Research Master Report

CHARACTERIZATION AND EVALUATION OF A DIRECT EXTRUSION SYSTEM OF PELLETS FOR 3D PRINTING OF RECYCLED MATERIALS

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ACKNOWLEDGMENT

Summary

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1. INTRODUCTION

Plastics are among the most abundant materials in our industrial environment. One of the reasons is their low cost. Due to their consumption, their production tends to increase. In 2015, global plastics production amounted to 322 million tonnes, with growth reaching a value of 335 million tonnes in 2016 [1].

Studies assume that between 1950 and 2015, cumulative waste production totalled 6300 Mt. Of all the plastics already manufactured in history, approximately 60% have been released and accumulated in landfills or in the natural environment, 30% are currently in circulation, and of these, only 9% have already been recycled. [2].

One of the most important manufacturing techniques is Additive Manufacturing. Through the use of recycled polymers as a raw material, it has been observed that the manufacture of additives can encourage the recycling and reduce the disposal of materials, thus becoming a means to promote sustainability and the circular economy (CE). The CE allows for a balanced integration of economic performance, social inclusion and environmental resilience for the benefit of current and future generations[3] of growing interest to governments, investors, business and civil society[4].

One of the most popular AM techniques is FDM, which uses plastic filament. The filament feeding system has become a well-established system for material extrusion processes because of its canonical simplicity, reliability and continuous feeding capacity[5]. However, it suffers from certain limitations. One of them is the cost of the filament, which is high compared to its original raw material and can be 5 to 10 times more expensive compared to the cost of raw polymers, which limits cost savings [6].

One of the alternatives that has been used to reduce this cost is the use of recycled materials as raw material for this filament, however, another problem is that the material to be used must be produced as a wire that is rigid enough to feed the process[5], which limits the amount of materials that can be used.

In order to optimize the use of 3D printers with recycled materials, we deduce through practical analyses and bibliographic reviews that a possible solution to this problem is to create a direct extrusion system to feed the 3D printers in order to reduce the cost of materials using recycled materials, increase the number of types of polymers that can be recycled and reduce part production time by eliminating the time required to manufacture this filament.

2. CONTEXT OF THE RESEARCH

The context of this research is based on three key elements: Additive manufacturing (3D printing), Fused Deposition Modeling and direct extrusion of recycled pellets, aiming to enhance circular economy.

2.1 Additive Manufacturing

The Additive manufacturing produces " objects " from a digital " model " by depositing the constituent material(s) layer by layer, using digitally controlled and operated material placement tools. This layered fabrication allows unprecedented freedom in the fabrication of complex, composite and hybrid structures with precision and control that cannot be made through traditional fabrication routes.[7] Contrary to milling or cutting a part from a material block, AM builds the part using powders or liquids. There are numerous means to print the layers so as to form the finish product. Some techniques liquefy the material or simply soften it to make the layers whereas others uses high powered UV laser to cure photo- reactive resin and “print” the object[8].As a powerful means of manufacturing, additive manufacturing (AM) is becoming a primary choice for realizing new design concepts and fast product production.[9]

2.1.1 What are the advantages of additive manufacturing?

Additive Manufacturing or 3D printing is a rapidly developing technology that promises to revolutionize the manufacturing sector with faster production times(for example rapid prototyping, in the automotive industry and also in the medical sector), less material waste, and the ability to print unique multimaterial configurations[10]. According to [11] the additive manufacturing has several benefits over subtractive manufacturing:

- The amount of material required is less than for a traditional subtractive method where material is removed from a block until the part geometry is achieved. As the part is built in additive layers during additive manufacturing, the amount of material can be closely controlled.
- The additive manufacturing is capable of producing parts or objects that more traditional methods cannot easily do such as creating multimaterial parts and biomedical objects including organs.
- The additive manufacturing can reduce time and cost of manufacturing.

2.1.2 Review of additive manufacturing types

Process Type	Process Description (from ISO 17296-1)	Focal AM Technologies	Principal Manufacturers	Principal Materials
Binder Jetting	Liquid bonding agent is selectively deposited to join powder materials	3D Printing (3DP)	Z-CORP	Various powers including plasters, sands, and composite materials.
			3D Systems ExONE	Various powders including stainless steel, cobalt, aluminium, copper, and sands, together with a range of metal alloys that can be bound with appropriate liquid binders.
Direct Energy Deposition	Focused thermal energy is used to fuse materials by melting as they are being deposited	Laser Cladding Laser Metal Fusion	Trumpf	Various metal powders including stainless steel, cobalt, aluminium, and copper
		Laser Metal Deposition	Optomec	Titanium, nickel, tool steels, stainless steel, cobalt, aluminium, copper, and various composites
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	Fused Deposition Modelling	Stratasys	Various thermoplastics including acrylonitrile butadiene styrene (ABS), acrylic-styrene-acrylonitrile (ASA), polyamide, polycarbonate, polypropylene
Material Jetting	Droplets of build material are selectively deposited	Multijet Modelling	Stratasys 3D Systems	Ceramics, liquid photopolymers, melted waxes
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	Selective Laser Sintering (plastics)	EOS 3D Systems	Polyamide, polyaryletherketone, polystyrene, and various composites
		Selective Laser Sintering (metals)	EOS Renishaw	Various alloys including aluminium, cobalt chrome, maranging steel, nickel, stainless steel, titanium
		Selective Laser Melting	ReaLizer	Various alloys including cobalt chrome, titanium, steel
		Electron Beam Melting	ARCAM	Various alloys including cobalt chrome, inconel, titanium
		LaserCUSING	Concept Laser	Various alloys including cobalt chrome, aluminium, titanium, bronze, nickel
Sheet Lamination	Sheets of material are bonded to form an object	Laminated Object Manufacturing	MCOR	Sheet paper
			EnvisionTEC	Various composite thermoplastics
Vat Photopolymerization	Liquid photopolymer is selectively cured by light activated polymerization	Digital Light Processing	EnvisionTEC	Various epoxy and nano-composite resins
		Stereolithography	3D Systems	

Table 1. Description of the main types of AM [12]

Because the focus of the research was to test and evaluate a new system that was potentially capable of using recycled polymers as raw material to feed 3D printers, all models cited in the table were analyzed, and the present research focused on the type of Fused Deposition Modeling (FDM) technology.

