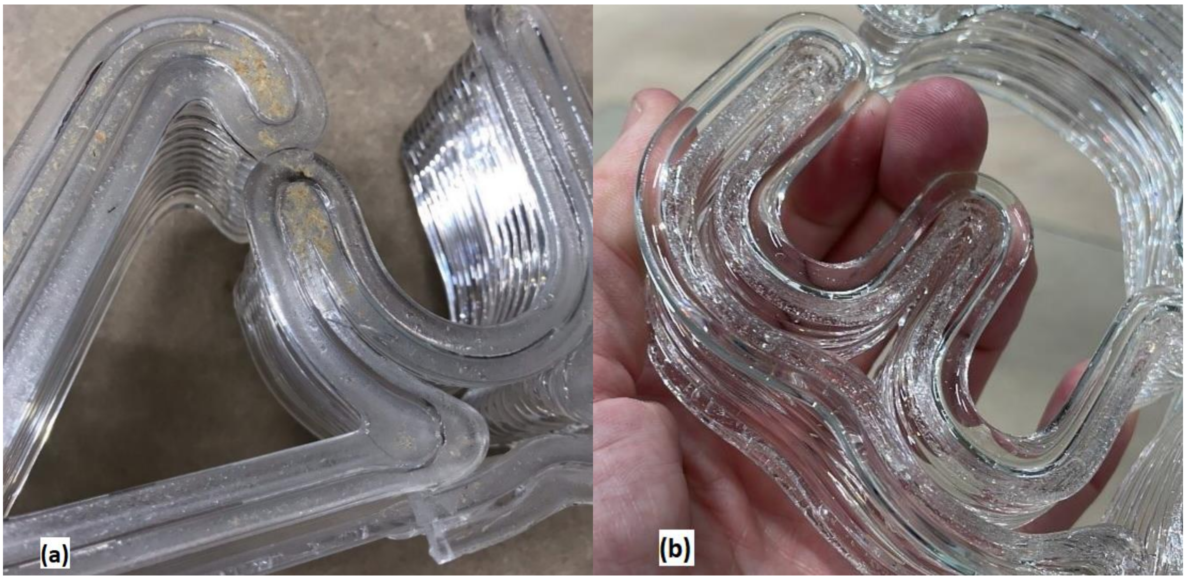


Figure 42- Part made on a MDF platform (a); Part made on a glass platform (b).

Chapter 5

# Case studies

## 5.1. Football dummy

Introduction: The project consisted of making a human-size dummy with AM technology, to be hit by balls in football practices. The dummy was also required to be transparent.

The main reason that disputed this project was the high demand and waiting time for the commercial football dummies, made by injection molding (shown in Figure 43). The main goal was to make one as capable as that one, but in a faster way.

Figure 43- Dummy project to be made through AM.

Development: Since the dummy needed to be transparent the material selected was the PETG. Others could be used, like PLA, but PETG was the one available at the time.

The main challenge was to change the dummy design to be viable to be manufactured by the LFAM equipment. Those design changes consisted mainly:

- Filling the dummy interior holes to eliminate the robot's travels which would extrude material during that time, ruining the part;
- Instead of making the dummy horizontally (laid down in the construction platform), with a small thickness (less than 40mm), it was made vertically with a double wall. This ensured both sides looked good and it helped to increase the impact resistance;
- Uniting the 2 walls in the middle of the part to increase the dummy’s resistance. This center contact zone was later changed to a continuous vertical line, instead of a full wall contact, to reduce the accumulated heat, which caused the layers to melt.

Results: The printed dummy had a height of 1800mm and a thickness of 50mm (Figure 44). After the construction, the dummy was hit several times with soccer balls and no cracks or delamination occurred.

