State of the art for characterization and evaluation of a direct extrusion system of pellets for 3D printing of recycled materials

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ABSTRACT : With the growing number of production and consumption of polymers in the world, there is a concern associated with their discarding. Seeing additive manufacturing as an opportunity to promote the circular economy, a limitation was noted associated with the system of feeding printers through a filament. Attacking this problem, this paper aimed to serve as a state of the art for a future work, where a new system of feeding of 3D printers by direct extrusion will be evaluated, comparing with the filament feeding system.

KEY WORDS : Direct extrusion, Additive manufacturing, feeding systems, benchmarking object, Fusd deposition modeling.

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 (Association of Plastics Manufacturers, 2018).

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. (Geyer, Jambeck, & Law, 2017).

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(Geissdoerfer, Savaget, Bocken, & Hultink, 2017) of growing interest to governments, investors, business and civil society(Pieroni, McAloone, & Pigosso, 2019).

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(Volpato, Kretschek, Foggiatto, & Gomez da Silva Cruz, 2015). 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 (Oakley et al., 2018).

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(Volpato et al., 2015), 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.

The present work uses the following structure :

- Section 2 clarifies terms about additive manufacturing, fused deposition modeling and direct extrusion.
- Section 3 presents a benchmarking about the direct extrusion models found in the literature.
- Section 4 exhibits the research methodology.
- Section 5 contains a literature review on benchmarkin objet as a justification for choosing the object that was used.
- Section 6 presents the state of the art conclusion and perspectives of this research.

2. Processes AM

2.1. The additive manufacturing

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.(Syed A.M. Tofail et al., n.d.) 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.(Jasveer & Jianbin, 2018)

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 EnvisionTEC	Sheet paper 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 (Eyers & Potter, 2017)

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

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(Cerda-Avila, Medellín-Castillo, & de Lange, 2018)(Durgun & Ertan, 2014). 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(Cerda-Avila et al., 2018)(Onwubolu & Rayegani, 2014).

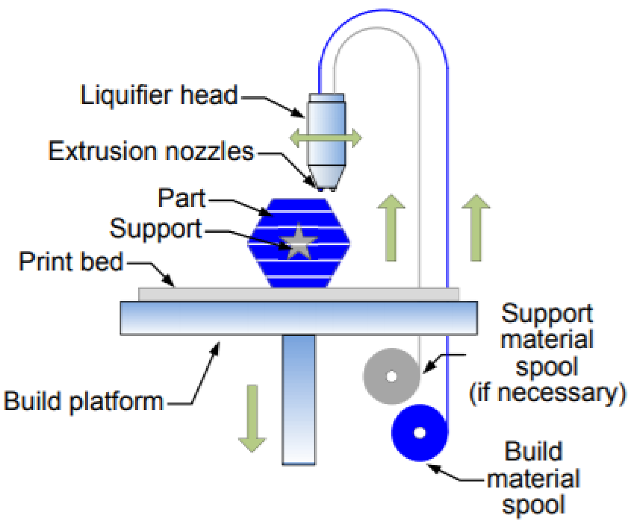


Figure 1. Schematic of FDM process.(Ning, Cong, Qiu, Wei, & Wang, 2015)

2.3. Direct extrusion

O processo de extrusão direta consiste em um sistema capaz de alimentar a impressora 3D, sem a necessidade de uma anterior fabricação de um filamento que posteriormente é introduzido junto a máquina. Ao excluir a fabricação do filamento, reduz o tempo da fabricação e aumenta a gama de materiais que podem ser utilisados para alimentar a impressora (Oakley et al., 2018).

There are essentially two main methods for processing pellets and transforming them into a filament: screw-driven systems and piston-driven systems(Volpato et al., 2015).