2.2. Fused Deposition Modeling (FDM)

One of the most commonly used AM techniques is the fused deposition modeling (FDM) due to several advantages including low technology and material costs, wide range of materials available, easy to operate, low maintenance cost, low temperature operation, compact design, office friendly, among others[13][14]. In the FDM process, the parts are created layer by layer. Each layer is created by depositing semiliquid material on a fixtureless platform in a temperature-controlled environment[13][15].

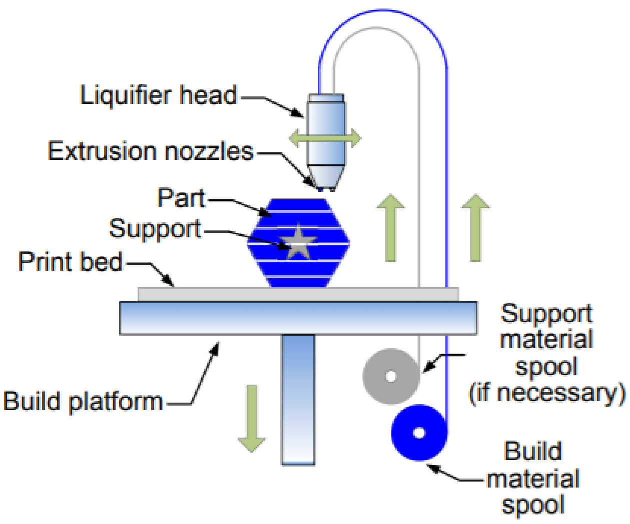


Figure 1. Schematic of FDM process.[16]

The manufacturing of an object by means of FDM-type 3D printing has the following sequence: 3D models are fed into 3D software to create printable 3D files, which are divided into thin 2D slices using slicing software packages. The generated slices are sent to the 3D printer to be built layer by layer until the entire object is obtained. as cited in figure yyyyy.[17]

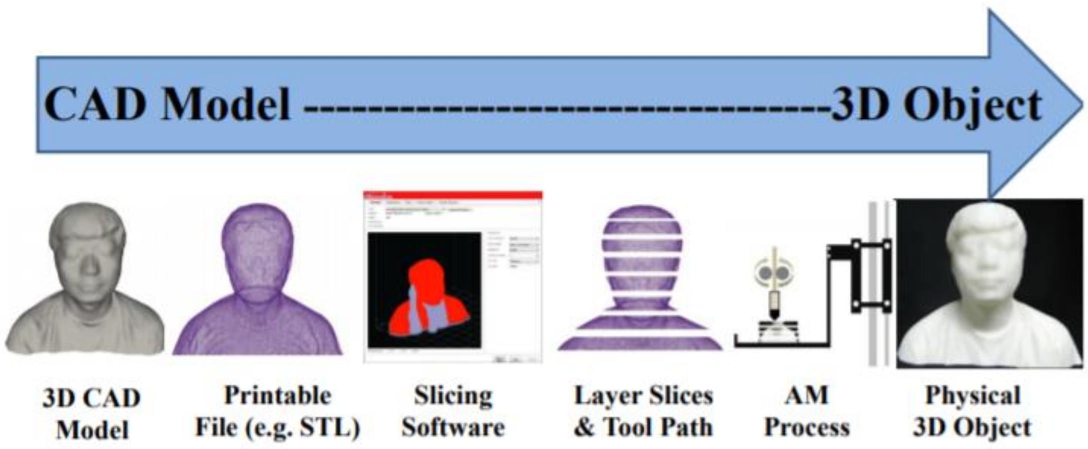


Figure yyyyy. General 3D printing process[17]

2.2.1 Applications of FDM

For [18] 3D application is technically possible or economically feasible largely depends on its production volume, part size, complexity, and material cost. With its reduced cost in relation to traditional manufacturing and with its strong richness of details, 3D FDM-type printing has become excellent for manufacturing customized parts and its applications are found in the literature in various sectors such as anatomical testing, functional tests, fast tool standards, detailed small parts, presentation models, food applications and even medical applications.

2.2.2 Comercial and Open-Source 3D printer

Open source refers to an ideology whose information is publicly available, usually under license. 3D printing is an old technology, however, this innovation has been limited for years due to patents, which has greatly increased its price. With the expiration of the patent, everything started to change. Adrian Bowyer of the University of Bath argued that a range of parts could be made by rapid prototype machines, making the 3D printer a viable technology for self-replication, and then the Rep-Rap model emerged[19].

In Open Source the advantages are related to information, which, unlike commercial printer technology, can be used free of charge by anyone to create, modify or improve the technology. In the AM context, this is very important for the universalization of access to 3D printing. Another advantage is the possibility of exploring the limits of additive manufacturing by experimenting with various combinations of parameters during the printing process[18].

2.2.3 FDM limits and opportunities

Despite being an excellent alternative in the field of additive manufacturing, it is worth mentioning that as all technology FDM also has limitations. Although the development of other raw materials is growing, the main raw material is polymers, which limits its use to the manufacture of plastic objects with limited mechanical resistance [16]. Another limitation is restricted accuracy and poor surface roughness, making a surface treatment process necessary, such as sanding for a better finish quality.[20]. It should also be noted that additive production in general is not yet advantageous for mass production, given that its unit cost is maintained for any variation in the quantity produced and is preferable for personalized production. This article aims to solve a problem related to the feeding of the printer through the filament that limits the options of raw material and increases the production time and evaluate the use of recycled pellets as pima material of this new system.

2.2. FabLab

Since few years ago, the ERPI laboratory have been taking in place a research platform about innovation processes called the Lorraine Fab Living Lab ® (LF2L) (figure zzzz). The LF2L is a research platform for prospective assessment of innovative usages [21].

The conceptual innovation framework of LF2L takes into consideration three mains stages: CoCreation (2D -concept), Prototype (3D -object) and Evaluation (4D -evolution in time). This approach involves different type of stakeholders (e.g. researches, companies, networks,) in order to have a foresight usage evaluation of a new concept, technology or project. This approach is useful to accelerate the deployment of industrial or urban demonstrators. In specific situation, Living Lab concept is adopted to analyze or develop projects or models for cities, territories and regions[22].

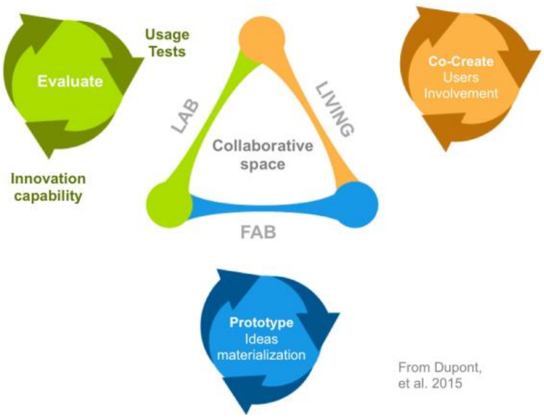


Figura 18: O Lorraine Fab Living Lab® (LF2L) de forma fácil e rápida para uma avaliação prospectiva[23].

