From plastic waste to frugal products - Mechanical properties evaluation

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Abstract

Plastic utilization has contributed to shocking waste generation numbers. Within the context of promoting sustainability and improving resources value, Circular Economy appears as an exciting solution to provide methodologies that can empower the connection of reducing environmental damages on the value chain of products and services. Additionally, 3D Printing has been proving to have an enormous potential to embrace circular economy principles, providing manufactures with innovative features to serve the market as they never though it was possible. With new practices, new products concepts appear and Frugal Innovation is transforming the product and business concept. These affordable solutions can provide sustainable practices to preserve natural ecosystems and effectively use resources.

With a complete literature review on the Plastic Market, Circular Economy, 3D Printing and Frugal Products, this master dissertation aims to provide a structure to prove the feasibility and possibility to explore plastic recycling to provide 3D printing feedstock and produce frugal products using all the approached concepts. It is assessed to a mechanical evaluation of five important mechanical properties of recycled ABS, PET and PLA. This evaluation provided a mechanical characterization and information that highlights a downgrade of the approached mechanical properties, comparing with virgin material. However, with the conclusions drawn from the obtained properties it was possible to produce three different frugal products. This proves the feasibility of recycling plastic waste to produce frugal products, taking advantage of new sustainable methodologies.

Keywords: Circular Economy; 3D Printing; Plastic Recycling, Frugal Products; Mechanical Properties

Resumo

A elevada utilização de plástico tem contribuído para números devastadores de desperdício e poluição. No contexto de promover a sustentabilidade e melhorar o valor dos recursos, Economia Circular insere-se com uma entusiasmante solução para providenciar metodologias que promovam a redução do impacto ambiental numa cadeia de valores de produtos ou serviços. Adicionalmente, Impressão 3D tem demonstrado um enorme potencial para usufruir de princípios de economia circular, providenciando aos produtores capacidades inovadores para servir o mercado, como nunca pensaram que fosse possível. Com novas práticas, surgem novos conceitos relativos a produtos e Inovação Frugal tem transformado o conceito de produto e negócio. Estes tipo de acessíveis soluções pode também providenciar práticas sustentáveis para preservar os ecossistemas naturais e uma utilização efetiva dos recursos.

Através de uma completa revisão de literatura assentada no contexto do plástico, economia circular, impressão 3D e produtos frugais, esta dissertação tem o propósito de providenciar uma estrutura para provar a viabilidade e possibilidade de explorar a reciclagem de plástico para fornecer feedstock para impressão 3D e produzir produtos frugais utilizando todos os conceitos explorados. Como tal, é realizada uma avaliação de cinco propriedades mecânicas importantes de ABS, PET e PLA reciclados. Esta avaliação forneceu uma caracterização mecânica dos materiais e informação que sublinha uma redução das propriedades mecânicas estudadas, comparadas com as de material virgem. Contudo, com as conclusões retiradas das propriedades obtidas foi possível produzir três produtos frugais diferentes. Tal prova a viabilidade de reciclar desperdício de plástico para transformar em produtos frugais, adotando sempre novas metodologias sustentáveis.

Palavras Chave: Economia Circular; Impressão 3D; Reciclagem de Plástico, Produtos Frugais; Propriedades Mecânicas

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List of Abbreviations

ABS : Acrylonitrile-butadiene-styrene
AM : Additive Manufacturing
ASTM : American Society for Testing and Materials
BCG : Boston Consulting Group
BoP: Bottom of Pyramid
CE : Circular Economy
CP : Cleaner Production
EU : European Union
FDM : Fused Deposition Modelling
HDPE : High density polyethylene
IT : Information Technology
IoT: Internet of Things
LDPE : Low density polyethylene
MFI : Melt flow Index
NAPCOR : National Association for PET Container Resources
PET : Polyethylene terephthalate
PLA : Polylactic Acid
PP : Polypropylene
PS : Polystyrene
PS : Polycarbonate
PVC : Polyvinyl chloride
RPET: Recycled Polyethylene terephthalate
SD : Standard Deviation
STL : Stereolithography
UNEP : United Nations Environment Programme
USD : United Stated Dollar
VC : Variance Coefficient
3DP : 3 Dimensional Printing
UK: United Kingdom

1. Introduction

1.1 Background and Context

One the most used materials in modern economy is plastic. Given the combination of a great versality and low acquisition cost, plastic use has grown exponentially over the past decades and is expected to continue this growth on the next 20 years (MacArthur, 2016). However, plastics products are, usually, associated with a short life spam and their intensive use is resulting on devasting ecological problems. For instance, greenhouse emissions in the production and after-use externalities costs related to plastic packaging have been estimated to be around 40 billion USD, by the UNEP. A major factor contributing to such problems is a shocking 32% of plastic packaging escaping from recycling systems, contributing to a terrific loss of 95% (between 80-120 billion USD) plastic packaging material value (MacArthur, 2016).

Additionally, the world population is consuming 1.6 times more than what can be sustained by our natural resources (Global Footprint Network, 2016). To preserve our planet and promote prosperity and development, a radical change in the current systems and practices is urgent. Circular Economy is a concept that intents to promote improvements on resource efficiency. It relies on reducing as much as possible waste and shifting the current take-make-waste model to a take-make-renew-take (Despeisse et al., 2017).

It is important to introduce new technologies that sustain the practice of circular economy. 3D printing has proven to be a technology that has tremendous potential to minimize production costs and enables companies to serve mass customized demands (Berman, 2012). It has also been seen as a technology that allows companies to produce quality products and also embrace circular economy principles. Indeed, the adaptation of this technology on the production of plastic products consuming plastic material waste is being seen as an efficient and cost effective practice to serve multiple industry sectors (Despeisse et al., 2017).

In addition, it has also been given importance to the investigation of FRUGAL products, that need to be extremely affordable and also sustainable, with high-quality offerings. Adopting frugality implies a development of a production practice that minimizes resources usage and align a design phase with reduction cost targets. It is also fundamental to align these methodologies with new technologies, to produce efficient and quality products (Maric, Rodhain, & Barlette, 2016; Roland Berger, 2015). Therefore, taking in account the aforementioned 3D printing features, it is totally justifiable the deployment of this technology to produce locally Frugal products.

This master dissertation is a research on the capabilities of the recycled plastic waste material on the production of Frugal Products using 3D Printing, a technology that is proving to be the future fundamental working tool. The master dissertation pursues to present the opportunity to increase waste plastic material value, aligned with an ideology rooted on circular economy principles.

1.2 Problem Characterization

Plastic has become one of planet Earth greatest environmental challenges, due to its massive use and, consequentially, after-use disposability culture. To invert this situation, governments are putting efforts to increase plastics recycling. For example, the European Union agreed in December 2017 to target 65% plastic recycling and a specific 50% plastic packaging to be achieved in 2025 ((UNEP), 2018). On the other side, the circular economy concept is currently a focus area, as it has revealed a great potential to improve sustainability and at the same time stimulate prosperity. This new paradigm requires a well-developed and revised approach, involving transitions on existing systems and also development of new innovative collaboration mechanisms. One technology that is proving potential to provide tools in effort to this transition is 3D Printing. Nonetheless, it is fundamental to connect 3D Printing-CE, establishing CE principles in the development and exploration of this new manufacturing technology ((UNEP), 2018; Despeisse et al., 2017). This master dissertation regards on the multiple application areas of 3D printing and its major productive and sustainable advantages. For instance, 3D Printing enables the production of various and complex designs without interfering with manufacturing capabilities and also has the potential to be a tool to work with recycled plastic waste material (Berman, 2012). The plastic recycling system to produce filament can be a feasible method to improve plastic recycling rates (Despeisse et al., 2017). This master dissertation statement arises by interpreting these concepts and their connection: by demonstrating how can recycled filament produced on a shredding and extruding recycling process be used to explore the characteristics and potential uses of such filament to produce frugal products with 3D Printing systems.

1.3 Master Dissertation Objective

With a complete theoretical basis, this master dissertation aims to analyse solutions to tackle the plastic waste problem presenting possibilities to use recycled filament and the feasibility of the connection of the concepts evolving the characterized problem. The developed research seeks to provide important information regarding mechanical properties of recycled plastic filament by presenting (1) The obtained mechanical properties of the studied recycled filaments, (2) The best printing temperature for the studied recycled filaments (3) A material characterization with the values obtained of the mechanical properties (4) Allocation of the materials to produce frugal products (5) 3D printed frugal products with the studied recycled filaments and their usability evaluation.

1.4 Master Dissertation Structure

The following structure represents the study developed in this dissertation. In chapter 2, it will be presented a complete problem contextualization and characterization. An introduction to the plastic background and its actual context will provide a better understanding on the necessity to improve plastic recycling rates. Chapter 3 provides a literature review on circular economy, relating its principles with the concepts that will be explored during this master thesis. It also incorporates the actual development on 3D Printing technology and the important points to consider for Frugal Products production. This chapter intents to demonstrate a lack of contribution in the considered connection between the approached concepts. With the contribution of the master thesis, the objective is to provide how can this gap be tackled. Chapter 4 presents the research methodology and adopted procedures to complete the objectives defined in this master thesis. Chapter 5 provides a presentation of the results withdrawn from the mechanical tests performed, which is followed by a discussion on the results to characterize the studied filaments with the values obtained for the mechanical properties. This chapter aims to provide knowledge and tools to explore the possible final applications of the recycled filaments. Chapter 6 arises as the final application of the research done, presenting three different frugal products produced based on the theoretical contents explored, each one produced with each different filament. Finally, chapter 7 presents a conclusion of all the content present in this master dissertation and provides suggestions for future work on this exploration field.

2. Plastic Market

This chapter presents a global overview of the "Plastic World" context. This material presents unrivalled advantages simultaneously with its low acquisition cost. Consequentially, we live in a world were plastic has become a material present everywhere. As this material is, normally, truly resistant to degradation, it has become a serious concern to manage plastic end-life. To understand all this context, it is important to take under consideration situation of current plastic production (section 2.1), the current plastic recycling paradigm (section 2.2) and the characteristics of the main types of plastic and their industry applications (section 2.3).

2.1 Plastic Market Context

Plastic is a lightweight, inexpensive material with resistant proprieties, having a wide range of applications ((UNEP), 2018). Plastics have an almost infinite variety of functions accounting from preserve and protect food, to produce electronic devices and contribute to a more efficient fuel usage on transportation (UNEP, 2014). Plastic can be defined as a polymeric material capable of being shaped into diverse final structures. It is derived from various resins each one with different capabilities. There are two main resins used to produce plastic: commodity resins and engineering resins. Commodity resins are composed by polyethylene, polypropylene, polyvinyl chloride and polystyrene. These resins offer the possibility to produce products with low cost and high volume, which are commonly known as disposable items and durable goods. Engineering resins are composed by polyacetal, polyamide, polytetrafluoroethylene, polycarbonate, polyphenylene, epoxy and polyetheretherketone. These plastics offer properties that can compete with die-cast metals in plumbing, hardware and automotive applications. Moreover, it is essential to emphasise that each polymer type can be subdivided into many subtypes, where any polymer can offer 20 or 30 different variations for use in explicit applications (Britannica, 2018).

Plastics have become the main material of the recent economy. The combination of plastics functional properties and low-cost acquiring prices are the main factors that contributed on a great increased of their usage in the past half-century (UNEP, 2014). Plastic usage is expected to increase exponentially in the next 20 years. The great versatility and low acquisition prices define plastics as the best option, when compared with alternatives, and it is reflected in the registered growth of market share. Nowadays, nearly everyone has contact with plastics everywhere and this material is often used in products with short lifespans (MacArthur, 2016; Van Eygen, Laner, & Fellner, 2017). The increase over the past 50 years of plastic production is notable, passing from 15 million tonnes (1964) to 311 million tonnes (2014) and, representing 26% of the total volume, plastic packaging is the largest application of plastic production (MacArthur, 2016). It is estimated that around 10 to 20 million tonnes of plastic are entering to the world's oceans per year, with associated costs of approximately US$13 billion per year in environmental damage to marine ecosystems (UNEP, 2014). In **Figure 1** it is represented the notable increase on plastic production over the last decades.

Due to the increase in production of day to day goods, associated with an increase on plastics usage, concerns about waste disposal management had become an environmental challenge worldwide. At the end of its lifecycle, a product has several possible ends, going from being recycled, incinerated, landfilled, dumped in uncontrolled areas or littered in the environment ((UNEP), 2018). With poor systems of waste disposal management, environmental pollution will increase and impacts on our ecosystems will be catastrophic (Islam, Meherier, & Islam, 2016).

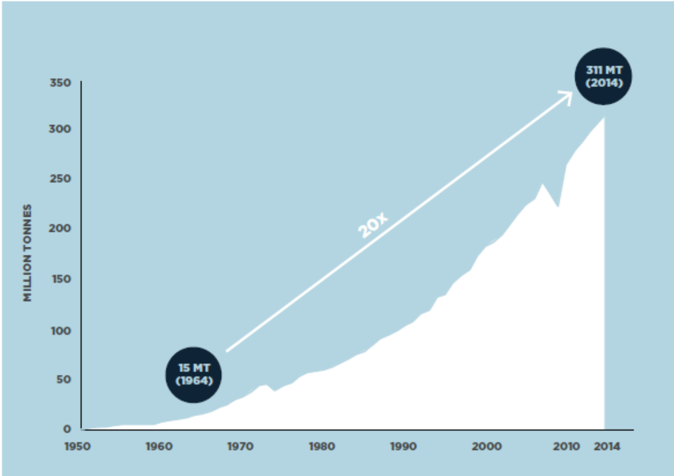


Figure 1 - Plastic production over the last decades (MacArthur, 2016)

Considering its multiple advantages, plastic packaging share, as a share of global packaging volumes, has reached 25% in 2015 as result of 5% annually plastic packaging market growth. These volumes are expected to continue their exponentially growth, reaching 318 annual million tonnes in 2050, that, in fact, is more than currently all plastics industry volumes (MacArthur, 2016).

The world distribution of the most common used plastics, single-use plastic, is presented in **Figure 2**, as the production per region in 2014.

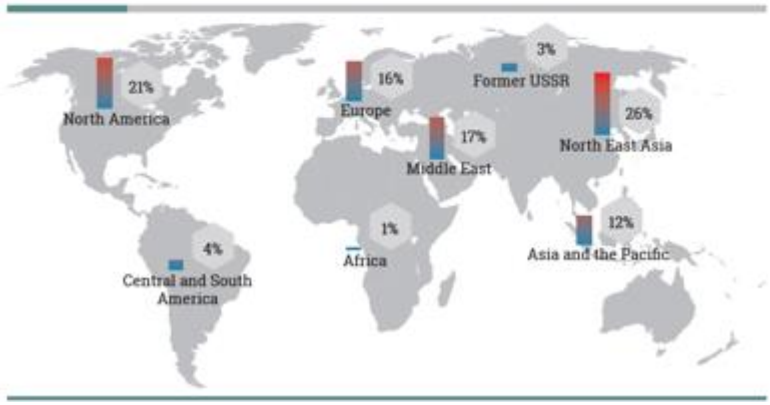


Figure 2 – Distribution of single-use- plastic by region (2014) ((UNEP), 2018).

North East Asia and North America are the world's biggest producer sharing almost half of the total world's production (47%). Europe and the Middle East are the second world's plastic producers sharing 33% of the total production ((UNEP), 2018). As result of a wide range of applications, plastics are used in almost every industry sector, leading to a demand of 48 million tons per year in the EU by 2014. **Figure 3** presents the 2014 EU plastics demand in the main market sectors (Hestin et al., 2017).

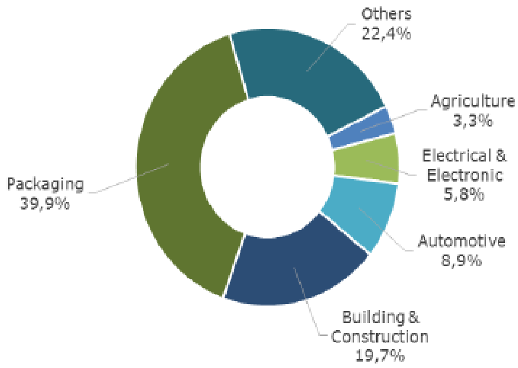


Figure 3 - Plastic demand per main market sector (Hestin et al., 2017)

Plastic packaging represents the biggest share of the plastic market, corresponding around 40% of the total demand. Based on an extrapolation from France, Germany, Italy, Spain and the UK, which represent the EU main waste generators, almost 23% of the plastics packaging waste flows is lost in landfills and 47% is incinerated. The remaining 30% of plastic packaging waste is recycled or exported. However, as the amount of plastics exported within EU or out of the EU is included in the recycling rate, the recycling rate can decline to 15%, when these exports are excluded (Deloitte Sustainability et al., 2017). The recycling rate can be established as a ratio between the weight of recycled waste with the total solid waste accumulated for disposal and incineration (Sidique, Joshi, & Lupi, 2010).

2.2 Plastic Recycling Context

Taking in consideration plastic packaging all over the world, a comprehensive global flow of plastic packaging materials can be found in **Figure 4**.

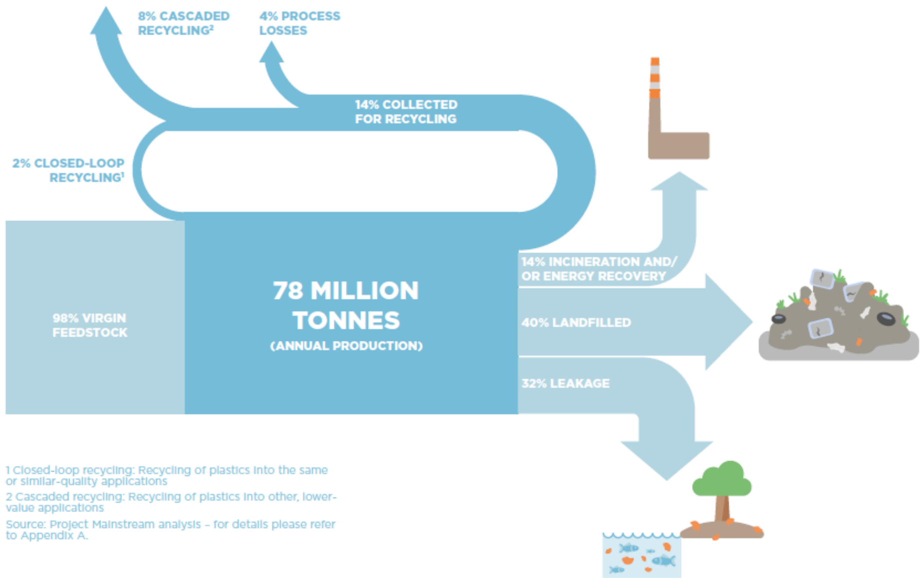


Figure 4 - Plastic Packaging Global Flow (MacArthur, 2016)

Almost half a decade after the launch of recycling symbol, values of plastic packaging collected for recycling are still low, reaching only 14%. PET is the plastic type with higher recycling rate, but even though with moderate values, considering that around 50% of PET is not collected for recycling and only 7% is recycled bottle-to-bottle (MacArthur, 2016).

In addition to 14 % of total packaging plastic production collected for recycling, also 14% is sent to an incineration and/or energy recovery process. This energy recovery process is positive, but there are some losses on the effort and labour required while creating the material. However, these processes compete with recycling. In fact, some energy recovery processes, such as recovery in mixed solid waste incinerators represent a solid rivalry to recycling. Considering their considerable relatively low operating costs, this recovery processes can push recycling mechanisms out of the market.

But the real problem appears when a devastating 72% of plastic packaging is not recovered resulting on landfilled litter and leaks to our ecosystems, where the values for landfilled and leaked are 40% and 32% of plastic packaging annual production, respectively. (MacArthur, 2016).

The problems concerning plastic packaging recycling are related to several global aspects. Multilayer packaging alongside with the high diversity of waste flows create problems in the recycling management. When in the same work area, the packaging's for products differ, the treatment of plastics cannot be done in the same recovery routes. This can be traduced, as, for example, it becomes problematic to treat clear PET bottles together with clear PET trays, since the diversity of trays is much higher when compared with PET bottles (Hestin et al., 2017).

Another problem occurs when a single product is incorporated with numerous resins using non-separable plastics, such as food bricks or flexible flasks. Multilayer packaging in general contains substances (polyamides) that produce undesired colouring of PET products and also modifies their intrinsic properties, resulting on difficulties to recycle (Hestin et al., 2017).

According the different work sectors, there are different requirements considering the quality of recycled resins. In the food industry, where plastic packaging has a great demand, food contact requirements represent an important concern, requiring well developed recycling schemes. Since the European Food Safety Authority defines requirements neglecting the environmental concerns of plastics waste treatment, companies do not incur in risks considering safety requirements, avoiding the utilization of recycled products (Hestin et al., 2017).

To conclude this analysis on the EU recycling performances, **Table 1** presents the collection and recycling rates of PET and polyolefins in 2014 on the above referred five main EU countries. It also presents the different collection schemes adopted, which cause impact on the variations verified on the overall performance of recycling.

Table 1 - Collection schemes in 5 important EU countries and their performances on the collection and recycling of PET and polyolefin plastics in 2014 (Hestin et al., 2017)

Country	Type of collection scheme	Collection rate	Recycling rate
France	Separate collection on HH bottles and flasks, and ongoing extension to all packaging	44%	21%
Germany	Deposit scheme for PET bottles and "yellow bins" for all others and separation by colour	76%	36%
UK	Significant non-collected amount of household containers	38%	22%
Spain	A separate collection scheme is in place but high amounts of plastic waste is collected from residual waste	41%	31%
Italy	A good level of separate collection in place	55%	42%

The implementation of a deposit scheme for PET bottles with a separate collection for other plastics, resulted on the great performance on the collection rate. Considering recycling rates, Italy has well developed and mature governments programs resulting on the verified good performances. However, France and Spain recycling performances are far below the desired targets. In France case, it can be justified with the poor design for separate collection. In Spain case, it has been verified a numerous amount of collected plastics from residual waste contaminating the plastic recycling stream. Even though UK large amount of plastic exported to extra-EU countries, it is the country that needs a tremendous effort to improve recycling schemes (Hestin et al., 2017).