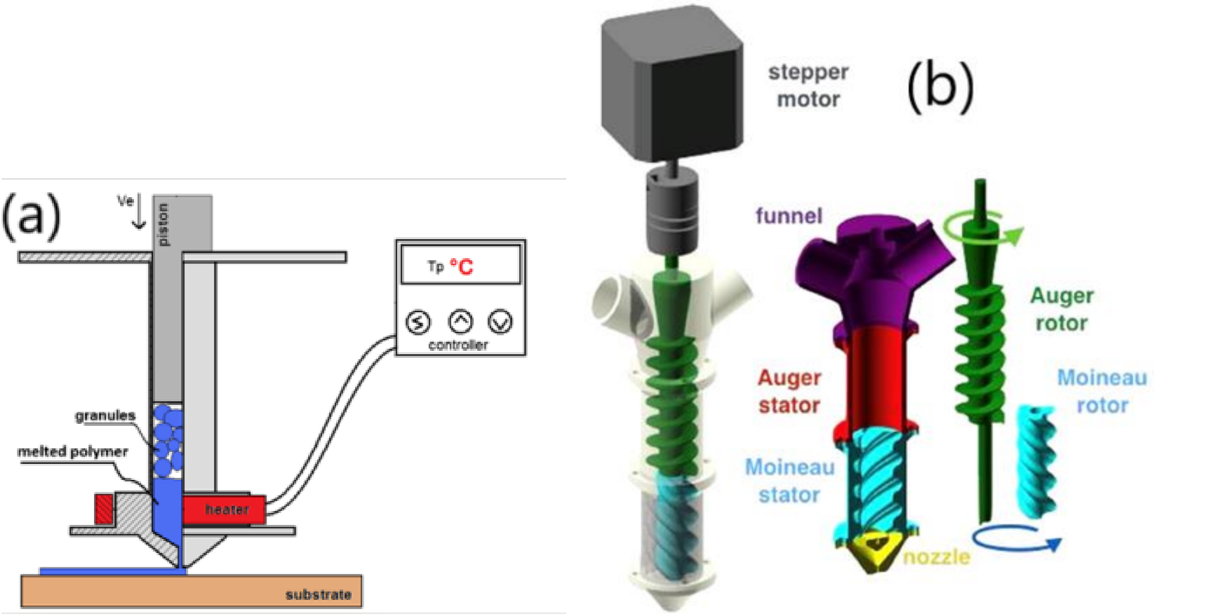


Figure 2. (a) Design of the extrusion piston(Volpato et al., 2015). **(b).** Schematics of a pellet extruder, combining together Auger and Moineau screws(Canessa, Baruzzo, & Fonda, 2017).

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 degradationPesquisar sem relação com reciclagem (Volpato et al., 2015).

(Canessa et al., 2017) 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 with out inclusion of air bubbles, since the Moineau pump itself cannotguarantee 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. (Kim, Cho, & Zielewski, 2019)

(Keating & Oxman, 2013) 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.

(Justino Netto & Silveira, 2018) 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.

The limited number of results for this research proves that it is not a saturated theme, suggesting that it is a rising theme, which makes research relevant.

4. Methodology and evaluation of the direct extrusion system

After a bibliographic review, the methodology was defined to demonstrate the technical feasibility of the direct extrusion process using recycled materials, as well as to compare this system with the filament fed system. To evaluate and compare this new extrusion system, it will be analyzed issues such as cost of acquisition of machines, time of manufacture of a part, difficulty of use, and giving a more important role to the quality of printing.

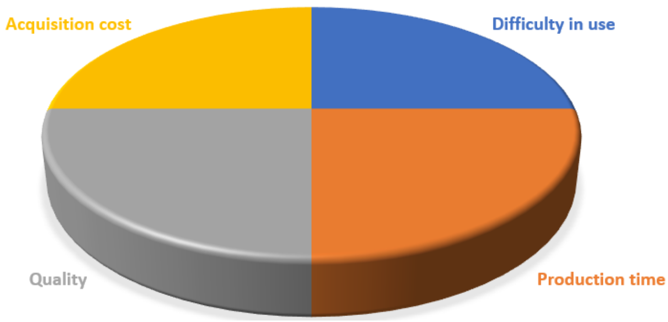


Figure 3. Evaluation types of this research.