Once a laboratory realizes an invention or an innovation, they have a facility to dissipate the idea through the network of existing laboratories making it reach several different places faster than a person or company. The context of this project is placed in the prototype phase. Taking into account the notion of sustainability, which is a currently important social issue, the FabLab concept goes in the direction of a notion of green FabLab with the purpose of better using the resources present in these spaces.

3 STATE OF THE ART

3.1 Problematic

How to set parameters for using a printer with direct extrusion feed (with virgin and recycled material) and compare performance with a filament-fed printer.

3.1.1 Research Questions

Starting from a research with a global question and a specific one, it was made an analysis through the VOSviewer software to observe recurrent words in the literature, with a global result showing that recycling and associated words is a theme that comes from a long time ago, the additive manufacturing associated with recycling is a more recent theme and did not show many results associated with direct extrusion (figure x). Already in the specific research was found a very small number of papers, but with the words highlights displayed in the jjj image.

Research question :

- GLOBAL: How much research has been done on the use of recycled materials as raw materials in the manufacture of additives?
- SPECIFIC: What are the developments in direct extrusion using pellet of polymers as raw material for FDM 3D printers?

Approach	**Population**		**Intervention**
Global	(Additive manufacturing) or (3d printing)	AND	(Recycling) or (Circular economy) or (Recycling polymer)
Specific	(Additive manufacturing) or (3d printing)	AND (Fused deposition modeling) or (FDM)	AND (pellet extrusion) OR (direct extrusion)

TABELA X palavras usadas na pesquisa

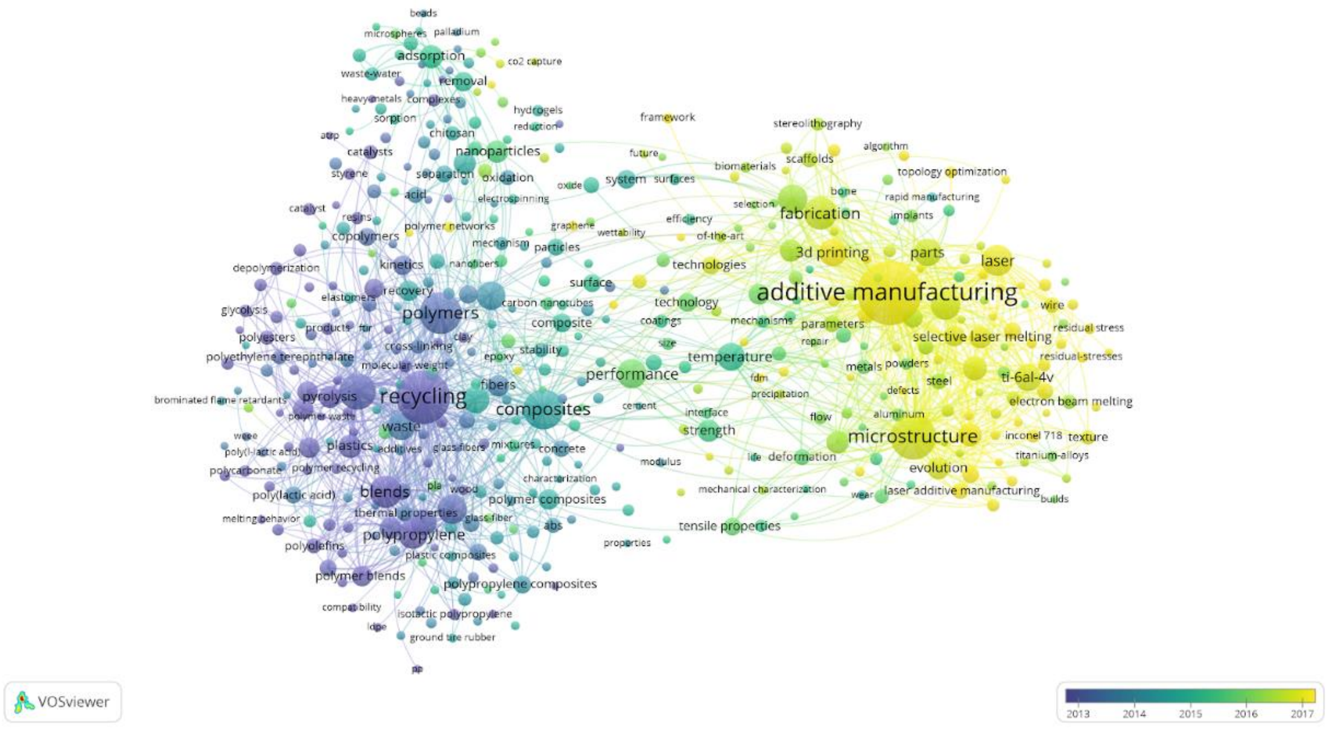
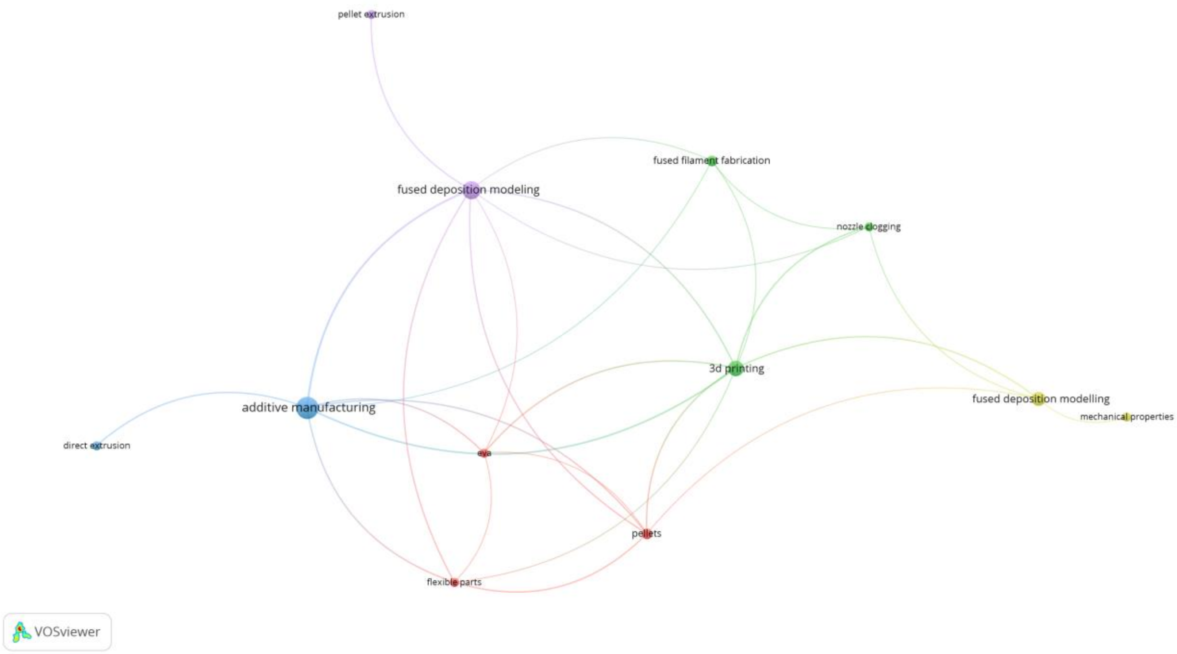