As mentioned before, the combination of the exponentially growth on plastic usage with weak waste disposal management usage triggered ecological problems. This is forcing governments and companies to concern on the improvement of plastics end-of-life management processes. Organizations have been developing performance indicators to quantify and measure the evolution towards a circular economy, establishing the recycling rate and material utilization rate, used to quantify the waste materials getting back into economy (Haupt, Vadenbo, & Hellweg, 2017; Mudgal et al., 2012; NAPCOR, 2016).

An important performance rate is the material utilization rate, and, on NAPCOR 2016 Postconsumer PET Container Report, it was defined as “An expression of material and system efficiency. How much usable end product (clean flake) reclaimers were able to produce from incoming material purchased.”(NAPCOR, 2016). These performance indicators have been important and frequently used to define goals and to establish policy documents (Haupt et al., 2017; Mudgal et al., 2012; NAPCOR, 2016). To define directions towards sustainability, a target of 22,5 % on waste plastic packaging to be recycled was defined by the European Union (Van Eygen et al., 2017). To accentuate the importance on increasing recycling values, reducing landfilling and grow resources efficiency margins, by 2025, this 22,5 % goal is intended to increase and reach a 55% waste plastic packaging to be recycled. Furthermore, five priory areas to work towards a circular green economy were established in the European Union and plastics are one of them in this action plan (European Commision, 2015).

2.3 Types of Plastics

As mentioned before, there is a wide range of plastic materials related to the polymer which they are composed. In **Figure 5** is represented the polymer identification code, usually present in all plastic products. These polymers are used in different industries consonant their properties. In **Figure 6** is represented the global market share of the most used resins and main applications.

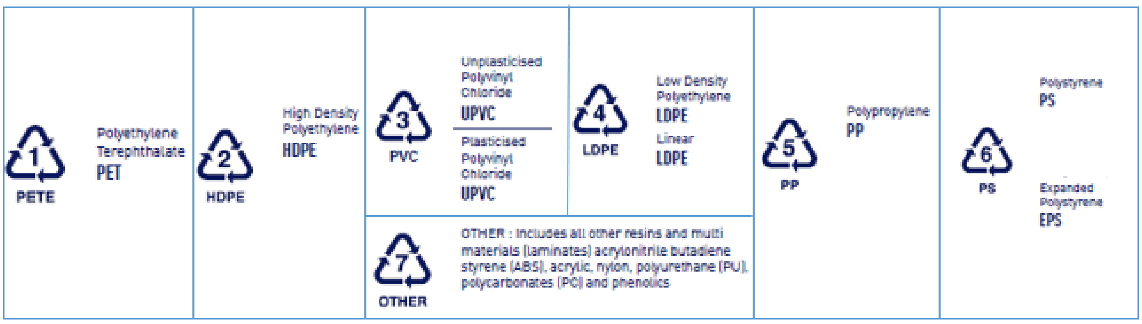


Figure 5 - Main Polymers and their identification code Adapted from (SUEZ, 2005)

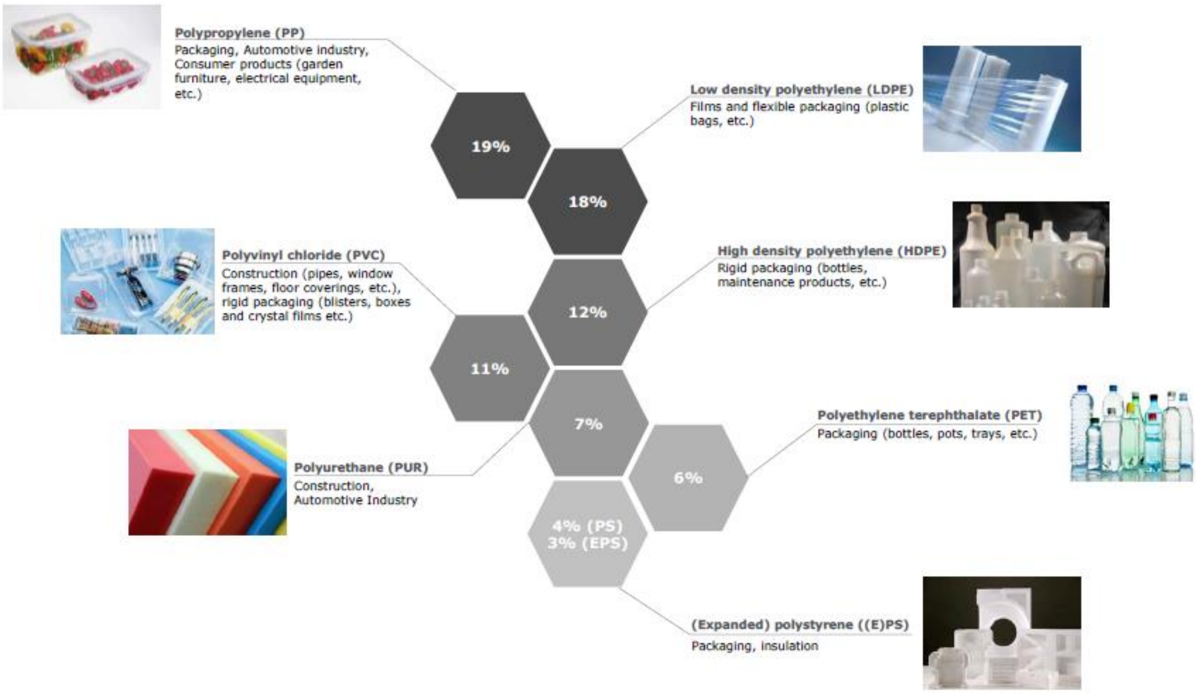


Figure 12 - Global Market Share of the most used resins and main applications in 2015 (Plastics Europe, 2015)

Polystyrene (PS)

Polystyrene is a synthetic resin produced by the polymerization of styrene, that is obtained when ethylene reacts with benzene in the presence of aluminium chloride. This polymer is a great electrical insulator, with optical clarity and offers great malleability and resistance to acids and alkalis. As physical properties PS is hard, amorphous with a density around 1.04 g/cm^3. Its maximum temperature for continued use reaches 100ºC and has a high tensile strength of approximately 35-55 MPa and a low impact strength around 15 - 20 J/m (Polymerdatabase, 2018). Such properties allow PS to be used with a great range of applications in rigid packaging, electronic products, coat hangers, medical disposables and yoghurt containers. The respective low costs to produce high volumes and ease of shaping using injection molding are convenient advantages of PS. However, PS is very inflammable and due to its high durability and low density results on pollution problems if not properly treated on its products end-life. (PACIA, 2005; Zhao, Lv, & Ni, 2018, Britannica, 2018, Polymerdatabase, 2018).

Acrylonitrile-butadiene-styrene (ABS)

ABS is a graft copolymer produced by polymerizing free-radical initiators with monomers of the mixture of styrene-butadiene with acrylonitrile and styrene monomers. This polymer is a good thermal and electrical insulator and it can be easily pigmented with different colours. Considering ABS mechanical properties, it is a strong and slightly flexible plastic, with an approximately density of 1.010 – 1.210 g/cm^3. It has Tensile Strength and Notched Impact Strength values around 40 - 50 MPa and 10 – 20 kJ/m^2, respectively. Its maximum continued use temperature is around 95 ºC (Zhao et al., 2018, Polymerdatabase, 2018, Michael F. Ashby, 2013).

Such engineering thermoplastics are most common used in automotive, aircraft, boating and electronic casing. ABS flexible and strength properties give it a high impact resistance and good dimensional stability, that makes it almost perfect for speedy prototyping systems. However, considering the emerging printing technologies, ABS presents some problems since it fumes when printing and also deforms when not being printed on a heated surface. It also represents environmental concerns, as this polymer is made out of oil. (Zhao et al., 2018) (Polymerdatabase, 2018) (Michael F. Ashby, 2013).

Polycarbonate (PC)

The production of PC is achieved when carbonic acid derivatives react with polyhydroxy compounds, resulting in a series of carbonate linkage polymers referred to as polycarbonates. PC offers good resistance to alcohols, oils and diluted acids and presents thermal stability with a good flame resistance. It also has a high electrical insulation resistance property. Regarding PC physical properties, it is a transparent polymer with density around 1.20 g/cm^3 and Tensile Strength and Notched Impact Strength values of 70 – 80 MPa and 60 – 80 kJ/m^2, respectively (Jayasuriya, 2017; Zhao et al., 2018; Plastipedia, 2018).

The great physical and chemical properties of PC make it one of the most widely used engineering resins. Similar to ABS, it is mainly used in the automotive, aircraft and boating industries, and also in the production of electrical and medical parts. When compared with other plastics PC is undoubtedly a material that offers an unbeatable strength combined with light weight. However, it has some problems concerning its low scratch resistance and necessity to include flame retardants in order to reach a stable flammability rating. (Jayasuriya, 2017; Zhao et al., 2018; Plastipedia, 2018).

Polyolefins (LDPE, HDPE and PP)

A polyolefin can be obtained from a polymerization of an olefin or alkene as a monomer. There are several polyolefins, still the mainly used are HDPE, LDPE and PP. High density polyethylene (HDPE) is a highly crystalline polymer with considerable resistance to alkalis, nonoxidizing acids and aqueous salt solutions. Characterized by a density of approximately 0.964 g/cm^3, it presents a Tensile Strength around 0.20 - 0.40 MPa and a maximum continued use temperature of 65ºC. Low density polyethylene (LDPE) presents similar chemical resistance to HDPE and is defined by a density range of 0.922 g/cm^3: It also shares similar values of Tensile Strength and maximum continued use temperature to HDPE. However, LDPE is more flexible and not so rigid as HDPE. Polypropylene (PP) is a semi-rigid translucent polymer that presents a good chemical and thermal resistance. It also offers an excellent electrical insulation at higher temperatures. PP is characterized by a density of 0.905 g/cm3 and it has a Tensile Strength around 0.95 – 1.30 MPa and a maximum continued used temperature of 80ºC (Laurence W. McKeen, 2012; Polymerdatabase, 2018; Plastipedia, 2018).

LDPE and HDPE present such versatile and flexible properties that make these thermoplastics widely used in the manufacture of bags, toys, containers, pipes, house-wares and industrial wrappings. With extremely high molecular weight HDPE, it is possible to achieve an exceptional resistant to impact material. PP is most common used in the production of ropes, plastic bottles and electric products (Laurence W. McKeen, 2012; Polymerdatabase, 2018; Plastipedia, 2018).

In a general context, polyolefins offer low production costs, light weight and a high chemical resistance. Moreover, it is possible to extend their mechanical properties through copolymerization, blending and mixture of additives. However due to weak intermolecular forces and high flexibility, HDPE materials tend to creep when, for long periods of time, subjected to high compressive forces. It is also an inflammable polymer, unless it is mixture with flame retardants. PP cons are related with an accelerated degradation, when in contact with certain materials such as copper and a high mould shrinkage (Laurence W. McKeen, 2012, Polymerdatabase, 2018, Plastipedia, 2018).

Polyethylene terephthalate (PET)

PET is a thermoplastic produced from the condensation reaction of dimethyl terephthalate and ethylene glycol. It has a great chemical resistance to diluted acids, oils, aliphatic hydrocarbons and alcohols, due to a robust chemical nature and their crystalline property. Regarding physical properties, PET has an approximately Tensile Strength of 2.5 MPa, a density of 1.37 g/cm^3, a maximum continued use temperate of 70ºC and a Notched Impact Strength between 1.5 - 3.5 kJ/m^2. (Plastipedia, 2018; Christopher Blair Crawford, Brian Quinn, 2017)

The great range of applications of this polymer make it one of the most present in current society. The major applications pass through packaging, overhead-project films and aluminium-coated reflective material. It is important to refer that plastic packaging is the most used plastic application. Such variety of applications are related to its advantages such as lightweight, transparency and a great resistance to degradation. However, considering PET materials long life spam, such materials represent a threat to environmental sustainability, when landfilled (Nicholas P. Cheremisinoff Ph.D, 2001).

PET can be fully recycled originating the well-known recycled polyethylene terephthalate (RPET). RPET is produced by recycling PET-based plastics. RPET offers a wide range of utilities in clothing, packaging, automotive parts, upholstery, strapping, sheet and film. However, the main application of RPET is in the production of beverage bottles (TheBalance, 2018).

Polyvinyl chloride (PVC)

Polyvinyl chloride resin is produced from the polymerization of vinyl chloride. Even tough PVC is mainly rigid, it has a notable property to absorb plasticizers and become a soft flexible film. It has an excellent resistance to chemicals such as diluted acids and alkalis. Considering its physical properties PVC is characterized by a density of 1.38 g/cm^3. It has Tensile Strength values around 55-80 MPa, a Notched Impact strength between 3-10 kJ/m2 and a max continued use temperature of 60ºC. (Plastipedia, 2018, Laurence W. McKeen, 2012). This polymer is one of the most consumed thermoplastic materials, more precisely on the electronic and electrical industry. (Zhao et al., 2018).

PVC offers the possibility to extend its range of applications, considering the extensive variety of additives that can be incorporated during PVC production, improving PVC materials mechanical properties. Additionally, when compared with other plastics PVC products can sustain a longer service life. However, as plastics in general, not also PVC production represents problems to environmental balance, it is also associated with a release of toxins linked to health problems. (ThoughtCo, 2018)

Polylactic Acid (PLA)

Polylactic Acid is mainly produced from lactides derived of the microbial fermentation of agricultural products, usually carbohydrate rich elements. PLA properties are dependent on the component isomers, processing temperatures and molecular weight. However, PLA density is approximately 1.25 g/cm^3 and its tensile strength varies from 53-70 MPa. The main applications of such sustainable alternative are for general packaging applications, as it owns similar mechanical properties to packaging thermoplastics. Since its intrinsic biodegradability, PLA can also be used to preparation of bioplastic, loose-fill packaging, compost bags and disposable products. Its main advantages are obviously connected to the fact of polylactic acid is a sustainable alternative to petrochemical-derived products. Regarding agriculture environmental problems, it has proved competences to reduce the quantity of used plastic for the production of horticultural products. However, this material production price too high to scale it up. Additionally, there are some challenges to achieve several mechanical properties similar with synthetic polymers, while maintaining biodegradability (Madhavan Nampoothiri, Nair, & John, 2010).

2.3 Conclusions

This chapter objectively provides a structured contextualization on the overall Plastic World Market. It aims to provide a complete information on the plastic utilization rate, with a deeper focus on plastic packaging, the largest market share of plastic utilization. Given the shocking numbers, it seems necessary to identify the plastic packaging flow and its recycling performances in the EU. The objective is to highlight the actual problems and to realize what the future perspectives are. Considering that this master dissertation intents to promote sustainability in line with production of plastic recycled products, it is also presented the main types of plastics industry utilization and their characteristics. The goal is to characterise their main features, for, further, have a direction on possible final applications with the recycled plastics. It is important to enhance that for a further successful implementation of the concepts and technologies studied on this report, it is important to approach them always with the circular economy concept as reference.

3. Literature Review

In this chapter it will be covered the circular economy concept along with an analysis on the key factors and methodologies for a successful implementation (section 3.1). It will also cover an interpretation on the synergies that can be obtained using digital technologies, which support and are supported by circular economy principles. In section 3.2 it will be explored the context of Industry 4.0 along with an analysis on FDM, the 3DP technology used in this master dissertation. In addition, it will be presented a state of art on the main aspects englobing the process to produce plastic feedstock for FDM. Finally, in section 3.3, it will be explored the Frugal Innovation concept and the characteristics that define a Frugal Product. The final goal of this research is to produce quality products using the aforementioned methodologies. Therefore, it will also be presented a possible methodology to interpret and define products quality. The intention is to provide the essential information on these topics and to demonstrate their interconnection. Indeed, this interconnection of technologies and ideologies to produce Frugal Products, has not yet been addressed as a matter of study.

3.1 Circular Economy

Circular economy (CE) has different definitions depending on the authors' fields of study. However, they all agree when it is defined as new economic model where products and processes development, as well as production and distribution activities, are designed to explore the maximum value of resources, eliminating waste as possible. It passes through a conceptualization of an economy where economic growth and resource usage are independent and not interlinked (Ghisellini, Cialani, & Ulgiati, 2016).

Circular economy is not a recent matter of study and it has previously been studied and defined by an environmental and economist researcher Kenneth Ewart Boulding as an implementation of a circular closed system, where exchanges of matter with outside environment are eliminated. Boulding stated that "*The essential measure of the success of the economy is not production and consumption at all, but the nature, extent, quality, and complexity of the total capital stock, including in this the state of the human bodies and minds included in the system.*" Boulding titled this economy as the "*the spaceman economy*", where the main concern of economies is sustainability and stock maintenance (Boulding, 1966; Ghisellini et al., 2016). Indeed, the optimization and examination of industrial systems operations are fundamental concepts when building and introducing worldwide circular economy definitions (Iung & Levrat, 2014).

It has become a focus area investigating the circular economy concept and develop better solutions to put this concept into practice. The momentum that circular economy has gained can be verified on the rapid growth of peer-reviewed articles where more than 100 articles were published in 2016, compared with the 30 articles published in 2014 (Kirchherr, Reike, & Hekkert, 2017). A radical improvement on resource efficiency with a substantial reduction on waste is one critical point in circular economy concept. The goal is to support companies and populations, using this concept as a principle to explore the potential improvements on life-style, environment and economy (Despeisse et al., 2017). **Table 2** presents some authors definitions on circular economy.

Table 2 - Circular Economy Definitions

(Yuan, Bi, & Moriguichi, 2006)	"The core of CE [are] the '3R' principles—reduction, reuse, and recycling of materials and energy. […] The approach is expected to achieve an efficient economy while discharging fewer pollutants. The strategy requires complete reform of the whole system of human activity"
(Zhijun & Nailing, 2007)	"is a mode of economic development […], requires compliance with ecological laws […]. It is, essentially, an ecological economy that follows the principles of "reducing resource use, reusing, and recycling""
(Kallis, 2011)	"a socially sustainable and equitable reduction (and stabilization) in a society's throughput where throughput denotes the materials and energy a society extracts, processes, transports and distributes, to consume and return back to the environment as waste"
(Macarthur, 2012)	"an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials"
(Jiao & Boons, 2014)	"a holistic concept covering the activities of 'reduce, reuse, and recycle' in the process of production, circulation, and consumption"
(Lieder & Rashid, 2016)	"CE is [a] closed loop material flow in the whole economic system […] in association with the so called 3R principles […] Taking into account economic aspects CE […] minimizes matter […] without restricting economic growth"
(Ghisellini et al., 2016)	"CE provides a reliable framework towards radically improving the present business model towards preventive and regenerative eco-industrial development as well as increased wellbeing based on recovered environmental integrity"

To conclude this overview on the circular economy concept, and despite the fact that, probably, circular economy will not ever have a singular meaning, a final definition, based on an analysis of several circular economy definitions can be stated with some consensus: Circular economy is an economic system composed by business models where the 'end-of-life' concept is eliminated as possible by reducing, reusing, recycling and recovering materials, all over the production/distribution and consumption processes. These processes should be seen from a micro (products, companies, consumers), meso (eco-industrial parks) and macro (city, region, nation) perspectives, with the purpose of establishing a sustainable development, providing environmental quality, economic prosperity and social equity and bringing benefits to current and future generations (Kirchherr et al., 2017).

The first studies on circularity concept were focused on the roots of circular economy, the 3R´s (Reduce, Reuse, Recycle). Moreover, recent studies expanded the 3R's to a 6R´s. In **Figure 7** is illustrated the circular economy framework that can be divided into two main topics: 1) 6Rs definition and 2) biological and technical cycles.

Starting from the 6R's definition:

The Reduction principle regards to a decrease on input of primary energy, raw materials and waste. Such reductions are intended to be developed through improvements on production efficiency (eco-efficiency) and consumption processes (Ghisellini et al., 2016).

The Reuse principle aims to promote operations to reuse products and components, that are not waste, with the same utility when they were conceived. This concept directly promotes environmental benefits as it requires less resources and energy, when compared with the production of new products from virgin material or even recycling (Ghisellini et al., 2016).

The Recycle principle regards recovery operations that pursue that recovery of waste materials and reprocess into products or materials, for their original or other the purposes. It does not include energy recover or processes to transform waste into materials that are to be used as fuel or for backfilling operations. Reduction of waste and environmental impacts as well as reutilization of still usable resources are the mainly opportunities offered by recycling (Ghisellini et al., 2016).

The Redesign principle contains the methodology of redesigning products and processes in order to increase efficiency and promote sustainable activities. This also would pass through the use of components and materials recovered from previous life-cycle (Jawahir & Bradley, 2016).

The Remanufacture principle involves the renovation of a used products into the original functionally or alike-new form, retaining as possible components from its reuse activity (Jawahir & Bradley, 2016).

The Recover principle is the activity that englobes collecting, disassembling, sorting and cleaning products at end-life-cycle for integration on new life-cycles. This is a pillar to this ideology, since all the other principles can only be put into practice if the waste/end-life products are recovered correctively (Jawahir & Bradley, 2016).