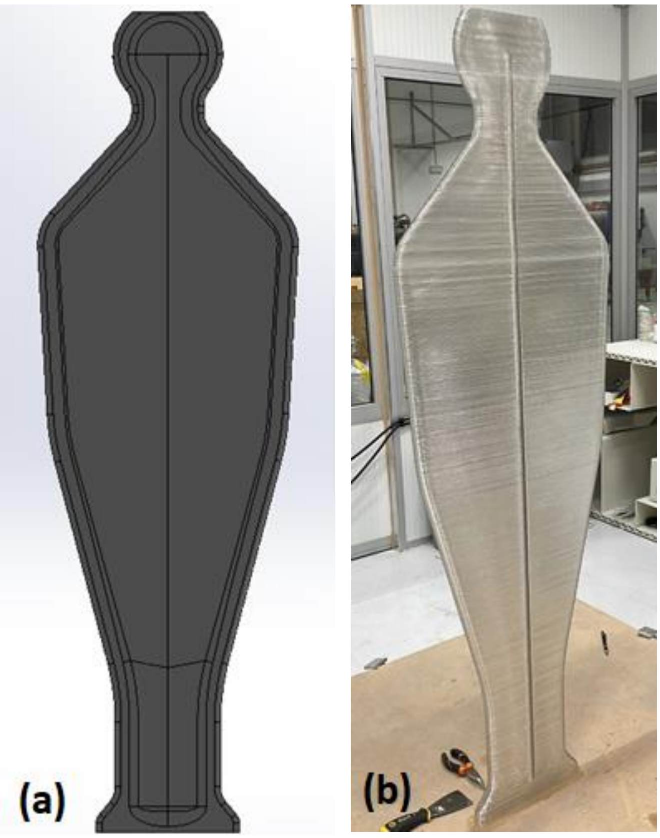


Figure 44- Final dummy created: solidworks model (a); printed part (b).

## 5.2. LFAM furniture

Abstract: The furniture sector is characterized by intensive labor and many manufacturing steps to obtain the final product, generating significant amounts of waste. The use of thermoplastics to produce furniture has several advantages over wood, such as the fact that many of them do not absorb moisture, have high durability, good mechanical strength, and resistance to atmospheric agents, in addition to being recyclable. Thermoplastics can therefore be a good alternative for replacing some conventional furniture, especially outdoor furniture (urban furniture, boats and applications involving contact with the sea), and applications where personalization and exclusivity are crucial [47].

Design for Additive Manufacturing and the choice of material are extremely important here, as furniture requires adequate mechanical resistance, good surface finish and good stability to ultraviolet (UV) rays. Thus, the challenge was to establish a suitable set of parameters for LFAM, especially in terms of the design and final quality of printed parts [21].

A systematic study enabled the successful printing of several parts of furniture using generative design [45]. All the parts used the same generative pattern of polygons. The company Spectroom took charge of that design part [48].

Along the work, 3 materials were tested:

- PP with 30% glass fiber;
- PETG;
- Recycled PET.

Results: PP was eventually excluded because it caused high contractions which were difficult to control, and the parts also had a rough surface, not very pleasant to the touch.

Although recycled PET showed some limitations with certain geometries, in other geometries they were overcome with an adequate selection of printing parameters.

The printed parts had some variability in color and layer width. The color problem could, however, be overcome with the proper use of dyes.

PETG was the material that showed the best results, with emphasis on its transparency, which gave the parts a unique appearance, impossible to replicate, for example, with wood. The Figure 45 shows those printed parts, having a construction height (which is the width of the part) of 500mm.

Figure 45- Furniture parts printed in PETG.

The work developed was a continuous process of improvement in part design and printing parameters.

For the printing path, it was necessary to conceive double and triple lines to “close” the path, while satisfying the aesthetics of the part at the same time (Figure 46).

The number of lines also had to be a compromise between design and mechanical properties. On the one hand, a greater number of lines confers greater mechanical resistance and reduces lateral contractions, on the other hand, it significantly increases the weight, and consequently the cost and time of production of the part. The tests performed allowed to reach that compromise.

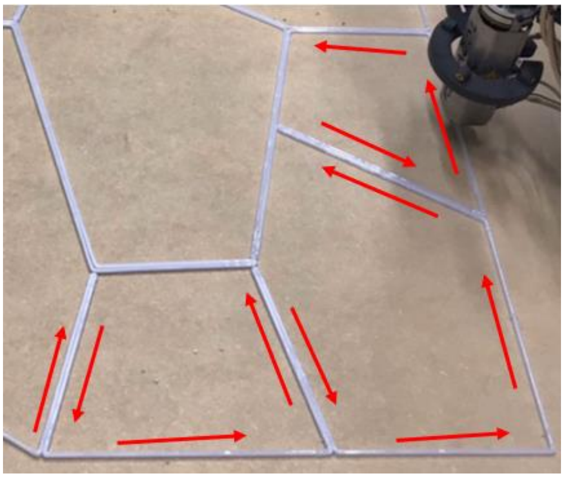


Figure 46- Construction path used when printing complex geometry.