Imagem x resultado VOSviewer



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3.1.2 Goal of the research

The objective of this research in the literature is to explain feeding by means of direct extrusion. In addition, to present a benchmarking against existing models in the literature on direct extrusion 3D printer feeding as well as some of their evaluation procedures, and to present methods that can be used to analyze the samples of different sizes of recycled pellets that will be used. Through this, emphasize the relevance of this research.

3.2 Direct extrusion

The direct extrusion process consists of a system capable of feeding the 3D printer, without the need of a previous manufacture of a filament that is then introduced into the machine. By excluding filament manufacturing, it reduces manufacturing time and increases the range of materials that can be used to feed the printer. [6]

There are essentially two main methods for processing pellets and transforming them into a filament: screw-driven systems and piston-driven systems[5].

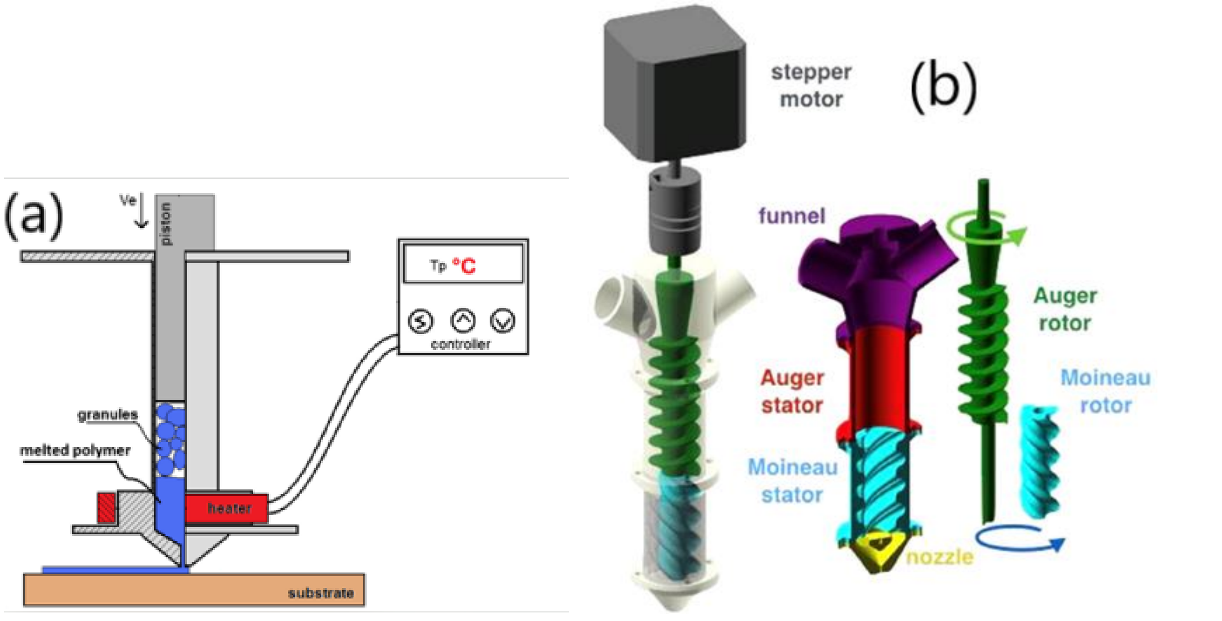


Figure 2. (a) Design of the extrusion piston[5]. **(b).** Schematics of a pellet extruder, combining together Auger and Moineau screws[24].

3.3 Benchmarking of Feeding systems for material extrusion processes

There is a researches that describes the development of a piston driven extrusion head that can extrude polypropylene granules into a filament. The head was designed to minimize the volume of material fused during the extrusion process and reduce the effect of material degradation. Mechanical tests were done [5].

[24] developed a mini extruder for pellets or granules of recycled plastic that can be used in a RepRap FDM 3D printer for rapid prototyping. The use of Moineau pump technology to add precise volumetric control to the extrusion of pellets opens extraordinary new possibilities. It is important to mention that a Moineau pump has to be coupled to a first stage Auger screw. This ensures a continuous feed of melted plastic without inclusion of air bubbles, since the Moineau pump itself cannot guarantee such condition.

Although it is not in the polymer area there is a work on 3D screw printing (STE), but focused on optimization in the ceramic area using the Taguchi method. [25]

[26] created and demonstrated a multifunctional robotic arm platform capable of all three major manufacturing categories (additive, formative and subtractive), the context of a new manufacturing approach. When evaluating additive manufacturing processes, 3D printing was selected as the manufacturing technique. More specifically, extrusion-based 3D printing

systems were used, where the deposited material solidifies due to thermal or chemical stimuli, implementing molten or cured deposition techniques, respectively.

[27] introduced the process design of a new printhead based on double screw extrusion. The purpose of the double screw is to allow the process input multimaterial mixing and direct 3D deposition with the resulting composite or polymer mixture. The main contribution of this work is to demonstrate how a systematic approach can help to design alternative printheads based on extrusion for AM.