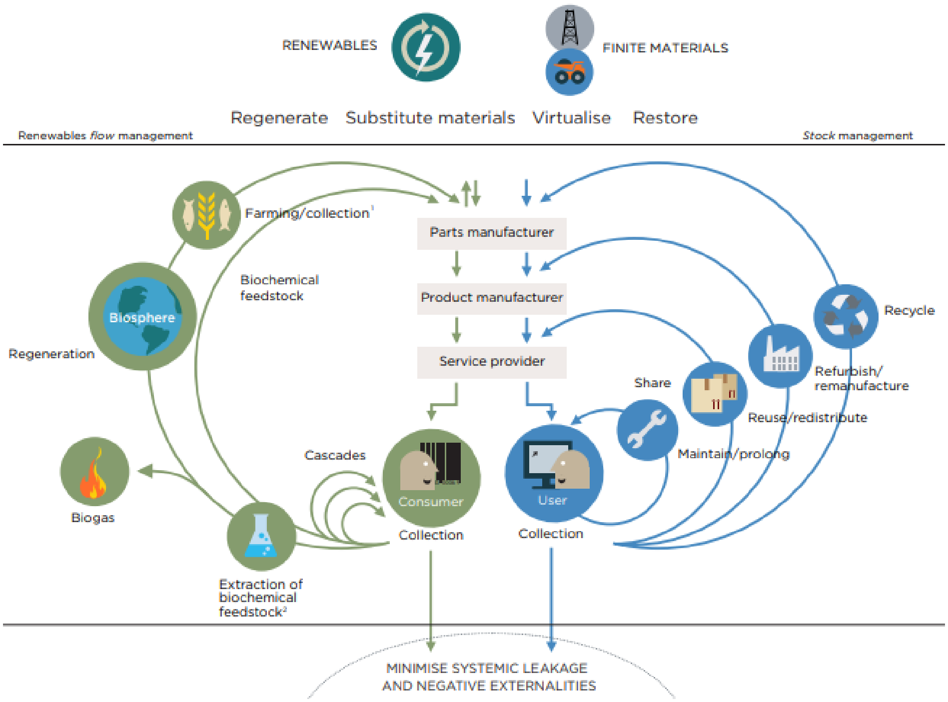


Figure 7 - Circular Economy Design (MacArthur, 2015)

Technological and biological cycles are the considered the possible cycles of two different types of resources. The biological cycle considers products that are consumed and have an easy and fast decomposition. In this case nature processes regenerate materials without human intervention. Biological nutrients are managed to promote their sustainability and the circular economy encourages the creation of conditions for the natural regeneration of such resources.

The technical cycle is related with the technologies and business models that are set to extract the highest possible value from products and materials. Thus, it is necessary a complete and well developed system to seize the value of end-life products (MacArthur, 2015).

Figure 7 illustrates the model that contemplates the aforementioned information. The biological and technical cycle are represented in green and blue, respectively. This model relies on three main principles: To Preserve and enhance natural capital; Optimize resource yields; Foster system effectiveness. The first principle regards the upper stage of the model where the objective is to manage finite stocks, balancing their use in line with renewable resources flows. For instance, such activities can pass through using as possible renewable sources of energy and, when it is not justified, adopting methods that preserve finite stocks. The second principle considers the second stage of the model, where takes place the main business activities. In this phase it is extremely important to maximize products, components and materials circulation rates by sharing and looping products, to extend as possible their lifetimes. The third and final principle aims to study and eliminate whenever it's possible the environmental negative externalities, resultant from industrial and business activities (MacArthur, 2015).

To promote this transition to Circular Economy there are three activity levels, such as the macro, meso and micro system that must be subjected to modifications. In the macro-systems perspective, the focus is to modify the industrial composition and structure of the entire economy. Regarding a softer point of view, meso-systems highlight the importance of eco-industrial parks as systems in regional levels. Furthermore, the micro-systems perspective takes into consideration the circularity of products, processes, individual enterprises and consumers and where is space to improve this concept (Kirchherr et al., 2017). .

However, over the past decades, society did not take into consideration this concept. Indeed, the world's industrial economy has stagnated with a linear model resource consumption based on a 'take-make-dispose' model. Productors extract raw materials to produce goods and supplies, selling them to consumers. In these model, products end-life would be a synonym of discarding. Consequentiality, a system based on consumption, neglecting circularity of materials, represents losses of value on all the material chain and negative effects on sustainability. This behaviour triggered serious resource and environmental problems all over the world. In response to this, investigations to improve resource efficiency and to discover new forms of energy had already began worldwide. Nonetheless, it has not been given the necessary importance to improvements on material recovery. As result, in 2010 the world's extracted raw materials entering on economic system reached 65 billion tones and is expected to growth to shocking 82 billion tonnes in 2020 (Macarthur, 2012).

In response to the verified devasting numbers regarding our resources sustainability, Europe, Japan, USA and Korea have already started to implement circular economy principles, fundamentally, in sectors related to waste management. These group of countries are structuring policies to reach synergistic effects focused on landfill prevention, procurement of resources and management of hazardous waste, based on circularity of materials. For instance, considering reductions on energy related to products, the European Union established an eco-design directive to promote a well-designed and integrated framework for minimum requirements applied to the mentioned use of energy (Sakai et al., 2011).

Methodologies to implement CE principles in production processes are an important matter of study. Such methodologies pass through an increase on eco-efficiency and a promotion of cleaner production (CP). Considering the increase on eco-efficiency, a model to adopt is to rethink processes, using fewer resources per unit of produced material and always use as possible harmful substances. It is important to remind that is also fundamental to keep high quality standards and product's performance. Cleaner production is considered a fundamental ideology to successful implement circular economy. It provides cleaner products and processes to achieve fewer emissions flows and reduce waste. Cleaner production considers three inter-dependent practices: Pollution Prevention, Toxic Use Reduction and Design for Environment. Design for Environment is a fundamental working methodology to achieve a sustainable product. Indeed, this sustainability depends on the processes and choices made in the early design stage (Figge, Young, & Barkemeyer, 2014; Ghisellini et al., 2016; Ramani et al., 2010). These early decisions should take in consideration issues regarding products end-life management, such as disassembly, ease of return, distribution and elimination of environmental impacts related to disposability (Prendeville, Sanders, Sherry, & Costa, 2014; Winkler, 2011).

Globally, CP promotes a continued revised application of a preventive environmental strategy considering systems that englobe products, processes and services, always regarding economic efficiency and quality standards (Li, Bao, Xiu, Zhang, & Xu, 2010).

Promoting circular economy creates new perspectives and new typologies of operators. As an important sub-sector of circular economy, waste management requires the introduction of new processes with new technologies such as "scavengers" or "decomposers". Such companies offer services to extract resources out of waste applying these recovery technologies. Scavengers are able to perform collection, dismantling, sorting and transport of waste resources of the disposal chain. Additionally, they redistribute them to decomposers companies that will give new value to the referred waste materials, by recycling it into new materials or parts of their original input flows (Ghisellini et al., 2016).

For a successful implementation of circular economy on company's business models, the traditional business model linear flow of "resources-products-waste" should be substituted by a new perspective "resources-products-waste-renewable-resources". For a business model implementation, the referred new flow implies critical modifications. Firms have the obligation to add or adjust their forward supply chain activities towards a reverse supply chain. This implies reverse logistics activities, such as inspection and evaluation of products current state, redistribution and recycling. Thus, it requires an evolution on technological equipment and skills and, at the same time, a development on knowledge areas of Life Cycle Assessment and Product Lifecycle Management (Urbinati, Chiaroni, & Chiesa, 2017).

These modifications imply an increase on interactions of all business's activities correspondent actors. It also establishes a new product value for customers, creating a new perspective of the buying process. In **Figure 8** is presented four modes of adoption of circular economy. The price/promotion variable represents the different level of value offered to customers. This value is traduced on the product functionality and also how important to companies is the promotion of products/services based on sustainability and circular economy practices. The "design for X practices" refers to degree of implementation of recycling, remanufacturing, disassembly and environment designs within the company's products/processes (Urbinati et al., 2017).

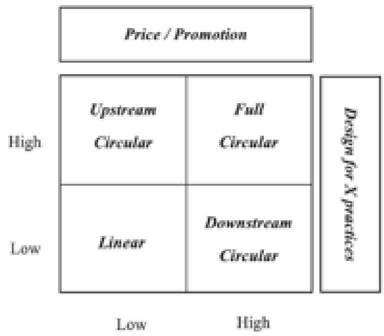


Figure 8 - The four modes of adoption of Circular Economy Principles (Urbinati et al, 2017)

Starting from the Downstream Circular adoption mode, it represents a state where companies concern on a price strategy and a marketing campaign based on the use and re-use of products. However, internal products development processes and activities do not represent characteristics of a circular economy-based company. In such a way, Downstream Circular companies are focused on the revenue stream, taking advantage of a market acceptance on the pay-per-use model (Urbinati et al., 2017).

Secondly, the Upstream Circular implementation represents companies that are focused on adopting circular principles along their supply chain activities, product development and internal processes. In this state, there is no concern on promoting their circular principles to customers on price or marketing campaigns and the revenue stream is based on cost efficiency (Urbinati et al., 2017).

Finally, the Full Circular adoption mode encompasses companies that are fully exploiting the circular economy principles, both internally and externally. In this case, there is a concern to align the selling activities and production system with the supplier's activities based on a circular sustainable concept. The objective is to promote a global closed effective system, in every single operation till the product being available to customers. These companies have concerns to inform customers of the implementation of sustainable practices (Urbinati et al., 2017).

To conclude the literature review on circular economy it is important to highlight the importance of the presence of digital technologies on circular economy in order to provide better tools to regulate and control production and waste. It is possible to obtain reverse material flows with optimized material flows. The formulation and integration of multiple Product Service-Systems (PSS), enabled by digital technologies, provide considerable economic, environmental and social benefits (Pagoropoulos, Pigosso, & McAloone, 2017).

Moreover, 3DP technology-based products known as "medium-lived complex products" such as medical products, automotive components, aerospace components and industry machinery, are inserted in the CE context. Indeed, their related distributed manufacturing configurations to decrease environmental impacts of supply chain are a focus point of circular economy (Despeisse et al., 2017).

To produce such products alongside with a successful application of CE it is required well a structured supply chain and production process. In this aspect, 3DP systems and, consequentially, working methods facilitate these requirements. To achieve them, it implies an incorporation of operational activities (design, process planning, manufacturing execution) to create information heuristics supporting the adoption of 3DP with CE roots. 3DP enables efficient processing/assembly activities and reduces supply chain sizes, which results on a better resource consumption measurement. Globally, 3DP promotes sustainable consumption and facilitates the development of previously mentioned design for environment methodologies.

Additionally, with 3DP-CE paradigm new entrepreneurial activities emerge around 3 topics, such as: Repair and Remanufacturing using 3DP; Production of 3DP filament with virgin and recycled materials; Local recycling systems to produce 3DP filament (Despeisse et al., 2017).

Figure 9 presents a compilation of the information presented in this chapter and contextualizes the connection between the approached topics on this state of art. It is really important to take into consideration that consumers play an important role in the transition towards the desired circular economy paradigm. They are responsible for promoting green principles and supporting attempts of sustainable models, in order to facilitate the upscaling of circular initiatives.

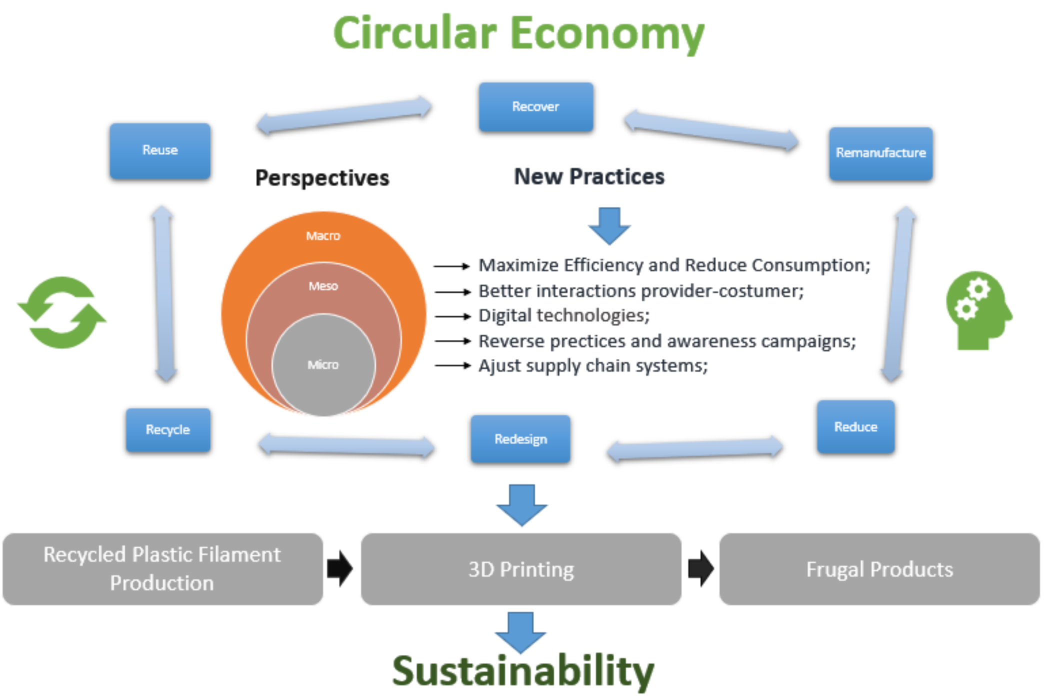


Figure 9 - Circular Economy Global context and 3D Printing connection

3.2 3D Printing Technology

3.2.1 Industry 4.0 and Additive Manufacturing

In the upcoming new industrial paradigm, interactions between manufacturing operations systems and information-communication technologies are features inserted in the so-called Industry 4.0. Industry 4.0 is related to the fourth industrial revolution. This paradigm is characterised by new levels of organization and control over the entire products value chain. Globally, in Industry 4.0 sensors, machines, workpieces and IT systems will be interconnected along all the value chain of companies (Dalenogare, Benitez, Ayala, & Frank, 2018; Dilberoglu, Gharehpapagh, Yaman, & Dolen, 2017). These features are bringing new tools to companies, changing the competition rules, company's structures and customer demands. With this transformation appears the concept of mass customization, with a new service approach towards increasingly individualized customer preferences. Indeed, mass customization is gaining more preponderance in business models and the upcoming Industry 4.0 technologies are vital to unlock mass production of customized products and make it feasible to companies (Dalenogare, Benitez, Ayala, & Frank, 2018; Dilberoglu, Gharehpapagh, Yaman, & Dolen, 2017; The Boston Consulting Group (BCG), 2015).

Globally, Industry 4.0 is defined by nine pillars: Big Data and Analytics, Autonomous Robots, Simulation, Internet of Things, Horizontal and Vertical System Integration, Cybersecurity, The Cloud, Additive Manufacturing, Augmented Reality. (Vaidya, Ambad, & Bhosle, 2018).

One major feature is the integration of Internet of Things (IoT) concepts on company's business models. Thus, such technologies allow companies to extract information and form statistical data from products, machines and production systems. Another important information that can be easily ready to analyse is the data from design records, customer's orders, supplier's deliveries, stock and logistic material (Dalenogare et al., 2018; Dilberoglu et al., 2017; Vaidya et al., 2018).

Additionally, since the manufacturing systems capability are dependent of the functionality of processes used in industrial organization, such as integration and self-optimization, there are also progresses in factory's production. Industry 4.0 upgrades these processes and creates a new paradigm defined by three major dimensions of integration. Such dimensions are known by horizontal integration across the entire value creation network; vertical integration and networked manufacturing systems; end-to-end engineering across the entire product life cycle (Dalenogare et al., 2018; Dilberoglu et al., 2017; Vaidya et al., 2018).

Another potential of 4.0 Industry is the augmented reality, an expansion of the view over company's activities, that provides workers better information to improve decision making and work procedures. Moreover, it will be possible to introduce real-time data in simulation systems, to traduce the physical world in a virtual world. This will provide companies trials to optimize activities settings in a virtual world and further traduce them in the real world. Thus, it will be necessary more production-related undertakings, requiring well developed data sharing across company's boundaries. As result, is important to explore the cloud functionalities, to enable this increasingly data deposited in the cloud and data-driven services for production systems (The Boston Consulting Group (BCG), 2015). Basically, in Industry 4.0 reality the entire value chain becomes fully integrated, sharing data across borders and providing companies with more efficiency and competences to compete in the markets.

Additive manufacturing (AM), is currently being take into serious consideration as the revolution in the industrial world. The production of customized products without incurring any major costs, as neither tools or molds are major advantages offered by this technology. Additionally, AM may lower barriers to companies on market entry in competitive markets, offering the ability to serve multiple services/products. (Weller, Kleer, & Piller, 2015). However, it is important to explore all the advantages and challenges, while incurring on this technology services, to figure how far could AM go and which industries could take advantage of its benefits.

AM can be defined as " the process of joining materials to make objects from 3D model data, usually layer upon layer" (Gibson, Rosen, & Stucker, 2013). It is a simple process where first, while scanning the targeted product with the 3D sensors, the obtained data is sent to a local or cloud server through cable or WiFi connection. The obtained 3D data is used to create reconstruction algorithms, which, depending on the nature of the product, will be used to apply segmentation and scaling algorithms. With all the gathered information it is created a printable 3D file (e.g., STL file), that can be modified with graphic tools. Finally, the final printable file is used by a 3D printer to create a physical product of the selected materials (Zhang, Dong, & Saddik, 2015). **Figure 10** represents the mentioned process of creating a 3D product.

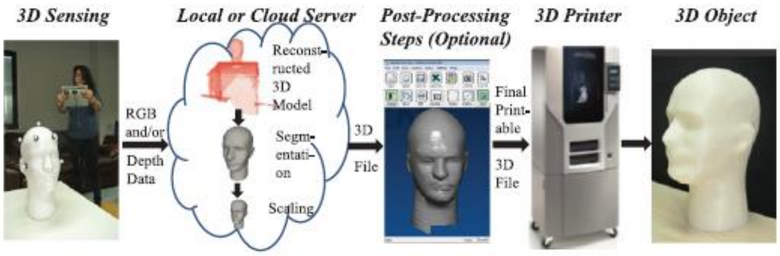


Figure 10 - Process to produce a 3DP object (Zhang et al., 2015)

The range of materials compatible with AM has increased significantly over the last years, being possible to work with raw materials, such as nickel-based chromium and cobalt chromium; stainless steel; titanium; polymers; and ceramics. Essentially, materials that can be liquefied, melted and re-solidified are suitable for AM technology (Berman, 2012; Weller et al., 2015). However, nowadays, considering the mechanical proprieties and the performance under submitted conditions, polymers are the most used material present in various sizes and composing many products (Mavri, 2015).AM also has the potential to provide various sustainability advantages such as reducing the generation of waste during manufacturing, as a result of it being an additive process. Material and energy consumptions are also reduced considering the effective process to create light weight components and optimise geometries. Reductions in transportation in the supply chain and inventory waste reduction, as AM allows to produce spare parts on-demand (Chen et al., 2015). As result, AM is expected to "become a key manufacturing technology in the sustainable society of the future" (Ford & Despeisse, 2016).The possible applications of AM in industries, presented on **Table 3**.

Table 3 - Uses of 3D printing across industries Adapted (Tofail et al., 2017)

Car Industry	Aerospace/Aeronautics	Medicine	Construction Industry
• Intregation of many parts in a unified composite part; • Construction of production means; • Fast standardization.	• Production of acessories of complex geometry; • Control of density and mechanical properties; • Productions of lighter acessories.	• Development of ajustable orthopaedic implants and prosthetics; • Use printed simulated corps for medical training; • Printing of biodegradable living tissues for tests.	• AM of concretes for conventional building; • Novel design of funcional concretes; • Building construction using materials found in the vicinity.

To summarize all the preceding analysis on AM characteristics and potential features we can define four key principles that differentiate this technology in the industry world: a versatile manufacturing machine; customization and flexibility for free; complexity for free; with reduced assembly work requirements (Weller et al., 2015).

Firstly, given that AM is capable of transforming any digital 3D model into a physical product, through standardized data interfaces, with a wide range of applications providing quickly and locally end products at a constant marginal cost, defining the first key principal: a versatile manufacturing machine (Garrett, 2014; Weller et al., 2015).

Furthermore, as tools or molds are no longer necessary before production starts sunk costs are eliminated. Also, products designs can be changed with zero costs and time penalties in manufacturing. These capabilities define AM as a technology with *customization and flexibility for free* (Weller et al., 2015).

Additionally, without increasing manufacturing cost, products can be more sophisticated, and companies can afford higher products variety. With this AM offers *complexity for free.* Finally, with fewer production steps involved and lower manual interventions throughout production process defines AM as a process with *reduced assembly work requirements* (Weller et al., 2015).

3.2.2 3D Printing Technologies

The 3DP technology can be divided in seven main emerging sub-technologies, which are chosen depending on a company's product, circumstances and preferences. These seven main sub-technologies are: Power bed Fusion; Vat Photopolymerization; Binder Jetting; Material Extrusion; Material Jetting; Direct energy Deposition; Sheet Lamination (Ernst & Young, 2016).

Material extrusion or Fused Deposition Modelling (FDM**)** is a rapid prototyping technology developed by Stratasys. In FDM molten thermoplastics are extruded from a nozzle head and further deposited on a heated surface, to produce parts layer-by-layer. Since FDM enables to eco-friendly produce complex geometrical parts, it is the mainly used additive manufacturing technology in several engineering applications (Mohamed, Masood, & Bhowmik, 2015). Thus, this is a complex process that presents various challenges to achieve the optimal printing parameters. To produce parts with good mechanical properties and a solid design, it is necessary to take in consideration several conflicting factors. There are five major factors such as: Built

Orientation, Layer Thickness, Air Gap, Raster Angle and Raster With (Carneiro, Silva, & Gomes, 2015; Mohamed, Masood, & Bhowmik, 2015).