4.1. Acquisition cost

The cost of the raw material for direct extrusion or for filament is the same value, because it is the same material, which for the experiment will be used recycled, and as the flow of the extruder nozzle is the same, it is understood that the consumption will also be the same for both models. Therefore, this research topic refers to the acquisition value of these machines and their accessories.

4.2. Difficulty in use

This topic discusses issues such as the difficulty in manufacturing a filament and handling its accessories, comparing empirically with the difficulty of handling and calibrating the direct extrusion system and its respective accessories.

4.3. Production time

Production capacity is the quantity of products manufactured in a certain period of time as explained in (James & Mondal, 2019). Bearing in mind that the higher the production speed of a machine, the greater its productive capacity and the greater its potential to generate income, this topic will examine the manufacturing time of a part, analyzing the entire context of production processes.

4. 4. Quality

As the number of processes and technologies increases, it also increases the need and demand for tools and procedures to evaluate the technological capabilities and limits of a specific process or even to compare the execution capabilities of different processes.(Rebaioli & Fassi, 2017). Although highly effective, the currently available AM software packages are not suitable for evaluating the print quality of a 3D model. (Jaiswal & Rai, 2019).

As already mentioned, this paper focuses on evaluations of the ability to print parts with precision, repeatability and surface finish, since it is understood that the focus of additive manufacturing is on providing a wealth of details in parts with complex shapes, which would be difficult to produce using traditional manufacturing techniques.

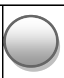
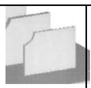
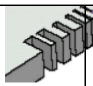
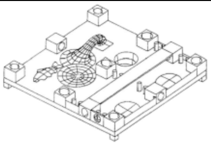
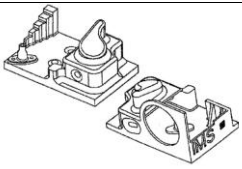
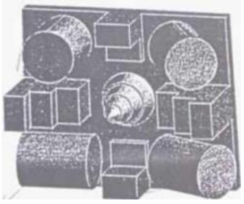
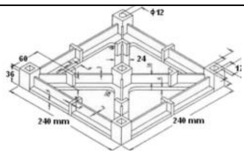
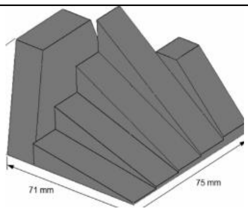
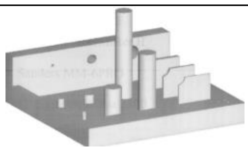
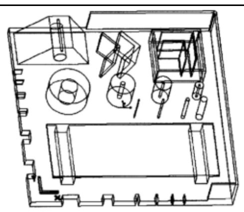
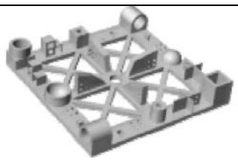
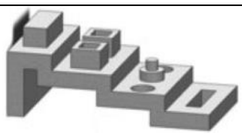
5. Benchmarking object

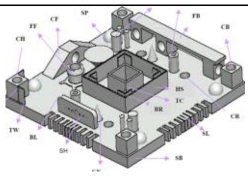
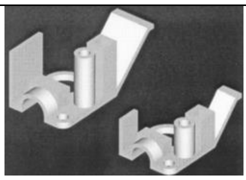
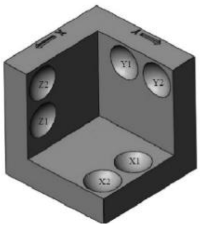
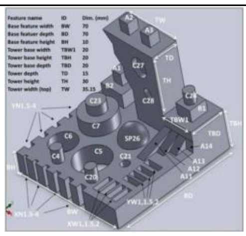
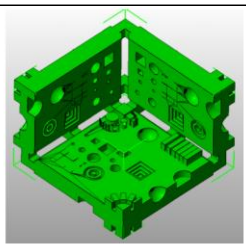
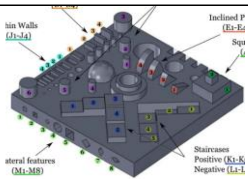
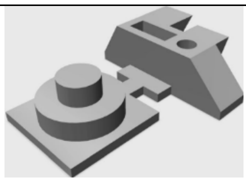
An important part of most benchmarking processes in additive manufacturing is the use of a benchmarking object(Decker & Yee, 2015). Benchmarking is a tool for comparing the performance of different similar systems (processes, organisations, machines) in order to establish standards of performance(Cruz Sanchez, Boudaoud, Muller, & Camargo, 2014). (Mahesh, Fuh, Wong, & Loh, 2005) 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).