[28]analyzed in its study a large-scale recycled plastic 3-D printer, where it was used to manufacture and test the mechanical properties of the parts that were made. To establish a baseline, virgin PLA pellets were first analyzed and then compared with four recycled polymers. First, the material size characteristics were quantified through digital image processing. Next, a print test of the power matrix and nozzle speed was performed to determine the optimum print speed and temperature for a given polymer raw material. Third, a set of drawbars was printed and pulled to confirm the mechanical properties of the plastic when it was printed with a pellet drive extruder system and was compared with the results with FFF/FDM 3-D printers, noting the number of fusion cycles.

[29] designed the use of a pellet-fed material extrusion machine to process heat-sensitive materials, in particular PVOH. Multimaterial printing was demonstrated by feeding PVOH with an additive at different rates and building a structure with homogeneously distributed composition. Tension tests and spectroscopy were used for evaluation, and printing of a part with various geometric dimensions was performed for demonstration criteria.

In his research[30] exhibits the design and development of a robotic system for printing thin shells on a complex 3D surface. A mandrel is used as a support surface, where the printhead extrudes the thermoplastic polymer presented to the pellet machine.

[31] has designed a large-scale 3D printer based on the molten deposition of plastic pellets. It consisted of a twin screw extruder and a large 3D forming platform. The developed machine was found capable of printing large quantities of plastic molds and products at a low cost and fast speed. In this article, the principle of operation and the main structure of the printer were introduced, and the physical model of the accumulation process was analyzed with stress tests. In addition, based on the accumulation model, some process parameters and their effects on surface accuracy and strength were researched and analyzed.

The work carried out by[32] demonstrated the development of an AM extrusion process based on pellets for the manufacture of flexible parts using EVA material. The capabilities of the system were examined by manufacturing flexible parts with various characteristics. In addition, tests of traction, hardness, hysteresis and microstructure of the manufactured part were performed to evaluate the quality of the printed parts. The results obtained indicated that the developed system is capable of producing highly flexible parts using EVA material. The system is restricted to EVA in the form of pellets.

[33] prototyped a mini extruder mounted on an industry robotic arm. It operates using bulk material in a granular form. Theoretical analysis and simulation work was done on optimizing nozzle geometry to eliminate the deposition defects that occurred in the conventional method of fusion deposition. Meanwhile, the robot arm makes the process a more flexible and viable alternative to prototyping a large part.

[34], exhibited the design and development of a pellet extruder capable of extruding mixtures of Harakeke flax fiber mixed with PLA polymer, with a pellet size ranging from 1-3 mm in diameter and length. Its system was designed from scratch, considering basic extrusion theory and utilizes advanced features such as liquid cooling, temperature control and controlled pellet feeding. Only mechanical tests were performed to evaluate the system.

[35]developed a new cast layer modeling process (FLM) based on CNC assisted pellets. It allows the manufacture of highly flexible parts, which is not possible through the cast filament manufacturing process (FFF), as buckling occurs when the flexible filament is fed into the blender head. Instead of the filament, the FLM process presented uses the pellet material. The work presented a parametric investigation in the FLM process developed, considering the ethylene vinyl acetate (EVA) material. The experiments were conducted using the 'one factor at a time' approach (OFAT). The effects of barrel temperature, bed temperature, screw speed, deposition speed, distance between the nozzle and the bed surface were studied on the melt flow rate, layer thickness and road width, and the results of the present study showed that the FLM process developed has the ability to manufacture parts using a set of appropriate process parameters.

3.4 Granulometry

With a focus on improving the performance of this new feeding system for 3D printers, this work analysed the relationship between the size of the recycled pellet used and the print result. To make this comparison it is important to introduce the study of granulometry.

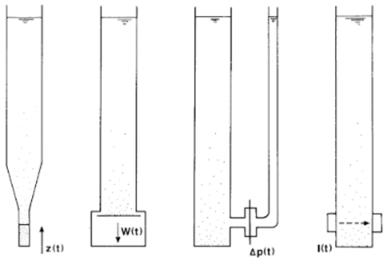
Granulometry, also known as particle size distribution, can be defined as “a description of the size and frequency of particles in a population [36]. The granulometry of materials is relevant in a wide range of applications, such as pharmaceutical production, food processing, paper making, textile fabrication, coating manufacturing, or modeling geological processes, because the properties of the final product or the observed phenomenon depend on the shapes and sizes of the particles[37].

The main types of particle size analysis are:

- Sieving [38]: This method consists of separating fractions of the sample by means of sieves (from the top to the bottom sieve with ever smaller holes), and then weighing and analysing them. A quantity of the sample is deposited in the upper part of the equipment, which after being activated generates vibrations causing the smaller particles to pass through the holes and the larger ones to be retained, making it possible to make the separation according to their size.

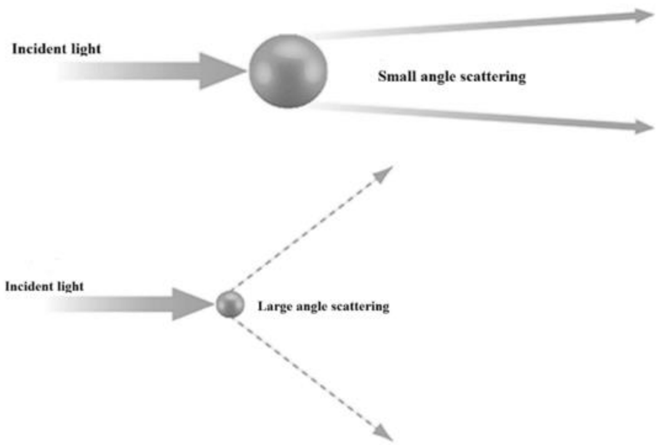
Peneiras para separação [39]

- Decantation of sediment grains through a water column; particles are deposited in the upper part of the tube filled with water, while the speed at which they sink is monitored and calculations are made associating the speed of stabilization of the grains at the bottom of the water column with their properties, weights and geometries. [40].



Colunas d’agua[40]

- Laser diffraction: A laser light source is usually directed through a small, diluted liquid suspension of the sediment dispersed in distilled water and the angle of diffraction of different grains is measured, the size of the particles determines the angle of diffraction of light. There is a negative correlation between the diffracted angle and the particle size, such that a small particle size produces a larger diffraction angle compared to a larger particle size. [41].