The first factor, Built Orientation, is the determination of the way in which the part is oriented inside the printer, related to X, Y, Z axes. The second factor, Layer Thickness, is the thickness of the layer deposited. The Air Gap is the gap between adjacent raster tool paths on the same layer. Regarding the production of small parts with the need to print it precisely, it is important to determine the angle of the raster pattern related with the X axis, the Raster Angle. Finally, the width of the material deposited for rasters is the named Raster With. With higher width values, it will be achieved stronger interior of parts. In fact, there have been developed various studies in order to draw conclusions on the best parameters to print parts with thermoplastics (Mohamed et al., 2015).

Ang, Leong, & Chua (2006) focused on ABS part printing and stated that mechanical properties and porosity were influenced directly by the air gap, raster width and built orientation. It was determined that the air gap was the factor with highest influence on the porosity and mechanical properties.

Considering tensile strength printing influencing factors, Chung, Lin, Wang, & Lin (2007) discovered that printing according the Z axis build orientation undoubtedly increased their parts tensile strength. However, regarding other important quality variables such as a minimum dimensional deviation and the minimum surface roughness, this investigation drawn three independent optimum solutions. Chung et al. (2007) could not determine a certain answer to provide the better parameters to maximize the tensile strength, also minimizing the dimensional deviation and surface roughness.

Sood, Ohdar, & Mahapatra (2009) investigated all the mentioned five mainly influencing factors and developed an optimizing mathematical model, regarding parts mechanical properties. It was stated that it is possible to reduce residual stress and deformation, also improving parts strength by increasing the layer thickness. It was also determined that smaller raster angles negatively affect these referred parts mechanical properties.

Finally, recently Rayegani & Onwubolu (2014) investigate the optimization of ABS parts tensile stress regarding factors such build orientation, air gap and raster angle and width. It was determined an optimal set of parameters with a build orientation and raster angle at 0º and 50º, respectively, an approximately raster width of 0.2034 mm and a negative air gap of 0.0025mm.

After an overview on 3D printing technology, an analysis on the differences of working processes, also underlining the major advantages and disadvantages, offered by this revolutionary technology can highlight the acceptance conditions to integrate 3D printing in industries.

Starting from a technological perspective, some opportunities and limitations can be emphasised:

Opportunities

- Direct digital manufacturing of 3D product designs, without the need for tools or molds (Weller et al., 2015).
- Change of Product designs without cost penalty in manufacturing (Weller et al., 2015).

- High manufacturing flexibility as objects can be produced in any order without cost penalty (Weller et al., 2015).
- Less raw materials required (Weller et al., 2015).

Limitations

- Solution space limited to size of printable materials and to the size of build space. (Weller et al., 2015).
- Significant efforts are still needed for surface finishing (Weller et al., 2015).
- Lacking design tolls and guidelines to fully exploit AM potential (Weller et al., 2015).

Analysing from an economic perspective, the major potential and limitations can pass through:

Opportunities

- Acceleration and simplification of product innovation (Weller et al., 2015).
- Reduction of assembly work with one-step production of functional products (Weller et al., 2015).
- Local production enabled (Weller et al., 2015).
- Inventories can become obsolete when supported by make-to-order processes (Weller et al., 2015).
- Resolving "scale-scope dilemma" as manufacturing for higher product variety does not incur in cost penalties (Weller et al., 2015).

Limitations

- High prices and investment (high costs of 3D systems) (Weller et al., 2015).
- Intellectual property issues, particularly regarding copyright (Weller et al., 2015).
- No economies of scale (Weller et al., 2015).
- Product offering limited to technological feasibility (solution space, reproducibility, quality) (Weller et al., 2015).
- Skilled labour and strong experience needed (Weller et al., 2015)

Introducing 3D printing technology on global markets seems to be the path to go, as the demand for 3D printing systems and related services has triggered a great increase in AM market volumes. These volumes were levelled up from US$1.5 billion in 2011 to US$4.2 billion in 2015, which corresponds to a 28 % annual growth rate. (Ernst & Young, 2016).

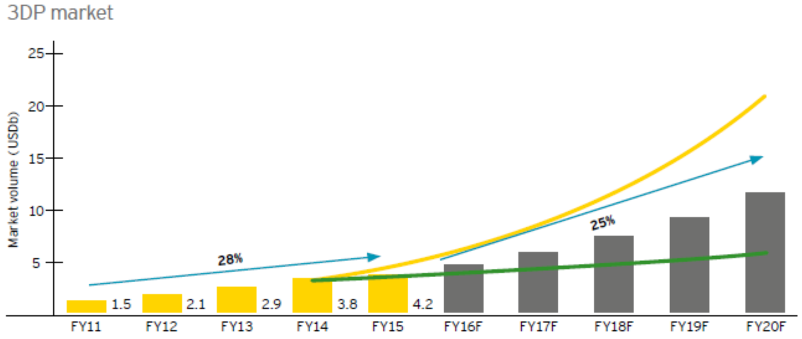


Figure 21- 3DP expected market volume (Ernst & Young, 2016)

It is expected that until 2019 this notable 28 % annual growth will continue and by 2020 the 3D printing market will slightly decrease this rate to a 25 % annual growth rate, resulting on a of US$12.1 billion total market value by 2020, as represented in **Figure 11** (Ernst & Young, 2016).

However, other market studies, based on 2015 financial year, for the 3D printing industry report different annual growth rates and overall market sizes. These different market studies differentiate on around 24 % for the growth rates and US$15 billion 1 for the overall market size, resulting, as presented on graph of **Figure 11** , on a lower boundary correspondent to a 10 % annual growth and an overall market value of US$6 billion in 2020, and on an upper boundary correspondent to a 34 % annual growth rate and accounting for an overall market value of US$20 billion in 2020 (Ernst & Young, 2016).

3.2.3 Filament producing process

As 3D printers are starting to be seen as feasible manufacturing tool, it is important to analyse the primary expense of operating with 3D printers: The filament or “3D ink”. Such operating costs can be reduced and at the same time pull the circular concept, using post-consumer plastics as feedstocks to produce filament. An exploration field to produce feedstock to 3D printers using a shredder designed to shred plastic products into small pieces and an extruder to produce the filament. With the plastic materials shredded, filament can be produced with commercial extrusion of plastic. In this process, plastic materials enter in a closed loop process to obtain recycled filament from post-consumer plastic, where waste is eliminated as possible (Kreiger, Mulder, Glover, & Pearce, 2014). Researchers through the world are creating small-scale plastic extruders, semi-automated open sources (RecycleBot), to prepare 3D printing feedstock from post-consumer plastics. The main projects of filament extruders of post-consumer plastics under development are the Lyman Filament Extruder, the Filabot and the MiniRecycleBot (Kreiger et al., 2014). The aforementioned process to produce recycled 3DP plastic filament increases the usable mass of post-consumer plastic, pulling again communities to a circular economy concept (Kreiger et al., 2014).

In **Figure 12** is presented a schematic demonstration of all the necessary steps to produce the 3DP recycled feedstock with HDPE, which can be adopted to similar plastic waste, such as PET, ABS and PLA.

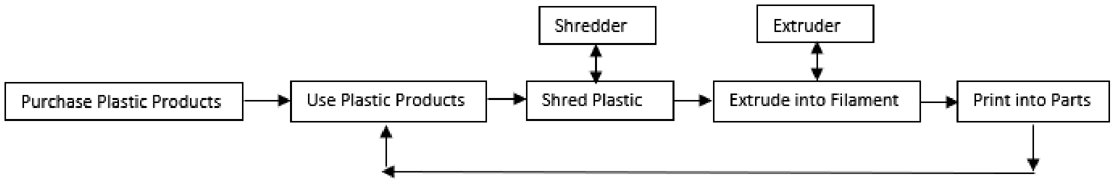


Figure 12 - Distributed HDPE Recycling Scheme adapted from (Kreiger et al., 2014)

I. Shredder

In plastic recycling it is necessary to shred products into smaller parts in order to produce feedstock to an extruder. There are two main reasons to material shredding: Volume reduction and Preparation for a certain process. So, to choose the right shredder it is important to know the purpose of the output. Open-source plastic recycling methods recommend that the material should be shredded into very small granulates in a range of 0.2 − 2 mm (Hill, 1986a).

Shredders can be subdivided into 3 main types. The type 1 are mostly used on the processes of shredding insulated cables compounded by rubber. The type 2 are the mainly used shredders, where urban waste, tyres and furniture are the primary materials used by these shredders. The type 3 have a mixture of properties from the previously mentioned shredders, but hey have small variations when considering the final purpose. These shredders are used to work with volume and elastic materials, hard to destroy (Hill, 1986b).

Regarding the utilization of waste plastic in recycling processes, it is fundamental to shred the waste material into small parts. This enhances portability, facilitates transportation and prepares the material for further processing. A waste plastic shredder is a machine that reduces plastic material into the desired volume. Globally, the first step in recycling processes encompasses this waste plastic reduction into pellets, powder or flakes. However, such machinery is, usually, very expensive and bulky, compromising recycling activities in developing countries with poor resources (Ayo, Olukunle, & Adelabu, 2017; Lettieri & Baeyens, 2009).

Therefore, to promote recycling activities in developing countries, (Ayo et al., 2017) published an interesting article concerning the development of a low cost waste plastic shredding machine. This machine was developed to be available locally, using available local materials and to be operated without the necessity of much skill.

This shedder was capable of producing an average output flow of 27.3 kg/hr, with a recovery efficiency of 95%. The average percentage shredded was 53.2% and 95% specifically for material made of PVC. The obtained particle size was around 13.3 mm^2. The obtained results were very enthusiastic, not also proving a good performance of this waste plastic shredder to small or medium scale recycling activities, but also the feasibility to be useful to work with large size plastic parts (Ayo et al., 2017).

II. Extruder

Plastic extrusion is a common process with great utility in the polymerization industry. This process is directly related to the production of recycled plastic filament. It is widely used with polymers and composites of casing, packaging and automotive industries. Currently, there are two types of extrusion processes using a single or a twin screw. Considering final shapes, flow rate of material and properties of the processed polymer, there are a range of possible extruders with different sizes, to serve the desired purpose (Ravi, Sudha, & Balakrishnan, 2011; Singh et al., 2017).

Basically, an extruder is compounded by a barrel segmented into three temperature zones. These three zones are called the barrel, adapter and die zone. Typically, a couple of heaters are assembled in the temperature zone, but in some small experimental extruders it can be used only one heater. In the extrusion process pre-shredded polymer enters in the barrel through a hopper. Thereafter, it is heated to the polymer melting temperature while passing through the temperature zones. In this process the material is push to the die zone by a screw, where it will be moulded to desired final solid shape. Usually, the final material form is in a cylindrical shape (Ravi et al., 2011; Singh et al., 2017).

One of the most important aspects considering extrusion systems is the quality of the extruded polymer. Fundamentally, the quality is associated with a controlled and uniform distribution of the temperature in the temperature zones. Additionally, the physical property of the polymer, time of cooling and the speed of rolling through the barrel are also important factors considering filament quality. This are the major factors considering the shape accuracy and properties of the extruded polymer. Moreover, some researchers argue that a high efficiency on this extrusion process can be obtain with a precisely controlled temperature in the all the zones (Ravi et al., 2011; Singh et al., 2017).

Considering the final shape of the extruded material, beside the polymer intrinsic properties, factors such as the pressure, flow rate of material and the die shape also take an important role. The polymer rheological property (viscosity) can be obtain by determining the MFI. The compression ratio of the screw is the ration between the channel depth in the material input (feed section) and the channel depth in the metering section. In order to obtain suitable pumping actions, the volume of material feed must be around 2 or 3 times the front volume (Singh et al., 2017). In **Figure 13** it represented a possible single screw extruder scheme.

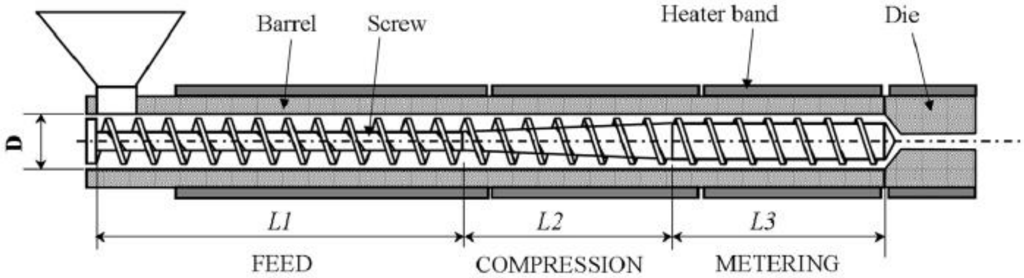


Figure 13 - Single Screw Extruder (Singh et al., 2017)

III. PLA, ABS and PET Recycled Filaments

Both, a decrease in costs and a growth in sustainability, have been observed when offering, with additive manufacturing, quality products made of waste plastic materials. In recent past, the most commercialized recycled filaments were made from recycled ABS and PLA. However, recently, researchers have been evaluating both, performances of processes to produce RPET filament and the final RPET filament, to be used in 3D printing technologies.

Considering the production of recycled PLA filament, Cruz Sanchez, Boudaoud, Hoppe, & Camargo (2017a) drawn some interesting conclusions on a process to produce filament with a diameter of 1.75 - 3 mm. This PLA filament was obtained with a melt spinning process, an important technique for continuously melt processing of PLA. It was used a scale laboratorial extruder, with 3 progressive controllers of extruding temperature of 160, 170, 180ºC. The screw speed was defined to 60rpm. At the end, it was assembled a conveyor system to control the take-up speed of the filament after the extrusion process. With this process Cruz Sanchez, Boudaoud, Hoppe, & Camargo (2017b) obtained filaments with an average diameter of 1.5 – 1.8 mm. The results gathered from studying the recycled PLA filaments proved that the mechanical properties of printed samples from one recycling cycle were similar in tensile strength and elastic modulus to parts printed on commercial systems. However, the 3D printing process decreases the mechanical properties. Despite that, the introduction of recycled PLA on open-source additive manufacturing proved to be real and feasible alternative to PLA used from commercial systems.

Regarding the development of recycled ABS filament, Costa, Timóteo, Campilho, & Valverde (2009) presented research on mechanical properties on a volume-based mixture with 10% iron powder and 90% ABS. This study was made in order to produce filament suitable to FDM printing machines. Regarding the mixture, it was chosen iron powder as it presents acceptable mechanical and thermal properties and potential to mix and surface bonding with polymers. Diameters of 1.75-1.80 mm are desired to fit an optimal efficiency of an FDM300 machine. To achieve such dimensions, it was important to precisely control variables such as screw speed, pressure and temperature. The results on the processability of such recycled composite in FDM300 machines, based on parameters such as temperature, pressure drop and velocity, revealed feasibility to the desired goal. The recycled filament was effectively processed in FDM 300 machine to produce sample products.

Taking into account the production of recycled PET filament, Zander, Gillan, & Lambeth (2018) made an extensive report on the feasibility of the considered filament on Fused Filament fabrication printing. The extrusion process was made with a precisely controlled temperature, with an extruder equipped of 8 temperature zones. The average temperature was 238 ºC and the screw speed was set to 100 rpm. The produced filament was cooled with a nitrogen conveyor and the final filament diameter was between 2.5 mm and 3.0 mm. This RPET filament was chopped into pellets and reintroduced in the mentioned process, to achieve a precisely uniform filament. With the obtained filament some parts were printed and submitted to mechanical tests. The results on this research proved that due to presence of contaminants and processing cycles, RPET can lead to a lower performance when compared with virgin PET. Despite this, RPET proved to be adequate for Fused filament fabrication printing, as the tensile strength was similar to printed parts from other commercial resins. Indeed, a RPET radio bracket part was printed and presented a similar performance to a part printed with commercial filament, regarding RPET filament as a real alternative for additive manufacturing, adding value to sources of recycled PET.

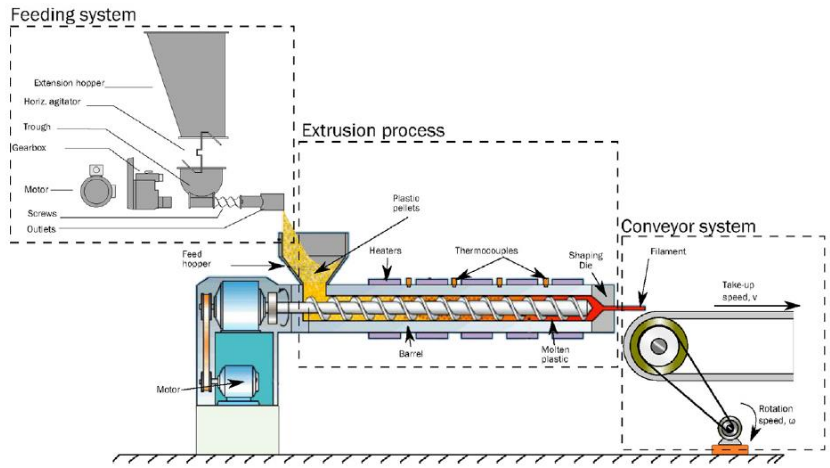


Figure 14 - Diagram of a possible plastic extrusion recycling scheme for prodcution of 3DP feedstock (Singh et al., 2017)

Figure 14 illustrates a possible plastic recycling scheme to produce filament to feed 3D printers. As referred on this review, is necessary a shredder and an extruder to produce the feedstock. Although it is a simple process, it is necessary to control several variables, such as temperature, screw speed, shredded flake sizes to produce filament with good quality. The recycled filament can be used to produce an extensive range of 3DP products, which support circular practices and innovative technologies.

3.3 Frugal Products

Frugal innovation has become an important theme in current society. The definition of frugal innovation differs on the researcher's approach but there is some consensus when stating it as a challenge to introduce something new or different (innovating) and at the same time being economical with resources (frugal). This concept has been majorly applied and analysed in emerging or developing countries and attempts to offer quality solutions (Pisoni, Michelini, & Martignoni, 2018). Therefore, to understand the difference on the different frugal innovation definitions and to create a solid idea on this topic, a briefly overview on this concept will be presented in the next paragraphs.

3.3.1 Frugal Innovation

Frugal Innovation can be approached in various perspectives. It seems relevant to present the evolution of the main definitions about Frugal Innovation to understand the path taken and future perspectives. Some authors consider that frugal innovation is present in the product scope (Kingsnorth, Tongaonkar, & Awojobi, 2011), while others mention it in the process or business model extents (Moore, 2011). However, to successfully implement this innovation concept it is crucial to redesign and adapt the processes to the environment where it will be put in practice (Kalogerakis, Tiwari, & Kalogerakis, 2014).

Table 4 - Frugal Innovation definitions done by each generation of authors/researchers

First Generation	Second Generation	Third Generation
Product-Oriented Definitions • Intregation of many parts in a unified composite partFrugal innovation seeks to minimize the use of material and financial resources in the complete value chain (development, manufacturing, distribution, consumption, and disposal) with the objective of reducing the cost of ownership while fulfilling or even exceeding certain predefined criteria of acceptable quality standards (Tiwari and Herstatt, 2012); • Frugal innovation is characterised by: low price, compact design, use of limited raw materials or reuse of existing components, ease of use and use of cutting-edge technology to achieve lower costs (Rao, 2013). .	**Market-Oriented Definitions** • Frugal innovations are originally developed products or services for very specific applications in resource-constrained environments. It is often quite disruptive (Zeschky et al., 2014); • A derived management approach, based on jugaad, which focuses on the development, production, and product management of resource-saving products and services for people at the BoP by achieving a sufficient level of taxonomy and avoiding needless costs (Brem and Wolfram, 2014). **Process-Oriented Definitions** • Frugal innovation as the means and ends to do more with less for more people (Radjou and Prabhu, 2015); • The design innovation process that properly considers the needs and context of citizens in the developing world (Basu et al., 2013).	**Criteria-Oriented Definitions** •Innovations are frugal if they simultaneously meet the criteria substantial cost reduction, concentration on core functionalities, and optimised performance level (Weyrauch and Herstatt, 2016); • Advanced Frugal Innovation (AFI) by leveraging advances in science and technology to capture the frugality inherent in a grassroots frugal innovation (Rao,2017a)

Basically, there have been characterized three main generations each one with a different scope. **Table 4** presents some important definitions done by each generation of authors/researchers.

The first generation can be described as a *product-oriented*, as product-based features of frugal innovation and characteristics of frugal products and services are the main focus of definitions on frugal innovation. According to these definitions, the main goal of frugal innovation is to reduce as maximum as possible the use of material and financial resources, given products inherent characteristics such as low price, compact design, limited use of raw materials or reuse of existing components, ease of use, and cutting-edge technology, with the goal of achieving lower costs (Rao, 2013; Tiwari & Herstatt, 2012).

The second generation of definitions introduces some variables that highlight differences and similarities between the various forms of resource-constrained innovations. In this generation there are two main criteria: a *market-oriented* and a *process-oriented* definition. In *market-oriented* criteria some authors defined frugal innovation as an approach focused on all the important areas of product selling such as development, production and product management, with the goal of developing resource-saving products and services for people at the BoP (bottom of pyramid) always eliminating unnecessary costs (Brem & Wolfram, 2014). In a *process-oriented* criteria authors propose a definition stating frugal innovation as the "means and ends to do more with less for more people" (Prabhu & Jain, 2015) or to focus on the design innovation process, having always in consideration the needs and context of societies in developing countries (Basu, Banerjee, & Sweeny, 2013).

Finally, the third generation represents a breaking point. In fact, the researchers went to back to the origin of the frugal innovation concept and defined three topics characterizing frugal innovation both in emerging and developed markets such as: substantial cost reduction, concentration on core functionalities and optimized performance level. Furthermore, another research done by (Agarwal, Grottke, Mishra, & Brem, 2017) defined other three fundamental criteria on constraint-based innovation such as: cost-effectiveness, ease-of-use and prescriptive variables.