Finally, the big challenge was working on the printing parameters to match the dimensions and tolerances assigned in the 3D file, modeled in the Rhinoceros 3D software. The line thicknesses had to match the model dimensions so that gaps did not exist in double or triple walls, which could compromise the strength of the part. The overlaps in the line´s intersections were also fundamental because if it was too much it would generate a lot of material accumulation and a possible crash, but if it was insufficient, it could create a structurally weak zone in the part.

## 5.3. Access ramp

Introduction: This project was a charity work for a handicapped person, with an electric scooter, who couldn’t enter a coffe house near his home because of the doorstep. In order to help him, Solidtech committed to building an access ramp, using LFAM technology for that.

The main goals here were to make it as fast and as cheap as possible. This meant that slow printing speeds needed to be avoided (a part of this size can take days to be done) and as light as possible (to save money on material).

Development: The first step of the project was to take the dimensions of the step, allowing to idealize a 3D model of the ramp (Figure 47), in Solidworks. The inclination and length of the ramp were dimensioned according to the Portuguese decree law nº123/97: “The maximum slope of the ramps is 6% and the maximum length of a single section is 6 meters. Each section will be followed by a resting level platform with the same width as the ramp and a length of 1.5 meters.”

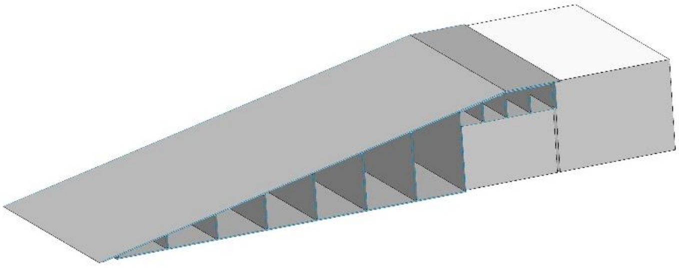


Figure 47- 3D model of the ramp.

The final dimensions of the ramp were:

- Height= 300mm
- Width= 700mm
- Length= 1800mm

The main challenge was to create, applying the DFAM, a geometry that had both a suitable printing path and a structural function. To accomplish that, interior supports (red zone in Figure 48) that intersect the lower surface (black zone in Figure 48) were added to the part. Those intersections used an overlap of 0.2mm to ensure good adhesion without having excess material accumulated.

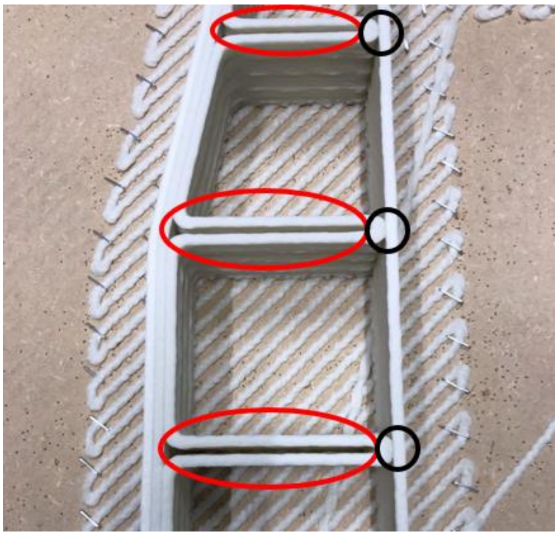


Figure 48- Interior supports and line´s intersection.

The next step was to select an appropriate material. PP30%GF was the obvious choice because of its good mechanical resistance and rough surface finishing, which increases the adherence between the scooter's wheels and the ramp.

Having completed the previous steps, it was then necessary to select the adequate printing parameters:

- A layer height (Lh) of 1.5mm was selected to decrease the printing time;
- Using the PP30%GF line's width graphs, the other parameters were selected using 2 conditions: to use a printing speed (V) as fast as possible and a line width (Lw) of 4,5mm. This allowed to select a value of 105RPMs for the extruder and 75mm/s for the printing speed;
- A cooling air pressure of 3 bar was selected based on our printing experience. Although the layer time (Lt= 2min and 45s) was not very low, the double and triple walls accumulate a lot of material, which increases the probability of having melted layers.