Laser [41]

- Image analysis: The typical sequence of operations for digital image analysis includes image acquisition and processing, particle measurement and data processing and interpretation, and is therefore considered to be objective, accurate and reproducible. It can measure accurately between 10 nm and 5 mm, but depends on the equipment used.[42]

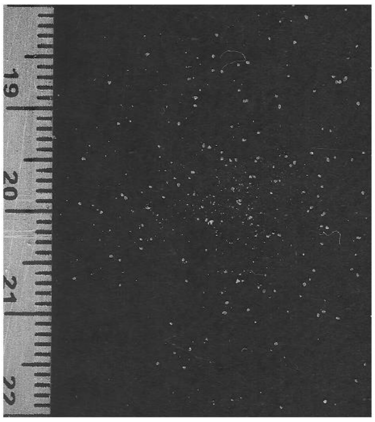


Imagem capturada por um scanner e régua como escala [43].

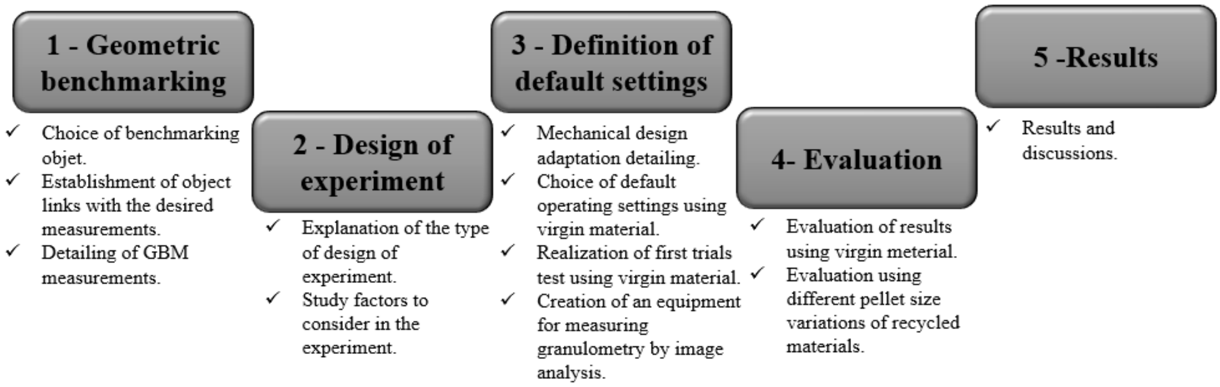
The present research made use of the study of granulometry through image analysis, because it is a field in prosperous growth due to the various uses of this tool [44], It has a lower cost compared to other options, and is suitable for pellet sizes ranging from 0.05 mm to 0.1 mm, and is accurate and reproducible.

3.6 Conclusion of the literature review

The work began by highlighting a current problem associated with the disposition of plastics in the world and by observing 3D printing as an opportunity to promote the circular economy. Within this context, the issue associated with 3D printing follows, where in the production of the filament that feeds the printer, it generates a limitation in the types of materials that can be used, besides the complexity and time that the manufacture of this filament requires. After several studies and bibliographic researches, a possible solution was observed, which tries to replace the filament feed with a direct pellet extrusion feed. However, there is currently a low number of studies associated with direct extrusion, and much less associated with evaluations for such a system, thus being a relevant and unsaturated topic. It was seen an opportunity to evaluate this type of direct extrusion, and with the use of granulometry, relate the printing quality (by geometric benchmarking) with the variation in the size of the recycled pellet used.

4 METHODOLOGY

After a literature review, the methodology was selected to indicate the course of the research aiming at an unprecedented evaluation approach for direct extrusion systems using recycled pellets. The research aims to choose a benchmarking objet and test the direct extrusion equipment with virgin PLA, after conducting an experiment to perform an image analysis procedure to evaluate the different variations in pellet sizes in the samples. Then test the direct extrusion system with the evaluated samples, relating quality to the pellet size. Finally, make comparisons of the results obtained with other forms, such as filament. The rrrrrrrrr image shows the summary of the methodology.



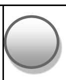
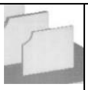
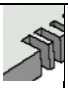
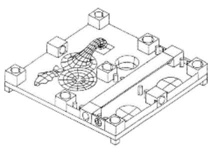
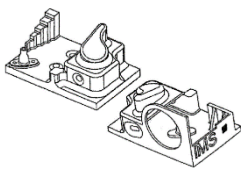
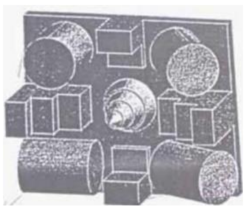
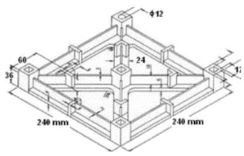
Below follows a more detailed explanation for each step.

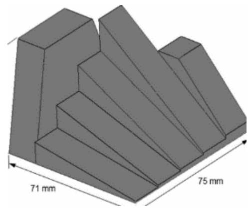
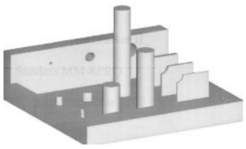
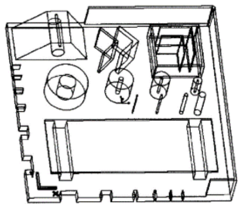
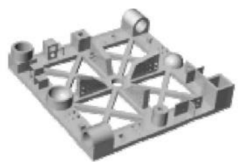
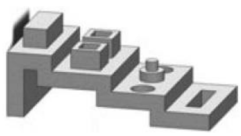
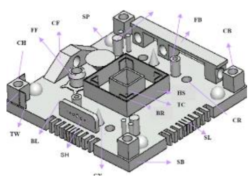
4.1 Step: Geometric benchmarking

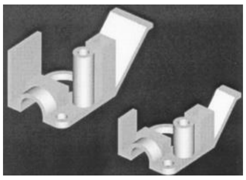
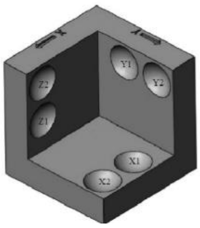
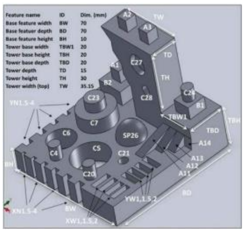
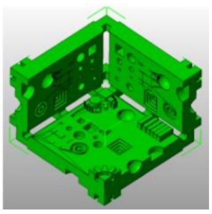
An important part of most benchmarking processes in additive manufacturing is the use of a benchmarking object[45]. Benchmarking is a tool for comparing the performance of different similar systems (processes, organisations, machines) in order to establish standards of performance[46]. [47] in his thesis explains that benchmarks for processes and systems can be classified into three main types:

- Geometric Benchmark: A geometric reference is used to verify the geometric and dimensional accuracy of the prototype. The desired accuracy requirement is often defined in terms of established standards. Typical geometric features incorporated in these geometric reference parts are circular holes, cylinders, thin walls, grooves and squares.
- Mechanical Benchmark: A mechanical benchmark aims to provide components that can be used to characterise the mechanical properties. The components can be fabricated simultaneously and later separated to test individual mechanical properties.
- Process Benchmark: Consists of thebenchmark artifacts with the aim ofestablishing the optimum process parameters (i.e., part orientation, support structures, layer thickness, speed).