3.3.2 Frugal Products Characteristics

Frugal innovation leads to frugal products and after analysing the various definitions of frugality concept it is relevant to define a model of a frugal product. So, frugal products can be defined as products and/or services that offer to customers great advantages being affordable, sustainable and easy-to-use (Hossain, Simula, & Halme, 2016). Indeed, frugal products have been developed taking in consideration markets and regions that work under the resource scarcity. So, it is important to comprise innovative combinations of available knowledge and technologies, to solve urgent local problems creating products with great value. Moreover, reducing the use of costly resources such as energy, capital, and time is always a basis on the development of frugal products (Hossain et al., 2016). Roland Berger defined the importance of the attributes of frugal products to customers and the average degree of fulfilment that current products provide to them, as provided in **Figure 15**.

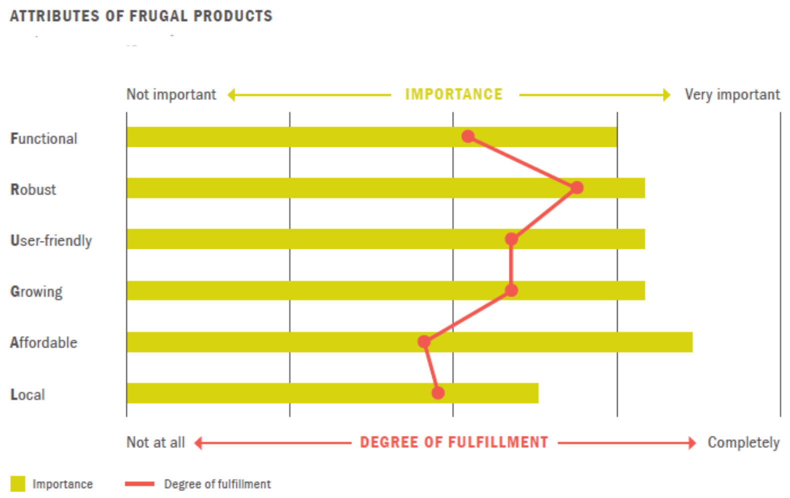


Figure 15 - Importance of the attributes of frugal products to customers and the average degree of fulfilment that current products provide to them (Roland Berger, 2015)

First, it is important to comprehend the origin of the word frugal that started as an acronym standing for “Functional, Robust, User-Friendly, Growing, Affordable and Local”. Basically, products that met these characteristics can be defined as simple products to meet basic needs (Roland Berger, 2015). Affordability seems to be the most critical characteristic and with the highest necessity to be improved. Therefore, when planning the development of a frugal product, it should be done a meticulously analysis on what will the customer be able to afford. With this information it is in charge that far-reaching management decisions, very well planned and accurately implemented, are an important factor to drive companies into a success path to introduce their frugal products. Thus, even more now than in past, it is crucial to create a strategy to ensure that frugal innovation is tackled and progressively realized from the ground up (Roland Berger, 2015).

Frugal Products can be directed to both developing and developed markets. As stated before, these innovations explore the primary and essential needs of a particular market/region. However, an objective is to expand their benefits worldwide, applying small adaptations consonant differences on fundamental needs of the target society/market. Since affordability is one of the principal factors affecting purchasing decisions related to these new solutions (frugal products), it is essential to cost-effectively exploit the available resources. Especially when the target to introduce them is low-income markets, where the majority of people live on an extremely limited income condition (Roland Berger, 2015; Tiwari & Herstatt, 2012).

The challenge to introduce a frugal products is to comprehend how can the disruptive products growth and if they have the potential to lead markets (Tiwari & Herstatt, 2012). Consequently, the introduction of Frugal Products using 3DP and plastic recycling, requires a sophisticated strategy. It is extremely important to develop a detailed study not only on the directed society needs and resources available, but also on all the necessary attributes that influence a product performance to a certain country or region.

3.3.3 Product Usability Test

In the development of Frugal Products, it is important to ensure that these products satisfy the desired attributes (Roland Berger, 2015). This measurement is a subjective appreciation that can be useful to construct a more concrete statement on the quality degree achieved in each product. To complete this purpose, it can be interesting to perform a usability test to collect information on customer product experience and create a feedback on the product satisfaction requirements. The essential objectives of the usability test are to assess to the product ease of use, ease of learning and the user satisfaction with the product experience. It is possible to evaluate these aspects in a wide range of dimensions, as long as the test is conducted to evaluate the user's experience, by recording their interaction and their feelings towards the product (Softwaretestinghelp, 2019).

With an analysis on a usability test it is possible to conduct the collected data to a validation process, this is, if the product fulfils the desired functions conceptualized by the producers. This is essential to create criterions to evaluate if the client will be satisfied with the features provided by the product. It is also important to understand if these features would spark a will to use the product again. These tests are usually performed in products early stage, since the feedback from the users will be used to modify the design of the product. However, it is important to continue running usability tests throughout all the product production process to create a product with the maximum possible satisfying quality (Softwaretestinghelp, 2019).

A common strategy to perform a usability test is to assess in real-time users and direct these users to perform a set of defined tasks. With such experience it is possible to collect data and define if the tasks were successfully performed or not, if the task could be easily performed and if the interaction was positive, triggering a satisfaction felling while using the product (Softwaretestinghelp, 2019).

To compose a usability test there are four main steps that should be completed. Firstly, it is necessary to identify and select the users that will be subjected to the usability test. It can be important to select users with similarities to the real-time customers in order to produce feedbacks that give more reliability to the results. Thereafter, it should be defined the tasks that the users will need to perform while using the product. These tasks need to be concise and well explained to direct the users to use the product for the purposes that the producer's intent to design the product. The list of actions that users will be subjected should be presented prior to starting the test. Afterwards, it is possible to initiate the "real" usability test. The users will perform the presented tasks and the product designer will collect and record useful information regarding the interactions of the users while using the product. Finally, it comes to analyse the results to form a structured report on the product performance to identify the potential areas to improve and the areas that prove to be working correctly. As mentioned before, Frugal Products intent to satisfy six important attributes, such as Functionality, Locally, Affordability, Robust, User-Friendly and Growing. This usability test can be performed, according these attributes, using the presented method to evaluate the quality content of a desired Frugal Product (Softwaretestinghelp, 2019).

3.4 Conclusions

Governments and Organizations have focussed their attentions to the verified resources consumption and expectations of serious problems regarding ecological and resources sustainability. Therefore, the introduction of circular economy to change actual practices has been an actual critical matter of study. This concept provides methodologies that contribute to an increase on resources circularity and a reduction on their consumption. It also forces companies to seize value on end-of-use products and seeks to eliminate as possible their environmental footprint. Thus, circular economy intents to increase companies' resources efficiency, contributing to a sustainable and profitable business model. With the introduction of this new concept, new technologies also appear to create synergies and maximizing as possible business advantages. 3D Printing is seen as technology which offers numerous advantages in various industrial sectors, more concrete in the production of plastic parts/products. Indeed, working with 3D printing allows producers to reduce material consumption and waste. Given that is possible to efficiently produce 3D Printing feedstock with recycled plastic resins, it seems attractive to explore the production of plastic recycled products with this innovative technology. And the question is what type of products? Frugal innovations rely on the development of something new or different, offering quality while preserving resources and being affordable. Considering this concept, it appears an opportunity to explore this connection. Here is the aim of this dissertation, to explore the characteristics of recycled 3D printed parts, in order to provide knowledge to produce frugal products using circular economy principles always as working pillars. It is also a matter of study in this dissertation, to explore the characteristics of recycled filament, comparing them with the available data on the engineering DataBase software CES-EDUPACK. All the research done and future work will always have the objective of providing sustainable products with quality content.

4. Research Methodology

4.1 Research Description

Based on the research of the provided literature concerning Plastic Market, Circular Economy, 3D Printing and Frugal Products, this dissertation pursues to provide a demonstration of the connection between these topics and deliver a structured and detailed assessment for possible frugal applications using 3D printing technology fed by recycled filament. Therefore, this work relies on the following research questions:

(1) *What are the mechanical characteristics and features offered by recycled plastic resins (PET, ABS and PLA)?*
(2) *How can recycled plastic filament be applied to produce frugal products?*
(3) *Which frugal products can be produced using 3D Printing and recycled filament as feedstock?*

As it could be verified from the literature review, any research has been done to pursue the development of frugal products, using recycled plastic waste and 3D Printing technology. Therefore, the following Master's Dissertation, has two main objectives: i) develop an analysis on the characteristics of recycled ABS, PLA and PET 3D filament using 3D Printing; ii) suggest possible frugal products produced with the studied concepts. The target is to provide possible 3D printed frugal products exploring the best characteristics of each plastic resin. It is important to remind that this research intends to highlight the value of adopting circular economy principles using 3D printing, while enhancing a solid method to improve plastic recycling and, consequently, sustainability of frugal innovation products.

4.2 Research Methodology

The Master's Dissertation methodology is represented in the scheme of **Figure 16**.

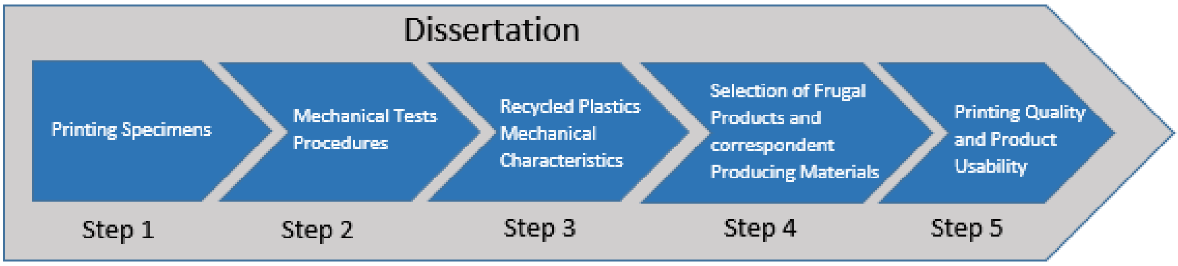


Figure 16 - Master's Dissertation Methodology scheme

An overview of the employed methodology is presented below.

<u>Step 1- Printing the specimens</u>

To develop plastic products with good quality it is important to study the properties of the desired type of plastic to be used for product production. Three different specimens, composed by recycled PET, ABS and PLA, will be printed to, further, be subjected to laboratorial tests, providing data on their mechanical properties. These plastics were chosen based on their different proprieties, presented in section 2.3, and their application on 3D Printing. ABS is known for being a more rigid and brittle material, when comparing with PET, which is more flexible and ductile. PLA is a biodegradable polymer which offers a range of application similar to the ones verified for PET materials. ABS and PLA have been widely used in the production of products with 3D Printing and it has been verified an interest to study the viability of introducing PET in this industry (Zander et al., 2018a). It is important to explore applications for recycled PET materials, given the considerable impact that the high volume application of this plastic is triggering on ecosystem's pollution. This first step encompasses the definition of all data required to print the specimens. These specimens will be further used to analyse mechanical properties of the desired plastics to produce frugal products. Thus, firstly it will be presented the three different filaments characteristics. These filaments were acquired from Refil, a company specialized in the production of feedstock to 3D printing, which offers numerous recycled filaments. Their methods to obtain the recycled feedstock are based on the shredding and extrusion methods presented in section 3.2.3. Thereafter, the equipment and the printing parameters used to print the specimens are going to be presented. The definitions of the printing parameters was discussed with 3D Ways, regarding their "know how" on the subject and based on other printing parameters used in previous researches done by Cruz Sanchez, Boudaoud, Hoppe, & Camargo (2017a) and Miguel & Oliveira (2018). 3D Ways is company that offers 3D Printing solutions, which has accepted to collaborate with this project and has been studying the best parameters to produce quality products. The specimens were produced at four different printing temperatures, to, further, with the obtained properties state the "printing temperature sweet spot" to produce the frugal products.

Step 2- Mechanical tests procedures

In order to evaluate the quality assessment of recycled plastics Vilaplana and Karlsson (2008) developed a conceptual framework regarding three main axes. This framework aims to provide a holistic vision on the material degradation: degree of degradation, regarding the variation in mechanical properties and structural changes (ex: crystallinity); degree of mixing, regarding the presence of polymeric impurities; low molecular weight compounds, regarding the presence of additives, contaminants and degradation products in the polymer structure. In the end it comes up to the researcher to decide the property/ies to study in his assessment (Vilaplana & Karlsson, 2008). Considering that this dissertation aims to determine how recycled plastic filament can be applied to produce frugal products, it was decided to evaluate the variation of the mechanical properties. It was considered to study this mechanical variation, since it is important to determine the material characteristics to produce a simple and functional frugal product with quality. Therefore, to conclude this step, the mechanical tests applied to assess the different specimens are presented. The mechanical tests performed were chosen based on similar researches on plastics mechanical properties and their overall setup is presented in section 4.2.1 (Cruz Sanchez et al., 2017a; Zander, Gillan, & Lambeth, 2018b). It was decided to perform a tensile, compression and torsion tests. The tensile and compression tests are well known when it comes to analyse mechanical properties and are often used by researchers. The tensile test is a fundamental mechanical test and it can provide knowledge whether if the material is brittle or ductile. It also provides information to measure the material's stiffness (Instron, 2019). The compression test is important to define the material brittle or ductility when subjected to compressive forces (Instron, 2019). The torsion test provides knowledge to qualify the product resistance, until the rupture, to torsional forces (Instron, 2019). The specimen's dimensions and geometry were chosen based on the ASTM International, which are international standards and guidelines to perform mechanical tests.

For each mechanical test, the involved procedure to perform the analysis is going to be described below in detail. In this procedure it will be stated all the important information, regarding objective of the test, the equipment used, the actions taken and the theoretical information required to extract the necessary properties from the data collect on the mechanical tests. There is an extended variety of types of plastics, each of them with their particular properties and with different preferable utilities.

Step 3- Recycled plastics mechanical characteristics

Thereafter in the third step, with the obtained data stated the characteristics of each type of plastic. In this characteristics statement it will be used the engineering software CES-EDUPACK, to perform an analysis on the property's variance, triggered by the recycling and 3D Printing process, and to provide an evaluation in terms of what these properties represent, this is, if they make the material flexible, stiff, resistance or weak (Grantadesign, 2019). It was chosen CES as basis to analyse the results, considering that this is an excellent software, which offers a complete wide range of quality information regarding almost every type of existent material. Finally, with the analysis performed to the tested recycled filaments, it will be presented a comparison between these plastics. This comparison considers the studied mechanical properties, in order to provide additional tools to decide which type of plastic to produce the frugal products that will further chosen.´

Step 4- Selection of Frugal Products and corresponding producing materials

The fourth step will incorporate the conclusions taken from the mechanical analysis to select the materials to produce the frugal products. It will be, firstly, presented the frugal produced decided to be produced with 3D Printing. The decision of the products was supported by information relative to applications fields of 3D Printing, which will be presented in the respective section, and also regarding the obtained properties of the tested materials to produce the products. It is important to remind that in order to clarify the frugality of the produced products, it was structured information, regarding frugality, to compose a table with seven fundamental frugal products characteristics taking under consideration the information presented in section 3.3 and an article by Kuo (2017). After the presentation of the frugal products, it will be presented the chosen materials to produce each item. As aforementioned, the decision of materials to be used will be sustained by the mechanical analysis done, in order to produce frugal products with the best quality possible.

Step 5- Printing Quality and Product Usability

To conclude, the product production, in the fifth step, it will be analysed the quality of the printed products and the usability of each products. The analysis on the quality of the products will be provided by printing the well-known benchy for each type of filament (3dbenchy, 2019).

Basically, it is a small boat which forces the printer to draw specific shapes in variable directions, with holes in a vertical axis and always without support material. The amount of verified deformations of the produced benchy define the dimensional accuracy of the printing filament.

4.2.1 Research Setup

The experimental setup aims to present an overview of the scheme relative to the mechanical tests, which intent to serve two main purposes: 1) to determine mechanical properties of the recycled plastics filament, ABS, PLA and PET; 2) to compare the obtained mechanical properties with the properties of the correspondent virgin materials presented on the software CES-EDUPACK. A scheme the experimental setup is presented on **figure 17**.

The setup can be divided into four main actions:

i) **Print the specimens:** composed by the recycled plastic filaments characteristics, the printers and parameters used to print the experimental specimens and the specimen's specifications.

ii) **Tensile Laboratorial Test:** composed by the equipment used to collect the experimental data.

iii) **Torsion Laboratorial Test:** composed by the equipment used to collect the experimental data.

iv) **Compression Laboratorial Test:** composed by the equipment used to collect the experimental data.

The scheme presented in **figure 17** reflects the steps done to perform the mechanical analysis. Firstly, the three different specimens were printed in the company 3D Ways, using the provided printers. The printing parameters, as previously mentioned, were discussed with 3D Ways, taking under consideration their knowledge on the field and literature on the matter. Thereafter, the printed specimens were submitted to the mechanical tests in their correspondent testing machines. The computer was used to collect the experimental data for further analysis.

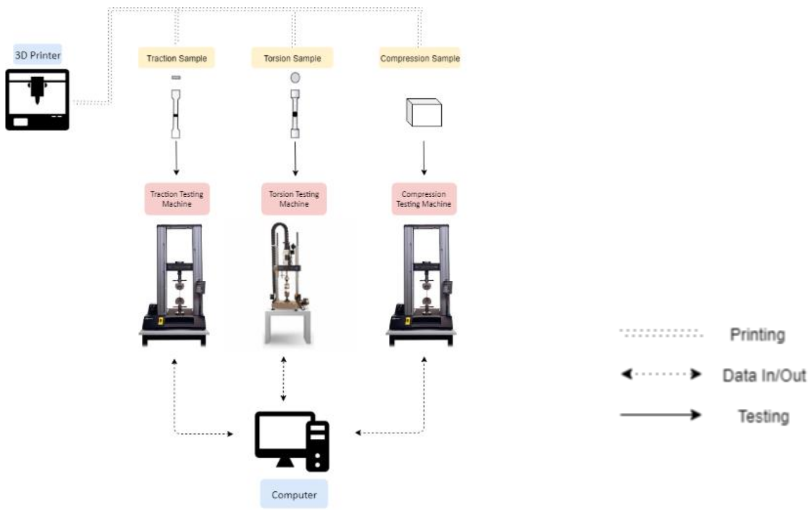


Figure 17 – Research Setup

4.2.2 Step 1- Printing the Specimens

To print the specimens, as mentioned in section 3.2.3, it is necessary to feed the printers with plastic filament. The filaments used were made from three different recycled plastics: ABS; PLA; PET. The recycled plastic filaments chosen were produced from the company Refil. The products choice was based on company principles, production process and quality. The process to produce the recycled filament by Refil follows the operations of shredding and extruding previously mentioned. As aforementioned it was chosen ABS, PLA and PET recycled filaments and their specifications are presented in **Table 5**.

ABS

This filament is 100% recycled and produced from car dashboards, door panels and other plastic car parts. Refil developed and optimized this filament throughout three years and claims that this recycled ABS filament has a performance identical to other filaments from premium brands (Refil, 2019).

PET

The PET filament is up to 90% recycled from used PET bottles. As all the filaments produced from Refil it has been optimized to reach a premium quality. Refil consider this PET filament a strong, flexible and clean plastic, having no constraints with food contact acceptability (Refil, 2019).

PLA

This filament is 100% recycled from used food packaging. It also offers a premium quality and it is suitable on an extensive range of FDM printers (Refil, 2019).

Table 5 – Filaments Specifications (Refil, 2019)

Characteristics	ABS	PET	PLA
Waste Source	Car Dashboard	Drinking Bottles	Food Packaging
Netto Weight	750 gr.	750 gr.	750 gr.
Package Size	215x205x65 mm	215x205x65 mm	215x205x65 mm
Package Weight	1 kg	1 kg	1 kg
Diameter	1,75 mm	1,75 mm	1,75 mm
Printing Temperature	230-260ºC	200-230ºC	190-215ºC

Printing the specimens also includes the definition of the printing parameters, which affect the quality of the products. In fact, as aforementioned in section 3.2.2, printing parameters is a current matter of study for many researchers and companies. Since the company 3D Ways accepted to cooperate in this project, providing their printers and their knowledge, the referred printing parameters were discussed taking in consideration the 3D ways workers suggestions. 3D Ways has been studying the best parameters to produce quality products and their parameters setup is also based in their customers feedback. In this discussion it was taken under consideration printing parameters used for the fabrication of identical specimens, in previous researches on the field (Cruz Sanchez et al., 2017b; Fernandes, 2016; Miguel & Oliveira, 2018). It is important to refer that the printing parameters are a complex matter of research in the 3D printing world. To choose the best parameters it is necessary to study the interactions between them. However, as this master dissertation main objective is to understand how can recycled filament be used to produce frugal products, it was chosen the most adequate influencing factor to modify in the production process, the printing temperature. It was chosen to print at four different printing temperatures to, with the mechanical analysis and dimensional analysis, define the best printing temperature ("sweet spot") for each studied filament.