<u>Results:</u> At the end of the construction it was possible to see a periodic defect (Figure 49) throughout the whole part (due to the speed variation of the robot), however, this wasn't a problem since it wasn't an aesthetical part. The defect ended up increasing the friction coefficient of the ramp surface, which was a lucky added value.

Figure 49- Periodic defect visible through the whole part.

A final test was done to check the structural integrity of the part. For that, 6 persons (approximately 450kg) stood on the ramp and no problem occurred. Figure 50 shows the built ramp being used.

Figure 50- Final ramp made from PP30%GF.

# Chapter 6

# Conclusions and future work

## 6.1. Conclusions

The work carried out required knowledge of several areas, namely materials and their properties, AM's printing parameters, and DFAM. This work proved that unique and personalized parts can be made successfully when systematically using DFAM. Each project however has its AM challenges.

One of the major problem difficulties in this work was to adjust the printing parameters when the part's geometry was very irregular. For example, when a part started with a big layer path and ended with a small one, varying the layer time. Adjusting the extrusion RPMs when changing the printing speed to maintain a constant Lw was essential but, at the same time, a challenging task that required many experimental tests to create graphs of the line width. Having in the future software more advanced that adjusts the printing parameters automatically would be a major advantage.

Concerning the technical conclusions:

- The speed has to be adjusted to the part geometry. The slower the printing speed the more precise the corners (and the general shape of the part) will be;
- The Layer height should be established according to the surface finishing requirements (the bigger the layer height, the bigger the staircase effect) and to the surface slope (smaller layer heights allow bigger slope angles);
- The air pressure on the cooling should always be adjusted in function of the layer time. Faster layer times require more air pressure. Also, some materials require more cooling than others. Generally speaking, thin walls and a large cross-sectional area promote the cooling of the part;
- The bigger the line width the smaller the lateral contraction it has. Thin walls tend to bend. Using double and triple walls solves this problem most of the time;
- Usually, parts that require a very good surface finishing need to be done at slow printing speeds (<35mm/s);
- For all the materials especially the ones that are dehumidified, whose pellets get to the extruder already pre-heated, it is essential to use the vibratory motor to prevent the pellets from sticking to the cup. This also helps to compact the material, ensuring a constant flow of material to the extruder's chamber.

To design according to the capabilities of the LFAM is essential to achieve good results. The surface's slope angle, radius of the corners, wall width, length of the straight walls, etc., must be carefully thought out to enable the part to be printed. Furthermore, in the design stage, several things (like the Lh and Lw) must be thought out in advance to give the 3D model of the part the correct dimensional tolerances. When done properly, it ensures sturdy intersections between the lines, strong layer adhesions and no contact zones with excess of material.

## 6.2. Further work

Making new and more tests would be very important to follow up on this work in the future. Many topics related to DFAM and LFAM are still awaiting to be studied.

Concerning the line width study, several tests are still missing to build accurate line width graphs for all the materials, using different nozzle diameters (D) and different layer heights (Lh).

Concerning the construction platforms, there are 2 topics left to investigate:

The first topic is finding how to firmly secure a part to the platform when the material contractions are very strong. For this, it would be advantageous to use a mechanical fixture that holds the part not by the first layer or by the raft/brim, which are the weakest adhesion zones, but instead by the following layers. Some companies already use this kind of securing method (Figure 51);

Figure 51- Mechanical fixture used to secure the parts to the construction platform [36].

The second topic is finding out how to secure a part to the construction platform without damaging any surface of the part. This is mainly for parts made on the glass platform which require both sides to have a good surface finish. A possible solution for this, which will be tested soon, at Solidtech, is a heating blanket that will be put under the glass (Figure 52). The idea is to heat the glass (up to 100ºC), promoting the adhesion between the two surfaces.

Figure 52- Heat blanket to heat the glass construction platform.

Concerning the materials, there are many interesting ones left to test. The recycled and bio-based ones are at the top of that list due to society's growing concern for the environment. To make sustainable LFAM parts can contribute to a green circular economy.

The use of dyes is also another very important topic in this matter because it allows to create even more unique parts, with color fade for example. Finding the right dye, however, can be tricky because different materials (PP, PET, PLA, etc.) require different dyes. Besides that, those dyes must have a compatible extrusion MFI so that it doesn´t change the material flow behavior.

Last but not least, working on new applications for different industries (automotive, marine, aeronautical, medical, etc.) would be the most exciting work because it would create new DFAM challenges and diversify even more the type of parts that can be printed using LFAM.

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