For the choice of the benchmarking object, each paper was not deepened in detail, but Table 2 was constructed that summarizes objects found in the literature and that was used to choose the object that will be used in this research, for more details some are found in the literature review made by [48].

AUTHOR	**FIGURE**							**WEAKNESS**
[49]		x	x		x		x	However, the freeform features are difficult to measure and the base surface is quite large, thus warping is likely to occur.
[50]		x	x	70°	x		x	They are hard to measure for a CMM. Too much time to measure all details, too much time to manufacture, too much material used.
[51]			x					Few geometric variations
[52]			x					It is unsuitable to study non-flat surfaces or to determine the minimum feasible feature size

[53]				10° to 90°				It cannot be used to evaluate circular or curved features.
[54]			X		X		X	No options for measuring holes or angles
[55]			x	?	x	x	x	Without spherical or semi-spherical parts and not fully comprehensive drawing on paper
[56]		x	x	10°, 20°, 40°, 70°	x		x	Has no rift
[57]			x				x	Although it can be used to study the manufacturing of features that need support structures, the object is missing some geometrical figures presented in this table.
[47]		x	x	45°	x	x	x	This object meets all requirements, the only weakness would be the

								fact of high material consumption and high printing time due to the richness of details.
[58]			x	?			x	In addition to the lack of geometrical figures presented in this table, there is no information on measurements in the paper.
[59]		x						Few geometric variations
[60]		x	x	15°, 30°, 35°, 80°		x	x	
[61]		x	x				x	Although highly complex, geometric figures are missing from this table.

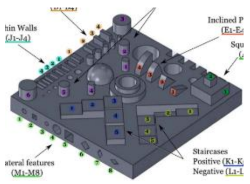
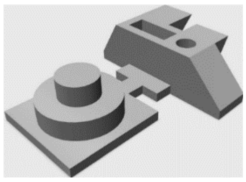
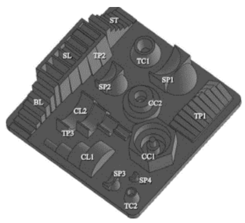
[46]		x	x	15°, 45°, 75°, 90°	x	x	x	According to the author, it requires a high amount of time to print the object.
[45]			x				x	Despite the low material consumption and the ease of measurement, it has become a very simple figure leaving much to be desired in terms of measurement variation.
[62]		x	x	Extensive quantity	x			Very good amount of variations, the only weakness is the lack of horizontal holes
[63]			X	40°, 5.5°, and others			X	It does not present some geometric figures in this table.

Table 2. Evaluation of benchmarking objets

In his article, [64] presents some items to consider in order to establish 'rules' for a geometric benchmarking model. Globally, benchmarking models should:

- Be large enough to test the performance of the machine near the edges of the platform as well as near the centre,
- Have a substantial number of small, medium and large features,
- Not take long to build,
- Not consume a large quantity of material,

- Be easy to measure,
- Have many features of a 'real' part,
- Have simple geometrical shapes, allowing perfect definition and easy control of the geometry,
- Require no post-treatment or manual intervention (no support structures),
- Allow repeatability measurements.

The measurability ofthe benchmark artifact is a key issue and it represents a tight constraint in the design process. Indeed, the test part has to be designed taking into account the selected measurement system, since the features that cannot be measured are useless and result in a waste of time and material[48].

It is worth emphasizing that the object of benchmarking should answer the questions mentioned above and contribute to the purpose of the research.

4.2 Step: Design of experiment

The purpose of DoE is to set up an experiment in such a way that insight in the effect of a set of input parameters on a certain response can be gained based on a limited number of carefully selected experimental runs[65].

The optimization procedure based on traditional experiment design methods requires abundant experiments to study the effect of each processing variable, leading to high optimization. For instance, experimental design of three factors and three levels requires $3^3 = 27$ sets of experiments using traditional methods[66]. An effective way to reduce the cost of process optimization is to reduce the number of experiments required. For a long time, the orthogonal design method (OE), a statistical design method proposed by Taguchi, has been widely applied to the optimization of processes and experiments because it only requires a small number of experiments, for example, the three-factor, three-level OE design requires only nine sets of experiments.[66].

[67] explains in its role how the Taguchi method proved to be a valid approach to evaluate the effects of the different factors present in the FDM, simplifying experimentation and evaluating multiple factors and their influence on component performance.

Taguchi allows the selection of a partial factorial test matrix to test multiple factors with several levels at the same time and to take into account the interactions between them with a minimum amount that can be further analyzed through the analysis of variance (ANOVA)[68]. Analysis of variance (ANOVA) is a statistical process that evaluates variance between individuals or groups of individuals to evaluate the effects of treatments. The use of ANOVA gives a statistical measure, which is the ratio of variance between groups, or variance due to treatments, divided by error, which is a result of variance within the group [69] [67]. The variance, or mean square, is calculated as the sum of squares divided by the degrees of freedom. The mean square due to treatment can then be divided by the mean square of error to obtain an value, which is useful in gauging the effect of each condition on the mean[70]. The process established to determine these properties can be used to optimize collective or individual FDM properties for other platforms and materials, allowing users to optimize for whichever properties are desired given their own specialized circumstances and equipment.[67].

Para realizar o estudo sobre influência dos tamanhos dos pellets reciclados injetados no sistema de alimentação por extrusão direta em relação a qualidade da impressão, foi feito o uso da granulometria para descrever as amostras usadas(retirer).

4.3 Step: Definition of default settings

The objective of this step is to enable the performance of tests by defining default usage settings. It is of paramount importance to establish usage parameters so that the experiment gains a pattern and can be easily replicated by anyone. This step is fundamental, because it describes the installation of the equipment with its challenges and facilities. It will also be performed tests with virgin materials in direct extrusion in order to evaluate the chosen standard configuration and acquire a result that will serve as a basis for comparison with the result obtained with the use of recycled pellets of different sizes.