Table 6 - Printing Parameters

	PET	PLA	ABS	
Parameters	Values	Values	Values	Units
Layer Thickness	0.2	0.2	0.2	mm
Bed Temperature	50	80	100	ºC
Nº Perimeters	4	4	4	
Top Solid Layers	6	6	6	
Bottom Solid Layers	4	4	4	
Fill Density	100	100	100	%
Travel Speed	100	100	100	mm/s
Nozzle Diameter	0.4	0.4	0.4	mm
Nozzle Speed	60	60	60	mm/s
G-code	Simplify 3D	Simplify 3D	Simplify 3D	

These printing temperatures were discussed with 3D Ways, regarding their custom printing temperatures and the advised printing temperatures from Refil. For the ABS it was chosen to print the specimens at 230ºC, 240ºC, 250ºC and 260ºC. For the PET it was chosen to print the specimens at 220ºC, 230ºC, 235ºC and 240ºC. For the PLA it was chosen to print the specimens at 200ºC, 205ºC, 210ºC and 215ºC. The values presented in table 6 are the printing setups performed to produce the ABS, PLA and PET specimens. The printing orientation was chosen based on the literature done on work done by Miguel & Oliveira (2018) and Fernandes (2016), and, as all the other printing parameters, it was discussed with 3D Ways. There are three considerations that are relevant to highlight in these printing parameters. Firstly, the travel speed, which corresponds to the printing speed of the filling structures, should be slightly faster and it was defined a value of 100 mm/s. Secondly, the nozzle speed should not have high values to provide a good adherence of the material to the printing bed. Finally, it is not necessarily obligatory to provide a heated bed to print with PLA filament, however using a heated bed can provide benefits concerning a more controlled cooling down (Fernandes, 2016). As aforementioned, all the decisions relative to the 3D printing technology were made in discussion with the suggestions of 3D Ways. These printing parameters are different to the observed parameters in the aforementioned researches, however they were taken in consideration and there are present some similarities. Regarding the printers used to produce the specimens, 3D ways provided this operation with two different printers. For the production of PET and PLA specimens it was used a Prusa MKS 3D printer. To produce the ABS specimens, it was used a CoreXY printer optimized by 3D Ways to a better performance with ABS filament.

The specimens that will be tested on the research of this dissertation will follow the parameters from standard test ASTM methods. ASTM are standards to follow on the experimental research to determine mechanical properties of materials. Given material restrictions, for each type of material, there were made three specimens for each printing temperature. There were printed the same number of specimens for each filament for the three mechanical tests. This gives a total of twelve specimens per filament for each mechanical test. Starting from the tensile specimens, their geometry is represented in **figure 18** and their dimension values are presented in **table 7**.

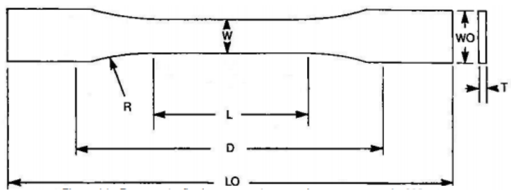


Figure 18 - Tensile Specimen Geometry

Table 7 – Tensile Specimen Dimension

	Type I	Sample
W [mm]	13 ± 0.03	13
T [mm]	3.2 to 7 ±0.4	3.2
LO [mm]	165	155
D [mm]	115 ± 5	115
L [mm]	57 ± 0.5	57
W0 [mm]	19 ± 6.4	20
R [mm]	76 ± 1	76

Regarding the guidelines of the ASTM D638-02a, the tensile specimen was made accordingly the Type I of the suggested samples. This standard recommends these dimensions for the majority of tensile tests specimens' production (ASTM International, 2003). However, there were made some small modifications to promote more precise results. Since the tensile testing machine reveals to have some inconsistencies reading lower strength values, it is recommended to produce a sample with large dimensions of the area subjected to traction, promoting higher values of the strength. It is important to mention that the central rectangular section is thinner than extremities to avoid a fracture near the grips. Consequentially, ($A0 = W \cdot T$) is the area subjected to the traction. It is also noteworthy to refer that in order to avoid a stress concentration on the transition between the grips section and the section subjected to traction, it was made a radius R for that effect (Fernandes, 2016).

Moving to the torsion specimens, their geometry is presented in **figure 19** and their dimension values are presented in **table 8.**

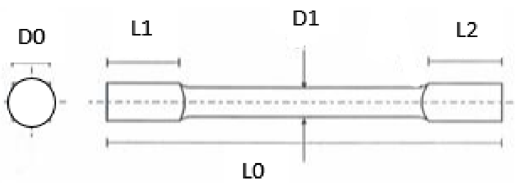


Figure 19 – Torsion Specimen Geometry

Table 8 – Torsion Specimen Dimension

	Sample
D0 [mm]	10
L0 [mm]	80
L1 [mm]	25
L2 [mm]	25
D1 [mm]	8

The torsion specimens were made accordingly the ASTM E143 – 13 standard test method. This standard recommends specimens in shape of cylinders, with a uniform diameter. Considering the same reasoning of the tensile specimens, the central cylindrical section is thinner than extremities to avoid a fracture near the grips. It is also important to guarantee that the specimens are solid in order to perform tests with credible results. In the determination of the shear modulus slight imperfections can produce errors on the values of this property. Finally, it is recommended to produce the gauge length with a dimension of four diameters. The produced gauge is a tube with an interior diameter of 5mm (ASTM, 2018).

Finally, the compression samples geometry is presented in **figure 20** and their dimension values are presented in **table 9.**

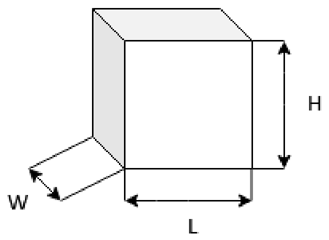


Figure 20 – Compression Specimen Geometry

Table 9 - Compression Specimen Dimension

	Sample
W [mm]	12
L [mm]	12
H [mm]	12

The compressions specimens were made accordingly the ASTM D 1621 – 00 standard test method. It is recommended to produce a cross section with a minimum of 25.8 cm^2 and a maximum of 232 cm^2. It was produced a cubic specimen with the dimensions presented on **table 9.** These specimens were produced in a cubic geometry to promote stability during the compression test. Accordingly the recommendations of the previous mentioned specimens, it is also important to guarantee solid shapes to promote as possible clean results (ASTM standard D1621, 2004).

4.2.3 Step 2 - Mechanical tests procedures

In the next sub-chapters, it will be stated all the detailed information concerning each step done to collect the desired data on the mechanical properties of the recycled filaments. Firstly, it will be presented the necessary information to print the samples, starting from the filament characteristics, followed by the printers and printing parameters and concluding with the specimen's specifications. Thereafter, it will be stated the information relative to the three different performed mechanical tests. Firstly, it will be explained the procedure relative to the tensile test. Thereafter, it will be presented the torsion test procedure, followed by the compression test procedure. To conclude this chapter, it will be explained the goals, concerning this master thesis objective, which this mechanical analysis pretends to serve.

I. Tensile Test Procedure

This tensile test aims to provide mechanical properties regarding the resistance of the material to tensile loads and the elasticity or stiffness of the material. Thus, it will be used the collected data to state three important mechanical properties: Young Modulus, regarding the elastic/stiff property; Tensile Strength, regarding the maximum supported tensile stress; Yield Strength, regarding the maximum stress supported until the material passes through elastic to plastic deformation (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012). These concepts will be explained with more detail in the next paragraphs.

Regarding the equipment used to perform this test, the testing machine used was an *INSTRON 5566.* This machine was setup with a load of 10 kN and a speed of testing of 2mm/min. It also necessary to introduce on the software the values of Thickness (T) and With (W), allowing the machine to determine and collect instant data related to the Strength (F) and displacement (Δl). The initial area (A0) can be obtained by multiplying T by W. In this traction test there are some precautions to take into consideration. To start this procedure, it is necessary to introduce some data on the software, such as the number of samples that will be tested (36) and the speed of testing. It is really important to guarantee that the axis of the specimen is aligned with the direction of the application of the load. Thereafter, it is possible to start the tensile test. However, it is extremely important to reset to zero the value of the measured strength before starting every traction of a specimen. When starting the test, the machine reads a small negative load value, which has no implications in the results. However, if in the next test the load value is not reset, the machine will accumulate this value. If this procedure continues sample after sample, the starting read load will increase to values that will interfere with the reliability of the results. Resetting this load value to zero will prevent the machine from reading mistaken values.

In this tensile test it is possible to determine the stress, σ, and nominal extension, ε, through equations **[1]** and [**2**]:

$$\sigma = \frac{F}{A0} \quad [1]$$

$$\varepsilon = \frac{\Delta l}{L} \quad [2]$$

With the properties' values, it is possible to draw the Stress-Strain curve for the tested specimen. In the Stress-Strain graph represented in **figure 21** there are highlighted two important stages and some properties that can be determined. The values of the variables A0 and L are presented in Appendix A. The linear zone represents the elastic deformation stage of the material, where, theoretical, the material has the capacity of returning to its initial geometry if the stress is removed. The second phase, when the graph is not linear, is the plastic deformation stage where the material starts to collapse. Basically, the atoms start to break their bonds and re-forming with neighbours. It this situation the material does not returns to its original form, when the stress is removed. With this information it is possible to determine two important properties: Yield Strength and Tensile Strength, relative to the mechanical resistance (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012).

The Yield Strength (σy) corresponds to the stress value where the material passes from elastic deformation to plastic deformation. This is represented in **figure 21** as point P and given that it is too difficult to precisely measure it, point P can be determined by drawing straight line parallel to the elastic stage with a 0.2% strain offset. The Yield Strength corresponds to the intersection point of this 0.2% offset line with the graph. The Tensile Strength (TS) is the maximum stress sustained by the material, before the occurrence of a fracture and is represented in **figure 22** by point M. Another important property is the Elastic Modulus or Young Modulus. It is relative to the toughness property, which is an information on the material's resistance to fracture, that is to say, the capacity to absorb energy and plastically deform before fracturing. It can be obtained by determining the slope of the linear stage, the Elastic deformation. In this analysis, the Elastic Modulus was determined by using linear regression. It was considered the maximum possible number of points to ensure that the determination coefficient (R^2) was greater than 0.99. Maximizing the value of R^2allows to determine a more coherent value of the slope of the line parallel to linear zone, and so a more precise value of the Elastic Modulus (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; Fernandes, 2016; William D. Callister & Rethwisch, 2012).

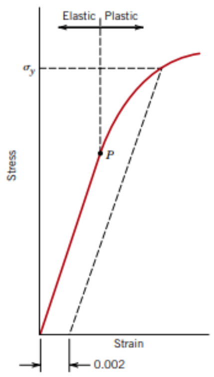


Figure 43 – Stress Strain Diagram Plastic/Elastic deformation representation (William D. Callister & Rethwisch, 2012)

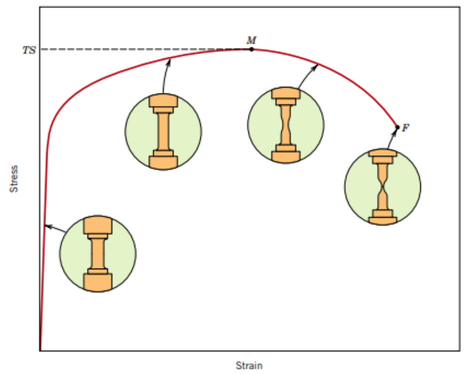


Figure 22 – Stress Strain Diagram Roture Point M representation (William D. Callister & Rethwisch, 2012)

II. Torsion Test Procedure

This torsion test is conducted to determine torsional properties of the material. A wide range of products and components are exposed to torsional forces during their application. Performing this torsional test can provide information to simulate real life conditions and with the collected data it is possible to state an important mechanical property: Shear Modulus, an interesting property to calculate the compliance of structural materials in torsion. It is important to refer that torsion is a variation of pure shear, when a structure is twisted as illustrated in **figure 23** (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012). This concept will be explained with more detail in the previous paragraphs.

Regarding the equipment used to perform this test, the testing machine used was an *INSTRON 8874.* The machine was set up with a rotation ratio of 5º/s. It is necessary to introduce on the Instron Fast Track 2 – MAX software the number of samples (36). Also, it is important to ensure that the grips are well positioned in order to produce the failure on the desired gauge of

50mm length. Thereafter, it is required to guarantee that the force applied by the grips does not fractures the specimen, to avoid inconsistent results. After this preparation, it is initiated the torsion test and the machine performs until the tested specimen fractures. The machine records the torque applied and the angle of twist, providing a Torque-Angle of Twist diagram. The machine collects the torque values in kN*m and the Angle of Twist in degrees. The standard test performed is directed to obtain the shear modulus, G, of the tested material. The shear modulus of a specimen with a gauge length, L, can be obtained using **equation [3].** The shear modulus is the material stiffness property and can be useful to define the rigidity of a material, that is to say, if it is necessary or not large amounts of force to produce deformation on the material. For example, a small value of shear modulus indicates that the material is flexible and, so, fluid substances are characterized by a zero value of shear modulus. The condition to use **equation [3]** is if the Torque, T, and Angle of Twist, θ, are chosen from the linear elastic region of the Torque-Angle of Twist curve (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012).

$$G = \frac{T * L}{J * \theta} \quad [3]$$

$$J = \frac{\pi}{2} * (c_2^4 - c_1^4) \quad [4]$$

J is the polar moment of inertia, that in case of hollow circular shaft of inner radius c_1 and outer radius c_2 can be obtain with **equation [4].** The value of the variable L is presented in Appendix A.

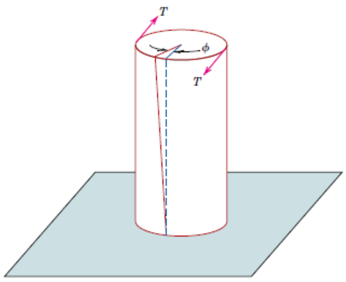


Figure 23 – Angle of Twist triggered by an applied Torque (Budynas & Nisbett, 2015)

III. Compression Test Procedure

This compression test is conducted to extract information of a material behaviour under compression forces. It is also an essential mechanical test to explore the capacity of brittle materials to maintain their integrity under compressive loads. By performing this compression test it is possible to state an important mechanical property: Maximum strength in compression, a property that indicates the point where a brittle material fracture. However, given that the materials to be tested are known to be ductile, they will continue their deformation until the load is no longer being applied (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012). This concept will be explained with more detail in the previous paragraphs.

A compression test is in fact comparable to a uniaxial tensile test. However, in the compression test the load is made in the opposite direction, to perform a compression on the specimen. Regarding the equipment used to perform this test, it was used an *INSTRON 5566.* The machine was set up with a speeding test of 1,5mm/m. The testing machine was assembled with two metal sheets on the grips zone, to promote a uniform force distribution. It is also important to ensure that the cube is well centred on the testing machine. It is necessary to introduce data on the software, such as the number of samples (36) and some specific dimensions, such as the width and length of the specimen. After this procedure, it is possible to initiate the compression test. The machine records the displacement and the load applied to the specimen. With such data it is possible to compute a Stress-Strain diagram using the equations and methods aforementioned in the traction test procedure. The values of the variables A0 and L are presented in Appendix A.

There were considered two properties of matter to extract from the diagrams: the Maximum Yield Stress,σ_y, and the Young Modulus. As explained before, the Young Modulus provides information relative to the stiffness of the material and it can be obtained by performing a linear regression on the elastic zone of the diagram. The compressive strength is evaluated by the maximum yield stress. This corresponds to the zone where the deformation changes from elastic to plastic, producing permanently deformations to the material. It can be obtained on the highest value of stress in the Stress-Strain diagram (Beer & Jonhnson, 1981; Budynas & Nisbett, 2015; William D. Callister & Rethwisch, 2012).

4.2.4 Step 3 - Recycled Plastics Mechanical Characteristics

The characterization of the mechanical properties of the recycled filaments is an important step in this master dissertation, considering that this characterization will provide essential information to understand the features provided by each type of studied material. Furthermore, the data withdrawn from the characterization will be taken under consideration to decide which material will be the most appropriate to produce each of the selected frugal products. Thus, the engineering software CES-EDUPACK will be used to provide two major conclusions on the material's mechanical properties: a comparison between the theoretical values for the studied materials; a conceptualization of what each property value traduces as a mechanical characteristic. This software has been developed over the past twenty years and it is an intuitive software which provides an extensive database of materials and process information, with a comprehensive range of supporting textbooks (Grantadesign, 2019). It is an excellent support to the researching of materials, engineering, design and sustainability. The theoretical values of the studied and tested plastics are available on CES. These values were validated by the CES work team with headquarters based in Cambridge, United Kingdom, and obtained in normal conditions following international standards (Grantadesign, 2019). To access the data it is necessary to select the material in matter and the software displays a complete list of theoretical values relative to mechanical properties. The conceptualization of the mechanical properties followed a framework, that resorts the property's scales available on the software. For each property value, these scales provide a notion of what does that value traduces in terms of mechanical characteristic, that is to say, if the observed value traduces a resistant, weak, strong, flexible or stiff material. In **figure 24** it is presented the framework done to serve this purpose. Each row corresponds to a property scale and the blue line corresponds to a density line of the values observed for all the polymers, where, in the middle of the line, the darker blue represents the most verified value. To conclude this analysis on the materials characteristics, it will be presented a comparison between the properties obtained for the three studied recycled plastics. This comparison will take under consideration the information offered by the property's values framework done before, to highlight the differences and similarities present on the studied materials.

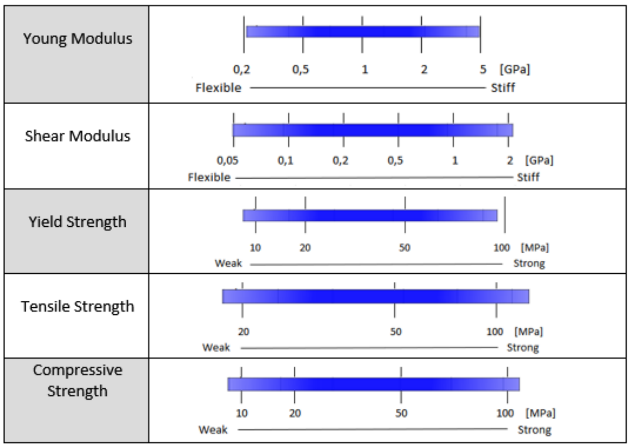


Figure 24 – Framework of the Studied Mechanical Properties (adapted from CES EDUPACK 2018)

4.2.5 Step 4 - Selection of Frugal Products and Correspondent Producing Materials

In the products choice it was taken under consideration the frugality of each product. To justify the frugality of the selected products it was created a table indicating seven fundamental frugal products characteristics. **Table 10** presents this information and it was sustained by the information presented in section 3.3 and a research done by Kuo (2017). Considering that this master dissertation intents to provide possible applications of recycled filament, taking advantage of 3D printing technology, in the respective section it is provided literature concerning possible 3D printed product applications. The products were chosen from two important open source web platforms, such as Thingiverse and MyMiniFactory. These platforms aim to expand the growth of 3D Printing by making possible to share and download 3D Printing files of a wide range of type of products. The information concerning the 3D printing files and design, regarding the selected products, is provided in the web platforms. Furthermore, it was decided with which type of recycled studied filament the selected products were going to be produced. This decision was influenced by: the final application of each product, which influences the type of loads that the

1. Focusing on the fundamental needs
2. Eliminating non-essential functions of products
3. Trimming down the processes
4. Affordability
5. Functionality
6. Ease of Use
7. Sparing use of resources

Table 10 – Seven Fundamental Frugal Characteristics (Adapted from Kuo, 2017)

product may be subjected and the necessities for resistance, flexibility or stiffness; the conclusion drawn from the analysis performed to the recycled filaments. Accordingly each recycled plastic mechanical characteristics and the products “mechanical needs”, it was allocated each recycled filament to produce each product.

4.2.6 Step 5 - Printing Quality and Product Usability

To conclude this research, the 3D Printing quality of the three studied filaments will be presented, alongside with the usability of each product. To perform the analysis on the 3D Printing quality of the three recycled filaments, as aforementioned, it was performed a commonly used test in the 3D Printing industry, the benchy analysis. The printed benchys was produced in 3D Ways with the using the same parameters of the analysed specimens. The 3D Printing temperature used for each type of filament was selected taking under consideration the analysis done to this parameter. This quality test basically consists, as previously explained, in producing a small boat, called *benchy,* which requires the printer to produce various complex geometries. Thereafter, the test passes through identifying any type of geometry imperfections and to measure the geometry dimensions in the printed *benchy* (Miguel & Oliveira, 2018). The printing quality depends on the quantity of imperfections detected which define a dimensional accuracy. To assess to the usability of the products it will be performed a usability test following the description made on section 3.3.3, to collect feedback from users. To test one of the three printed products it was necessary medical assistance, which was not possible to assess. Thus, instead of a usability test, it was assessed to an article concerning the development of this product, which tested it with proper conditions.

4.3 Conclusions

In this methodology description firstly, it is briefly explained the whole process of this research methodology. Thereafter, the steps done are presented individually with thoroughly explanations of all the considered points of interest. The first step done in this experimental research was printing the specimens. This step involved a wide range of details, starting from selecting the recycled filaments to use as feedstock and ending with the selection of the adequate ASTM standards (which define the geometry of the specimens). The second step intents to present a concise explanation of the procedures adopted to collect the desired mechanical data, concerning each different mechanical test. The three different mechanical tests results will be used to determine the best printing temperature for each recycled filament and their respective mechanical characteristics. The third step presents the methodology adopted to characterize the materials with the mechanical properties obtained in the mechanical tests. This characterization assents on two reasonings. Firstly, a comparison between the values of the properties obtained from the mechanical analysis to the recycled filament and the theoretical values presented on CES. Secondly, a conceptualization of what each property value traduces in terms of a mechanical characteristic. This material characterization will be important to, further in this dissertation, decide with which type of recycled filament will the frugal products be produced. The fourth step aims to present an explanation of the decision made to select which type of products to be produced with the recycled filaments. The allocation of the recycled filaments to each frugal product was based on the conclusions withdrawn from the mechanical analysis and considering the final applications of the products. The final fifth step intents to present the methodology adopted to test the dimensional quality of the recycled filaments and to determine the usability of the printed products. To access to the usability of each product it was performed a usability test following the information provided in section 3.3.3.

The research methodology described on this section intents to clarify all the steps done and principles adopted to achieve the desired objective of this master dissertation. Thus, the subsequent sections will precisely present the collected data from the mechanical analysis and the conclusions withdrawn to support the frugal products production.