This work focused first on geometric references understanding that after an analysis of the geometrical benchmarking it is possible to establish parameters and configurations of use that can later be used to measure mechanical benchmarking, and then, process benchmarking.

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 (Rebaioli & Fassi, 2017).

AUTHOR	FIGURE							WEAKNESS
(Childs & Juster, 1994)		x	x		x		x	However, the freeform features are difficult to measure and the base sur- face is quite large, thus warping is likely to occur.
(Aubin, 1994)		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.
(Jayaram, Bagchi, Jara-Ammonte, & O'Reilly, 1994)			x					Few geometric variations
(Ippolito, Iuliano, & Gatto, 1995)			x					It is unsuitable to study non-flat surfaces or to determine the minimum feasible feature size
(Reeves, 1998)				10° to 90°				It cannot be used to evaluate circular or curved features.
(Symposium & 1998, n.d.)			X		X		X	No options for measuring holes or angles
(Xu, Wong, & Loh, 2000)			x	?	x	x	x	Without spherical or semi-spherical parts and not fully comprehensive drawing on paper
(Pérez, 2002)		x	x	10°, 20°, 40°, 70°	x		x	Has no rift
(Roberson, Espalin, & Wicker, 2013)			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.
(Mahesh et al., 2005)		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.
(Pennington, Hoekstra, & Newcomer, 2005)			x	?			x	In addition to the lack of geometrical figures presented in this table, there is no information on measurements in the paper.
(Boudiaf, Moussaoui, & Dahane, 2016)		x						Few geometric variations
(M. Johnson, Rowell, Deason, & Eubanks, 2014)		x	x	15°, 30°, 35°, 80°		x	x	
(Williams & Seepersad, 2012)		x	x				x	Although highly complex, geometric figures are missing from this table.
(Cruz Sanchez et al., 2014)		x	x	15°, 45°, 75°, 90°	x	x	x	According to the author, it requires a high amount of time to print the object.
(Decker & Yee, 2015)			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.

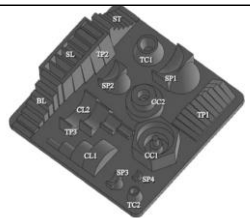
(Minetola, Iuliano, & Marchiandi, 2016)		x	x	Extensive quantity	x			Very good amount of variations, the only weakness is the lack of horizontal holes
(Creative Tools AB, 2019)			X	40°, 5.5°, and others			X	It does not present some geometric figures in this table.

Table 2. Evaluation of benchmarking objets

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(Rebaioli & Fassi, 2017).

In his article, (Moylan, Slotwinski, Cooke, Jurrens, & Donmez, 2012) 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.

In addition to answering many of the above criteria, the object cited on site (Creative Tools AB, 2019) 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 recognizable shape easily and that prolongs the life of a piece printed in 3D as a toy or gift(Creative Tools AB, 2019), contributing to the technological purpose and the circular economy.

6. Conclusions and prospects

The objective of this research is to serve as a state of the art for a work that will be developed. The paper began by highlighting a current problem associated with the disposal of plastics in the world and observing in 3D printing an opportunity to promote the circular economy. Within this context follows the issue associated with 3D printing, where in the production of the filament that feeds the printer, 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 literature searches, a possible solution was observed, which tries to replace the filament feed with a direct extrusion feed. However, there is at present a low number of studies associated with direct extrusion, and even less associated with evaluations for such a system. A future work aims to compare this type of direct extrusion with that of filament and evaluate issues such as cost of machine acquisition, difficulty of use, production time, and evaluate giving an emphasis on the quality of printing by the methods displayed in this work.

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