4.4 Step: Evaluation

Step 4 aims to evaluate the results obtained with the use of virgin material in order to use it as a reference. Another objective is to carry out tests with feed by means of direct extrusion using pellets of recycled materials of different sizes and to compare them with the results obtained from virgin material.

4.5 Step: Results

The purpose of this step is to bring a summary of all the conclusions of analyses made so far and show the technical feasibility of the direct extrusion system using, first virgin material and then different sizes of recycled pellets.

5 EXPERIMENTAL CASE

This research was carried out on the Lorraine Fab Living Lab innovation platform, in the prototyping area, through the Research Team on Innovative Processes (ERPI), associated with National School in Industrial Systems Engineering (ENSGSI), with the contribution of the Superior Level Personnel Improvement Coordination (CAPES), with the purpose of evaluating the direct extrusion system fed by different variations in sizes of recycled pellets.

5.1 Direct extrusion equipment

Initially, the 3D universal equipment V3 pellet extruder was purchased, supplied by the manufacturer Mahormuniz[71], which its function is to make 3D printers feedable by direct extrusion, replacing the use of filaments. According to the suppliers, this is a simple and compact mechanical system that can melt crushed plastic to be used directly in 3D printing. It is fully compatible with any 3D printer to generate cost savings and help the environment, and can be supplied with virgin and recycled materials, with pellets ranging from 1 mm to 4 mm[71].

Fugura hhh. A) objeto montado, b) objeto desmontado

When acquiring the product, it is shipped with all non-plastic parts, and all plastic parts are made available free of charge on the manufacturer's website under the *.stl* format and can be designed on any 3D printer.

Then this equipment was coupled to Créality CR-10S pro, said as a printer for professional and amateur use that has the following features[72]:

- Large construction volume of 300 x 300 x 300 x 400mm
- Automatic levelling function
- XY-axis positioning accuracy: 0.012 mm
- Molding technology: FDM
- Printing speed: ≤180mm / s, normal printing speed 30 - 60mm / s

- Printing accuracy: ± 0.1mm
- Layer Thickness: 0.1-0.4mm
- Number of nozzles: 1
- Nozzle temperature: ≤260 ° C
- Platform Temperature: 0 to 110 degrees
- Printing material: PLA, ABS, PVA, PVA, PP, filled wood, etc.
- Nozzle diameter: 0.4mm
- Voltage: 110-240V
- Working power: Input; 100 - 240V, 5.9A, 50 / 60Hz, output: DC 24V, 21A

A impressora usa os software... para ....

Créality CR-10S pro

Após a montagem do equipamento ficando da forma exposta na figura rrrrr(colocar figura com eles montados) foi escolhido o benchmarking objet para realizar os testes com materiais virgens. Foi aplicado no sistema de extrusão direta os parâmetros de configurações sugeridos pelo fabricante em utilização de filamento, a fim de adquirir um resultado que, posteriormente, será usado para avaliação da impressão usando pellets reciclados.

5.2 Benchmarking objet

This work focused primarily on the understanding of geometrical benchmarking. After an analysis of geometric benchmarking, it is possible to establish parameters and configurations of use that can be applied later to carry out the study of mechanical benchmarking and then that of process benchmarking.

Justified by the study done in this paper, this topic clarifies the choice of the Benchy object. In addition to responding to many of the criteria presented in topic 4.1, the object cited on the site

[54] was chosen as a benchmarking object because it is a measurable object, economical in terms of materials, and the great differentiation is due to the fact that it has an attractive and easily recognizable shape and that prolongs the life of a piece printed in 3D as a toy or present[54], contributing to the technological purpose and the circular economy.

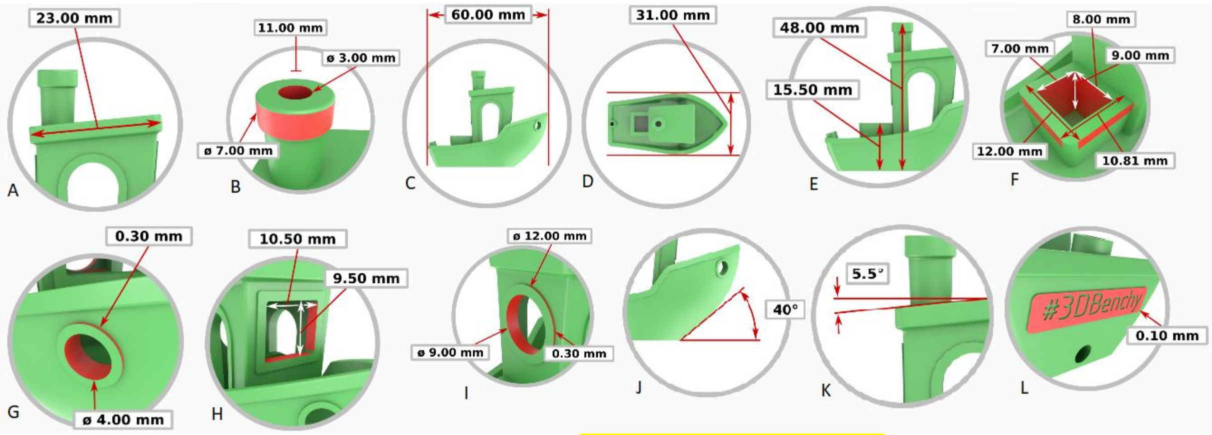


Imagem llll. Benchy MEDIDAS

According to information provided on the website [54], 3DBenchy is a 3D model designed specifically for testing and benchmarking of 3D printers. It is a small recognizable object that can be downloaded for free, made and shared. It is designed to offer a wide range of challenging geometric features for 3D printers and evaluate different problems related to additive manufacturing. The different surfaces of the *#3DBenchy* model reveal typical problems related to surface finish, model accuracy, deformation, etc. All of this information has made the Benchy the number one in general statistics on the Thingiverse website.

5.3 Design of experiment

In this research, DoE was used to create an experimental matrix in order to analyze configurations of use and quality of an FDM direct extrusion printer using virgin and recycled material. This matrix was refined by the Taguchi method in order to reduce the number of tests.

It has been demonstrated that factors such as material extrusion temperature, T, component manufacturing orientation and layer thickness, δ, strongly affect the strength and durability of components produced via FDM.[73].

Descrever fatores que serao controlados no equipamento, tabela e taguchi

6 RESULTS

6.1 Analysis of the Results

7. CONCLUSIONS

8. PERPESCTIVES

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10. ANNEXES

ANNEXED : RETURN OF EXPERIENCE

RETORNO DE EXPERIÊNCIA

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