5. Results and Discussion

5.1 Mechanical Tests Results

The following section will cover the analysis of the three different mechanical tests. Firstly, the tensile test results will be presented, followed by the torsion and compression tests results. This section is sub-divided in two main steps. Firstly, section 5.1 only aims to present the values of the mechanical properties obtained from the performed mechanical tests. Thereafter, it will be presented in section 5.2 the analysis of the mechanical tests results to state the mechanical characteristics of the studied recycled filaments. For each mechanical tests the results were presented though the following structure: i) Presentation of the experimental Curves Diagrams, regarding the four different printing temperatures; ii) Presentation of the obtained properties for the tested specimens per printing temperature; iii) Presentation of the average mechanical properties of each including all the data collected. The properties calculated based on an average of all the tested specimens, for a given material, intents to analyse the material properties when recycled and the 3D Printing process, without considering the influence of the printing temperature. In the tables the standard deviation (SD) and the variance coefficient (VC) are also presented in order to analyse the robustness of the results. The values highlighted with red correspond to the highest average value obtained for the correspondent property.

5.1.1 Tensile Tests Results

As aforementioned, with the Stress-Strain diagrams it is also possible to determine the desired properties, such as the Young Modulus, Yield Strength and Tensile Strength. In the following analysis, it will be presented, for each material, the Stress-Strain curves as well as the tables representing the mechanical properties analysed from the three trials performed, at each printing temperature. Starting by the ABS samples, in **figure 25** it is presented the Stress-Strain curve correspondent to the average of values collected, for each printing temperature.

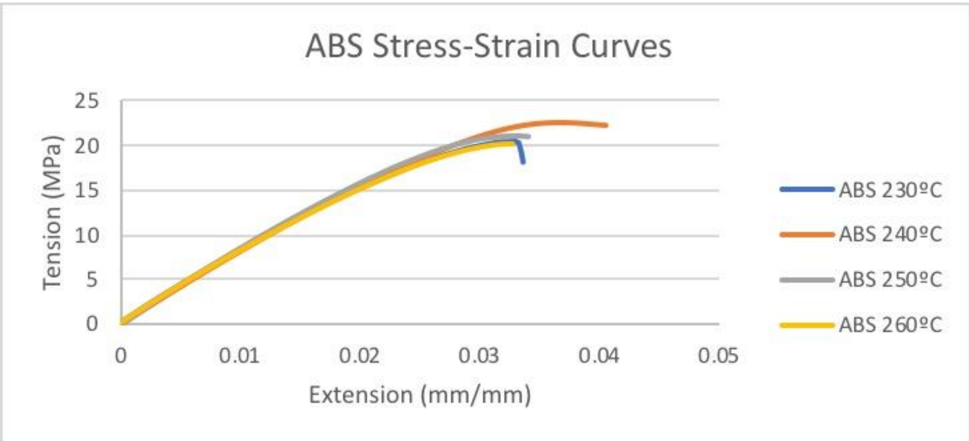


Figure 25 – Recycled ABS Stress-Strain Diagrams at each printing temperature

The ABS samples revealed to have similar Strain-Stress curves, independently of the printing temperature. This can traduce similar values for the three properties in study. It is important to refer that all the ABS specimens fractured almost immediately after their maximum Tensile Strength values. The ABS mechanical properties obtained from the tensile test are presented in **table 11, 12, 13 and 14,** at each printing temperature.

Table 11 -Mechanical Properties obtained from the tensile tests of Recycled ABS Specimens printed at 230ºC

	Specimens Number					
230ºC	ABS 1	ABS 2	ABS 3	Average	SD	VC
Young Modulus [MPa]	815,23	776,78	765,29	785,76	26,15	3,33
Yield Strength [MPa]	18,69	17,99	17,81	18,16	0,47	2,56
Tensile Strength [MPa]	22,33	20,01	20,16	20,83	1,30	6,25

Table 12- Mechanical Properties obtained from the tensile tests of Recycled ABS Specimens printed at 240ºC

	Specimens Number					
240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Young Modulus [MPa]	792,29	776,63	781,21	783,38	8,05	1,03
Yield Strength [MPa]	19,46	19,44	19,42	19,44	0,02	0,11
Tensile Strength [MPa]	22,44	22,46	22,56	22,49	0,06	0,29

Table 13 – Mechanical Properties obtained from the tensile tests of Recycled ABS Specimens printed at 250ºC

	Specimens Number					
250ºC	ABS 7	ABS 8	ABS 9	Average	SD	VC
Young Modulus [MPa]	842,64	821,56	801,27	821,82	20,69	2,52
Yield Strength [MPa]	18,92	18,55	18,84	18,77	0,20	1,05
Tensile Strength [MPa]	21,38	20,97	21,28	21,21	0,22	1,02

Table 14 -Mechanical Properties obtained from the tensile tests of Recycled ABS Specimens printed at 260ºC

	Specimens Number					
260ºC	ABS 10	ABS 11	ABS 12	Average	SD	VC
Young Modulus [MPa]	805,25	765,09	766,83	779,06	22,70	2,91
Yield Strength [MPa]	18,98	17,36	18,16	18,17	0,81	4,45
Tensile Strength [MPa]	21,45	19,23	20,27	20,32	1,11	5,46

As observed in the curves of **figure 25,** at each printing temperature, the ABS specimens Yield Strength and Tensile Strength values present similar values. For the Young Modulus it was verified a higher value for the specimens printed at 250ºC and a similar value for the other printing temperatures. In one hand the 240ºC printing temperature presented the greater values of Yield Strength and Tensile Strength. In the other hand the 250ºC printing temperature presented the greater value for the Young Modulus. It is also possible to verify that the variance coefficient presents low values for all the properties at the four different printing temperatures. Regarding the collected data from all the samples and focusing on the ABS overall properties, setting aside the printing temperature influencing factor, **table 15** presents the average values for the ABS mechanical properties.

Table 15 – Recycled ABS Mechanical properties average of all the collected data from tensile tests

	Average all Temperatures	SD	VC
Young Modulus [MPa]	792,51	25,03	3,16
Yield Strength [MPa]	18,63	0,68	3,67
Tensile Strength [MPa]	21,21	1,11	5,25

The mechanical properties of ABS can be traduced as: **Young Modulus 792,51 MPa; Yield Strength 18,63 MPa; Tensile Strength 21,21 MPa.**

Considering the PET samples, in **figure 26** it is presented the Stress-Strain curve correspondent to the average values for each printing temperature.

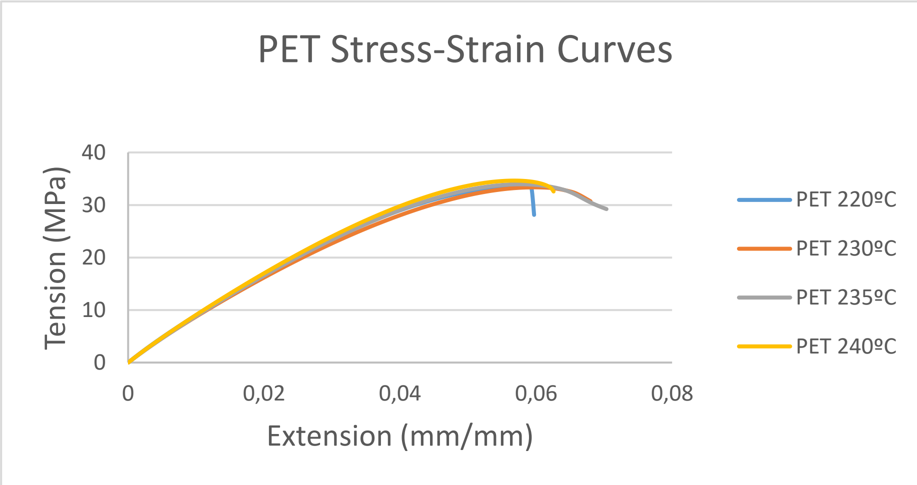


Figure 26 - Recycled PET Stress-Strain Diagrams at each printing temperature

It is notable that for all the printing temperatures, the Stress-Strain curves presented are, in fact, similar, presenting an identical behaviour in the elastic and plastic deformation zones of the diagram. However, the 220ºC printing temperature has a detail that probably influenced this temperature results. It was verified a fracture of only one specimen in one of the three tested samples printed at this temperature. Since only three specimens printed at 220ºC were tested this fracture can be an isolated case or not. It would be necessary to test more specimens to study this occurrence. The values of mechanical properties of the PET specimens are presented in **table 16, 17, 18 and 19,** at each printing temperature**.**

Table 16 - Mechanical Properties obtained from the tensile tests of Recycled PET Specimens printed at 220ºC

	Specimens Number					
220ºC	PET 1	PET 2	PET 3	Average	SD	VC
Young Modulus [MPa]	805,42	750,15	741,63	765,73	34,64	4,52
Yield Strength [MPa]	29,16	28,86	28,45	28,82	0,35	1,23
Tensile Strength [MPa]	34,04	33,64	32,68	33,46	0,70	2,09

Table 17 - Mechanical Properties obtained from the tensile tests of Recycled PET Specimens printed at 230ºC

	Specimens Number					
230ºC	PET 4	PET 5	PET 6	Average	SD	VC
Young Modulus [MPa]	729,01	745,00	713,41	729,14	15,79	2,17
Yield Strength [MPa]	28,52	29,02	29,02	28,85	0,29	0,99
Tensile Strength [MPa]	33,05	33,34	33,81	33,40	0,38	1,15

Table 18 - Mechanical Properties obtained from the tensile tests of Recycled PET Specimens printed at 235ºC

	Specimens Number					
235ºC	PET 7	PET 8	PET 9	Average	SD	VC
Young Modulus [MPa]	775,24	761,76	754,56	763,86	10,50	1,37
Yield Strength [MPa]	28,83	28,78	29,12	28,91	0,19	0,64
Tensile Strength [MPa]	33,57	34,32	34,07	33,99	0,38	1,11

Table 19 - Mechanical Properties obtained from the tensile tests of Recycled PET Specimens printed at 240ºC

	Specimens Number					
240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Young Modulus [MPa]	784,23	782,87	799,64	788,92	9,32	1,18
Yield Strength [MPa]	29,35	29,16	29,37	29,29	0,11	0,39
Tensile Strength [MPa]	34,43	34,43	35,09	34,65	0,38	1,10

Similar to the results presented for the ABS samples, the PET specimens' mechanical properties Tensile Strength and Yield Strength values seem to be solid, presenting similar low values of the variance coefficient. The Young Modulus presents, again, a slightly variation consonant the printing temperature. In one hand, the specimens printed at 220ºC and 235ºC presented identical Young Modulus values. In the other hand, the 230ºC printing temperature presents the lowest Young Modulus value and the 240ºC printing temperature the highest value for this property. In this case, the highest printing temperature, 240ºC, revealed the greater values of Young Modulus, Yield Strength and Tensile Strength. **Table 20** presents the average values for the mechanical properties of all the data collected from the tests to the PET specimens.

Table 20 - Recycled PET Mechanical properties average of all the collected data from tensile tests

	Average all Temperatures	SD	VC
Young Modulus [MPa]	761,91	28,22	3,70
Yield Strength [MPa]	28,97	0,29	1,01
Tensile Strength [MPa]	33,87	0,67	1,97

Table X can traduce the mechanical properties for PET as: **Young Modulus 761,91 MPa; Yield Strength 28,97 MPa; Tensile Strength 33,87 MPa.**

Finally, in **figure 27** it is presented the PLA samples Stress-Strain curve correspondent to the average values for each printing temperature.

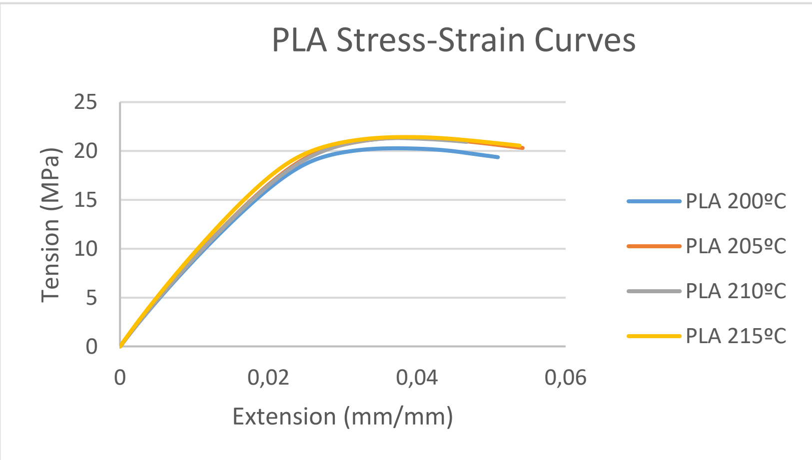


Figure 27 - Recycled PLA Stress-Strain Diagrams at each printing temperature

Once again, as the other recycled plastics, the PLA Stress-Strain curves presented a similar behaviour. In the elastic deformation zone, it can be observed an identical pattern for all the printing temperatures. However, in the plastic deformation zone, the lowest printing temperature is highlighted by a smaller value to its maximum tension. The values of mechanical properties of the PLA specimens are presented in **table 21, 22, 23 and 24** at each printing temperature**.**

Table 21 - Mechanical Properties obtained from the tensile tests of Recycled PLA Specimens printed at 200ºC

	Specimens Number					
200ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	821,73	816,81	817,44	818,66	2,67	0,33
Yield Strength [MPa]	18,93	18,20	18,64	18,59	0,37	1,98
Tensile Strength [MPa]	21,03	19,64	20,26	20,31	0,70	3,44

Table 22 - Mechanical Properties obtained from the tensile tests of Recycled PLA Specimens printed at 205ºC

	Specimens Number					
205ºC	PLA 4	PLA 5	PLA 6	Average	SD	VC
Young Modulus [MPa]	898,42	845,40	788,44	844,09	55,00	6,52
Yield Strength [MPa]	18,95	19,48	19,39	19,27	0,28	1,47
Tensile Strength [MPa]	21,89	21,42	21,42	21,58	0,27	1,24

Table 23 - Mechanical Properties obtained from the tensile tests of Recycled PLA Specimens printed at 210ºC

	Specimens Number					
210ºC	PLA 7	PLA 8	PLA 9	Average	SD	VC
Young Modulus [MPa]	801,46	884,27	836,23	840,66	41,58	4,95
Yield Strength [MPa]	19,31	19,08	19,02	19,14	0,15	0,79
Tensile Strength [MPa]	21,82	21,18	21,18	21,40	0,37	1,72

Table 24 - Mechanical Properties obtained from the tensile tests of Recycled PLA Specimens printed at 215ºC

	Specimens Number					
215ºC	PLA 10	PLA 11	PLA 12	Average	SD	VC
Young Modulus [MPa]	920,09	875,01	893,41	896,17	22,67	2,53
Yield Strength [MPa]	19,10	19,08	19,07	19,09	0,02	0,08
Tensile Strength [MPa]	21,27	21,62	21,45	21,45	0,17	0,81

In these tests made to PLA specimens it was verified, once again, a good concordance on the values for the Yield Strength and Tensile Strength. All the different printing temperatures revealed similar values to these properties with low values of the variance coefficient. However, as observed on the diagram, the specimens printed at 200ºC presented the lowest value the Yield Strength and Tensile Strength. Regarding the Young Modulus, the 205ºC and 210ºC printing temperatures traduced similar values to this property. The lowest printing temperature also presented the lowest value for the Young Modulus. It is reflected that the 215ºC printing temperature reproduces the highest values of the Young Modulus, and the 205ºC printing temperature presented the highest values for the Tensile Strength and Yield Strength. **Table 25** presents the average values for the mechanical properties and their standard deviation, regarding the data collected from all the PLA samples.

Table 25 - Recycled PLA Mechanical properties average of all the collected data from tensile tests

	Average all Temperatures	SD	VC
Young Modulus [MPa]	849,89	41,99	4,94
Yield Strength [MPa]	19,02	0,35	1,83
Tensile Strength [MPa]	21,18	0,66	3,13

Table 25 can traduce the mechanical properties for PLA as: **Young Modulus 849,89 MPa; Yield Strength 19,02 MPa; Tensile Strength 21,18 MPa.**

5.1.2 Torsion Tests Results

As mentioned in the section where the torsion test procedure is presented, evaluating a Torque-Angle of Twist diagram can be useful to extract properties concerning the resistance to shearing stresses, such as the Shear Modulus. Therefore, similar to the interpretation done on the tensile test, it will be presented the Torque-Angle of Twist diagrams and the tables representing the mentioned mechanical properties, for each material. It is important to refer that the Torque values presented on the diagrams are accordingly the units given by the testing machine. However, given that the values obtained are of small magnitude, to simplify the presentation of the results, they are represented on the tables in N*m.

Starting by the ABS specimens, in **figure 28** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.

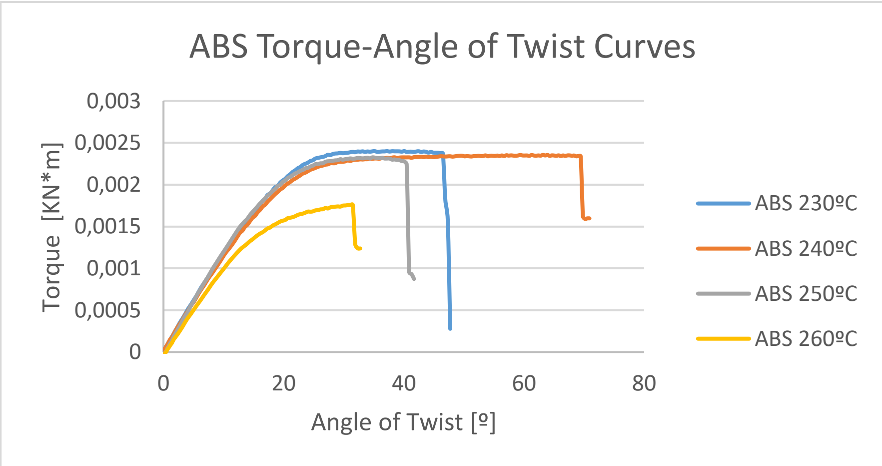


Figure 28 - Recycled ABS Torque-Angle of Twist Diagrams at each printing temperature

The behaviour in elastic deformation zone is identical for the 230ºC, 240ºC and 250ºC printing. However, it can be verified some differences on the curves presented in the plastic deformation zone. The 230ºC and 250ºC printing temperatures reproduced similar curves, with a slightly greater angle of twist, until the collapse, for the specimens printed at 230º. The maximum Torque was similar for these both printing temperatures. The 240ºC printing temperature revealed the greater angle of twist, until the fracture and a similar maximum Torque to the 230ºC and 250ºC printing temperatures. The highest printing temperature reproduced the smallest angle of twist curve. The ABS specimens' shear modulus is presented in **table 26, 27, 28 and 29,** at each printing temperature**.**

Table 26 - Mechanical Property obtained from the torsion tests of Recycled ABS Specimens printed at 230ºC

	Specimens Number					
230ºC	ABS 1	ABS 2	ABS 3	Average	SD	VC
Shear Modulus [MPa]	836,86	887,81	800,10	841,59	44,05	5,23

Table 27 - Mechanical Property obtained from the torsion tests of Recycled ABS Specimens printed at 240ºC

	Specimens Number					
240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Shear Modulus [MPa]	754,78	794,74	1058,44	869,32	165,00	18,98

Table 28 - Mechanical Property obtained from the torsion tests of Recycled ABS Specimens printed at 250ºC

	Specimens Number					
250ºC	ABS 7	ABS 8	ABS 9	Average	SD	VC
Shear Modulus [MPa]	715,32	791,16	918,62	808,37	102,74	12,71

Table 29 - Mechanical Property obtained from the torsion tests of Recycled ABS Specimens printed at 260ºC

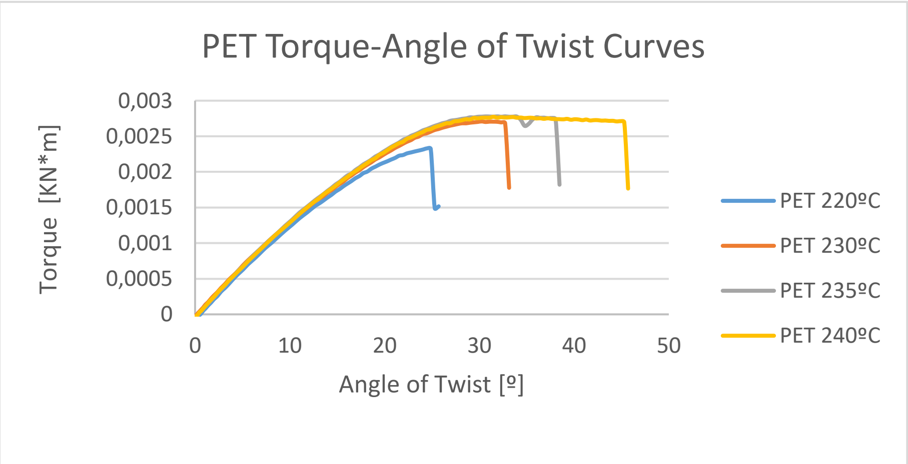
	Specimens Number					
260ºC	ABS 10	ABS 11	ABS 12	Average	SD	VC
Shear Modulus [MPa]	685,86	692,07	599,19	659,04	51,92	7,88

The values obtained for the shear modulus presented similar values for the 230ºC, 240ºC and 250ºC printing temperatures. The lowest value of the shear modulus was found with the highest printing temperature. The maximum value for the shear modulus was found on the 240ºC printing temperatures. The values obtained for the variance coefficient were slightly higher for the 240ºC and 250ºC printing temperatures. **Table 30** presents the average of the shear modulus from all the collected data, setting aside the influence of the printing temperature.

Table 30 - Recycled ABS Shear Modulus of the average of all the collected data from torsion tests

	Average All Temperatures	SD	VC
Shear Modulus [MPa]	794,58	122,07	15,36

The ABS mechanical property obtained from the torsion tests can be traduced as: **Shear Modulus 794,58 MPa.** Considering the research on the PET relative torsion properties, in **figure 29** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.



56 - Recycled PET Torque-Angle of Twist Diagrams at each printing temperature

It can be observed that the four printing temperatures have a similar pattern on the elastic zone of the diagram. Considering the plastic zone of the diagram, the curves obtained for three highest printing temperatures are, in fact, similar. The specimens produced at these printing temperatures revealed, approximately, equal values of maximum Torque applied by the machine. However, there is a slightly increase of angle of torsion until the fracture, as the printing temperature also increases. The lowest printing temperature, 220ºC, provided the lowest values of the Torque and Angle of Twist. The PET specimens' mechanical properties are presented in **table 31, 32, 33 and 34** at each printing temperature**.**

Table 31 - Mechanical Property obtained from the torsion tests of Recycled PET Specimens printed at 220ºC

	Specimens Number					
220ºC	PET 1	PET 2	PET 3	Average	SD	VC
Shear Modulus [MPa]	892,74	987,17	547,85	809,26	231,26	28,58

Table 32 - Mechanical Property obtained from the torsion tests of Recycled PET Specimens printed at 230ºC

	Specimens Number					
230ºC	PET 4	PET 5	PET 6	Average	SD	VC
Shear Modulus [MPa]	676,33	1122,50	1042,66	947,16	237,92	25,12

Table 33 - Mechanical Property obtained from the torsion tests of Recycled PET Specimens printed at 235ºC

	Specimens Number					
235ºC	PET 7	PET 8	PET 9	Average	SD	VC
Shear Modulus [MPa]	987,04	1004,15	737,52	909,57	149,25	16,41

Table 34 - Mechanical Property obtained from the torsion tests of Recycled PET Specimens printed at 240ºC

	Specimens Number					
240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Shear Modulus [MPa]	836,13	1057,92	795,50	896,52	141,25	15,75

As reflected in the Torque-Angle of Twist diagrams, the 230ºC, 235ºC and 240ºC printing temperatures promoted specimens with similar properties regarding the shear modulus. The lowest printing temperature produced the lowest mechanical property value. The highest value for the shear modulus was obtained with the 230ºC printing temperature. The values obtained for the variance coefficient are, in fact, higher than the values verified for the ABS specimens. **Table 35** presents the average of the shear modulus from all the collected data of the PET specimens.

Table 35 - Recycled PET Shear Modulus pf the average of all the collected data from torsion tests

	Average all Temperatures	SD	VC
Shear Modulus [MPa]	890,63	174,58	19,60

The PET mechanical property obtained from the torsion tests can be traduced as: **Shear Modulus 890,63 MPa.**

Finally, regarding the presentation of the PLA relative torsion properties, in **figure 30** it is presented the Torque-Angle of Twist curve correspondent to the average of values collected, for each printing temperature.

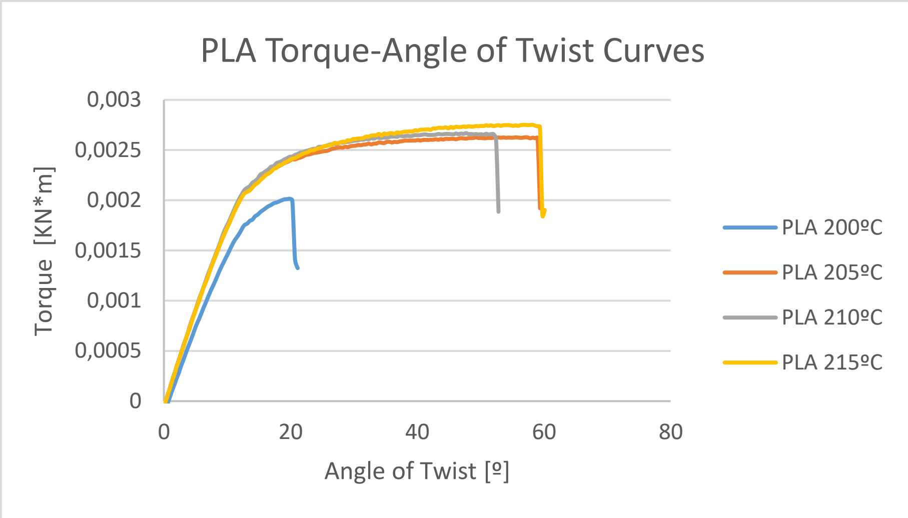


Figure 30 - Recycled PLA Torque-Angle of Twist Diagrams at each printing temperature

For the PLA specimens it was verified a significant difference on the curve obtained for the lowest printing temperature, when comparing with the curves of the other three printing temperatures. The 205ºC, 210ºC and 215ºC printing temperatures presented an almost equal linear region, correspondent to the elastic deformation. In the plastic deformation, the 205ºC and 215ºC printing temperatures also presented a very similar pattern, with a slightly higher value of angle of twist, until the fracture, when compared with the 210ºC printing temperature. The PLA specimens' mechanical property is presented in **table 36, 37, 38 and 39,** at each printing temperature**.**

Table 36 - Mechanical Properties of Recycled PLA Specimens printed at 200ºC

	Samples Number					
200ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Shear Modulus [MPa]	852,62	738,81	1010,00	867,14	136,18	15,70

Table 37 - Mechanical Properties of Recycled PLA Specimens printed at 205ºC

	Samples Number					
205ºC	PLA 4	PLA 5	PLA 6	Average	SD	VC
Shear Modulus [MPa]	1079,25	978,01	1496,12	1184,46	274,61	23,18

Table 38 - Mechanical Properties of Recycled PLA Specimens printed at 210ºC

	Samples Number					
210ºC	PLA 7	PLA 8	PLA 9	Average	SD	VC
Shear Modulus [MPa]	833,95	1435,66	1574,63	1281,41	393,70	30,72

Table 39 - Mechanical Properties of Recycled PLA Specimens printed at 215ºC

	Samples Number					
215ºC	PLA 10	PLA 11	PLA 12	Average	SD	VC
Shear Modulus [MPa]	1356,13	950,12	1295,99	1200,75	219,12	18,25

As reflected in the Torque-Angle of Twist curves diagram, the three highest printing temperatures share similar values regarding the shear modulus. Additionally, the lowest printing temperature presented the lower value relative to the shear modulus. The maximum value for the shear modulus with 210ºC printing temperature. The variance coefficient presents, again, higher values than the ABS and PET specimens. This is can be verified by observing higher differences between the values obtained at each specimen at each printing temperature. Finally, **table 40** presents the average of the shear modulus from all the collected data of the PLA specimens.

Table 40 - Recycled PLA Shear Modulus of the average of all the collected data from torsion tests

	Average all Temperatures	SD	VC
Shear Modulus [MPa]	1133,44	285,05	25,15

The PLA mechanical property obtained from the torsion tests can be traduced as: **Shear Modulus 1133,44 MPa.**

5.1.3 Compression Tests Results

Finally, with the data collected from this mechanical test, it was possible to reproduce the Stress-Strain diagrams obtained from cubic specimens under compression. Such curves allow to determine some mechanical properties, such as the Young Modulus and the Yield Stress. To perform this analysis, it was followed the interpretation made on the previous mentioned mechanical testes. The Stress-Strain curves will be presented together with the tables regarding the mechanical properties, for each material. The Young Modulus is here presented to confirm that, theoretically, it should be equal to the Young Modulus obtained from tensile tests, however it was verified as considerable reduction for the value of this property obtained with the compression tests.

Starting by the ABS samples, in **figure 31** it is presented the Stress-Strain curve correspondent to the average of the values collected, relative to the Tension and Extension, at each printing temperature.

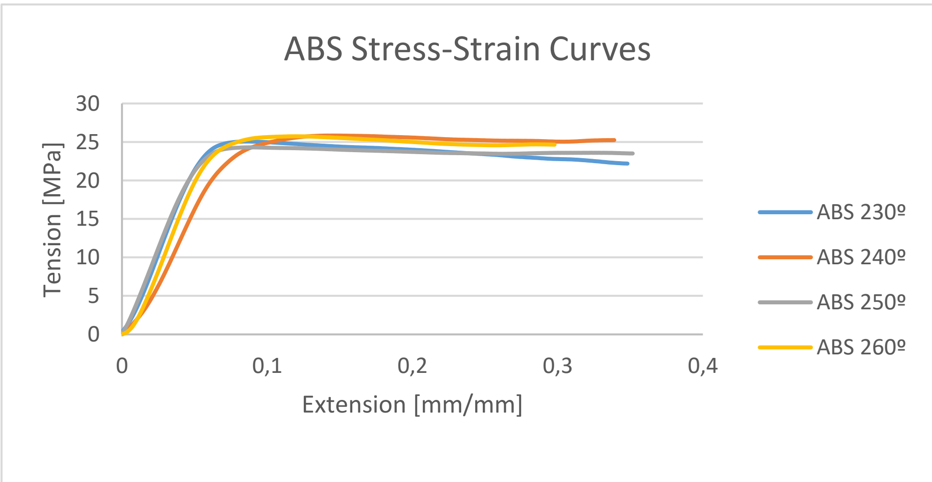


Figure 31 - Recycled ABS Stress-Strain Diagrams at each printing temperature obtained from compression tests

The Stress-Strain curves obtained for the ABS specimens at each printing temperature, were, in fact, quite similar. In the linear zone of the diagram, the specimens produced at 230ºC and 250ºC printing temperatures presented the most identical behaviour. The specimens produced at 240ºC presented the lowest slope in the elastic deformation. However, in the plastic deformation this specimens curve appears to present the highest curve in the diagram.

The ABS specimens' mechanical properties are presented in **tables 41, 42, 43 and 44**. Each table represent a different printing temperature.

Table 41 - Mechanical Properties obtained from the compression tests of Recycled ABS Specimens printed at 230ºC

	Specimens Number					
230ºC	ABS 1	ABS 2	ABS 3	Average	SD	VC
Young Modulus [MPa]	405,76	460,25	425,78	430,60	27,56	6,40
Yield Stress [MPa]	24,34	25,64	25,47	25,15	0,70	2,80

Table 42 - Mechanical Properties obtained from the compression tests of Recycled ABS Specimens printed at 240ºC

	Specimens Number					
240ºC	ABS 4	ABS 5	ABS 6	Average	SD	VC
Young Modulus [MPa]	395,53	352,09	428,35	391,99	38,25	9,76
Yield Stress [MPa]	26,80	25,18	25,62	25,87	0,84	3,23

Table 43 - Mechanical Properties obtained from the compression tests of Recycled ABS Specimens printed at 250ºC

	Specimens Number					
250ºC	ABS 7	ABS 8	ABS 9	Average	SD	VC
Young Modulus [MPa]	458,17	408,35	522,67	463,06	57,32	12,38
Yield Stress [MPa]	26,34	21,97	24,95	24,42	2,23	9,13

Table 44 - Mechanical Properties obtained from the compression tests of Recycled ABS Specimens printed at 260ºC

	Specimens Number					
260ºC	ABS 10	ABS 11	ABS 12	Average	SD	VC
Young Modulus [MPa]	455,26	472,55	497,18	475,00	21,07	4,44
Yield Stress [MPa]	25,86	25,60	26,08	25,85	0,24	0,93

As reflected in the Stress-Strain diagram the specimens produced at 240ºC present the lowest value of young modulus and the highest value for the yield stress. It is possible to verify that the yield stress is quite similar for all the printing temperatures. The young modulus presents some variations depending on the printing temperature, where the 260ºC, 250ºC and 230ºC printing temperatures are the ones which presented more similar values for this mechanical property. The variance coefficient present low values for the two properties obtained at all the different printing temperatures. The maximum values for the young modulus and yield stress were found on the 260ºC and 240ºC printing temperatures, respectively. Regarding values of young modulus and yield stress obtained from the average of all the collected data, **Table 45** presents these values. As the traction and torsion analysis, this table aims to set aside the printing temperature influencing factor, to focus intrinsically on the ABS properties.

Table 45 - Recycled ABS Mechanical Properties of the average of all the collected data from compression tests

	Average all Temperatures	SD	VC
Young Modulus [MPa]	440,16	47,05	10,69
Yield Stress [MPa]	25,32	1,23	4,87

The ABS mechanical properties obtained from the compression tests can be traduced as: **Young Modulus 440,16 MPa; Yield Stress 25,32 MPa.**

Regarding the results on the PET compression properties, in **figure 32** it is presented the Stress-Strain curves correspondent to the average of the values collected, relative to the Tension and Extension, at each printing temperature.

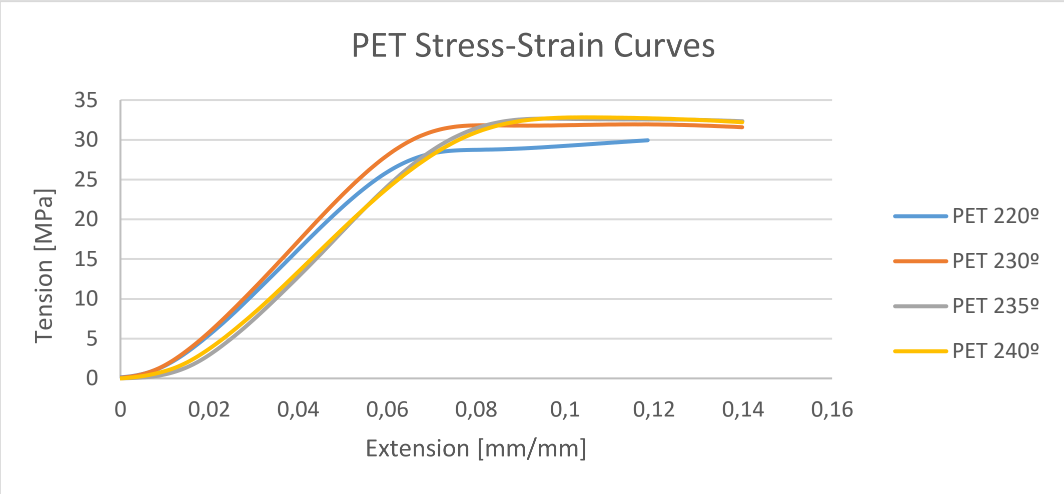


Figure 32- Recycled PET Stress-Strain Diagrams at each printing temperature obtained from compression tests

The slope on the linear zone observed from the specimens produced at 220ºC, 235ºC and 240ºC seems to be identical. The specimens produced at 230ºC presented a higher slope, correspondent to a greater value for the young modulus. Regarding the plastic deformation zone of the diagram, the specimens produced at the three highest printing temperatures reached a comparable yield stress. The specimens produced at the lowest printing temperature, 220ºC, reached lower values for the yield stress, which can be verified on the diagram by presenting a lower Stress-Strain curve. The two highest printing temperatures revealed an identical pattern on the entire Stress-Strain curve. The PET specimens' mechanical properties are presented in **tables 46, 47, 48 and 49**. Each table represent a different printing temperature.

Table 46 - Mechanical Properties obtained from the compression tests of Recycled PET Specimens printed at 220ºC

	Specimens Number					
220ºC	PET 1	PET 2	PET 3	Average	SD	VC
Young Modulus [MPa]	504,98	551,56	526,44	527,66	23,31	4,42
Yield Stress [MPa]	28,57	28,81	28,83	28,73	0,15	0,51

Table 47 - Mechanical Properties obtained from the compression tests of Recycled PET Specimens printed at 230ºC

	Specimens Number					
230ºC	PET 4	PET 5	PET 6	Average	SD	VC
Young Modulus [MPa]	581,89	558,37	557,85	566,03	13,73	2,43
Yield Stress [MPa]	32,22	31,42	31,83	31,82	0,40	1,26

Table 48 - Mechanical Properties obtained from the compression tests of Recycled PET Specimens printed at 235ºC

	Specimens Number					
235ºC	PET 7	PET 8	PET 9	Average	SD	VC
Young Modulus [MPa]	543,65	530,37	521,41	531,81	11,19	2,10
Yield Stress [MPa]	32,75	32,28	33,00	32,67	0,36	1,11

Table 49 - Mechanical Properties obtained from the compression tests of Recycled PET Specimens printed at 240ºC

	Specimens Number					
240ºC	PET 10	PET 11	PET 12	Average	SD	VC
Young Modulus [MPa]	532,06	507,72	527,43	522,40	12,93	2,47
Yield Stress [MPa]	32,46	33,05	32,98	32,83	0,32	0,99

In consensus with the curves presented on **figure 32**, the young modulus value obtained by the specimens produced at 220ºC, 235ºC and 240ºC is similar. Regarding the yield stress, the lowest value obtained was from the specimens produced at the 220ºC printing temperature. The other three printing temperatures produced specimens with similar values for the yield stress. The variance coefficient presented, again, low values for the analysed properties. Considering the maximum value of the young modulus, it was obtained from the specimens produced at 230ºC. The maximum value of the Yield Stress was reached from the specimens produced with the 240ºC printing temperature. Regarding values of PET young modulus and yield stress from the average of all the data collected, **Table 50** presents these values, alongside with the standard deviation.

Table 50 - Recycled PET Mechanical Properties of the average of all the collected data from compression tests

	Average all Temperatures	SD	VC
Young Modulus [MPa]	536,97	22,48	4,19
Yield Stress [MPa]	31,52	1,75	5,54

The PET mechanical properties obtained from the compression tests can be traduced as: **Young Modulus 536,97 MPa; Yield Stress 31,52 MPa.**

Finally, from the data collected of the PLA specimens, in **figure 33** is presented the Stress-Strain curves correspondent to the average of the values collected, relative to the Tension and Extension, at each printing temperature.

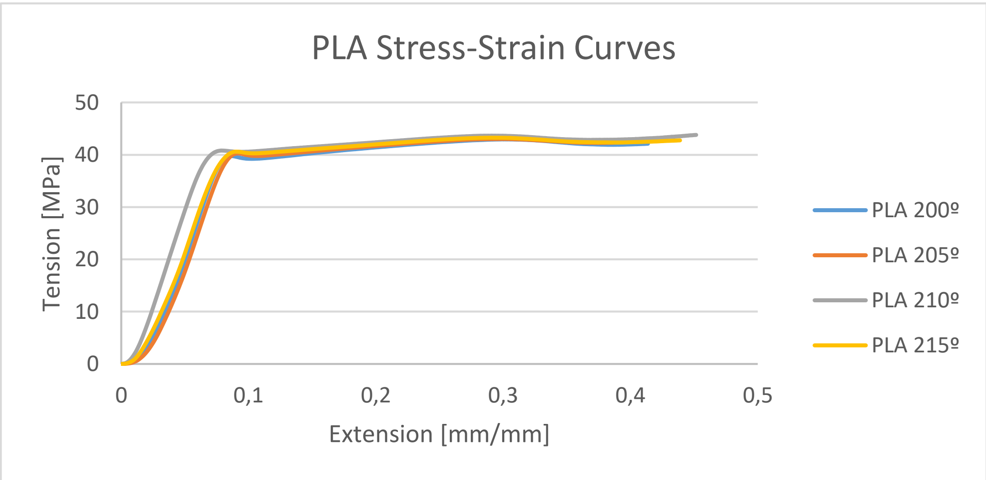


Figure 33 - Recycled PLA Stress-Strain Diagrams at each printing temperature obtained from compression tests

By observing the elastic deformation zone of the Stress-Strain diagram is possible to verify that the PLA specimens printed at 200ºC, 205ºC and 215ºC reproduced a similar behaviour. This can be traduced in comparable values for the young modulus. The specimens printed at 210ºC presented a higher slope on the referred elastic zone, which traduces a higher value for the young modulus. On the plastic deformation zone of the diagram, it is verified an identical pattern from all the printed specimens. The PLA specimens' mechanical properties are presented in **table 51, 52, 53 and 54**. Each table represent a different printing temperature.

Table 51 - Mechanical Properties obtained from the compression tests of Recycled PLA Specimens printed at 200ºC

	Samples Number					
200ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	621,20	605,12	619,26	615,20	8,78	1,43
Yield Stress [MPa]	40,34	39,74	39,46	39,85	0,45	1,12

Table 52 - Mechanical Properties obtained from the compression tests of Recycled PLA Specimens printed at 205ºC

	Samples Number					
205ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	634,66	615,03	619,26	622,99	10,33	1,66
Yield Stress [MPa]	41,05	40,27	39,46	40,26	0,80	1,98

Table 53 - Mechanical Properties obtained from the compression tests of Recycled PLA Specimens printed at 210ºC

	Samples Number					
210ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	623,00	757,24	755,13	711,79	76,90	10,80
Yield Stress [MPa]	40,91	40,32	41,28	40,84	0,49	1,19

Table 54 - Mechanical Properties obtained from the compression tests of Recycled PLA Specimens printed at 215ºC

	Samples Number					
215ºC	PLA 1	PLA 2	PLA 3	Average	SD	VC
Young Modulus [MPa]	605,67	614,15	600,88	606,90	6,72	1,11
Yield Stress [MPa]	40,20	40,98	40,64	40,61	0,39	0,96

Accordingly the patterns verified on the Stress-Strain diagram, the specimens printed at 200ºC, 205ºC and 215ºC presented comparable values for the young modulus. The specimens printed at 210ºC verified a greater value for this property. Considering the yield stress, as verified in the curve's analysis of **figure 33,** all the printing temperatures reproduced similar values. The maximum values for the young modulus and yield stress were found on the specimens produced at the 240ºC printing temperature. Finally, the value of PLA young modulus and yield stress from the average of all the data collected is presented in **Table 55**.

Table 55 - Recycled PLA Mechanical Properties of the average of all the collected data from compression tests

	Average of all Temperatures	SD	VC
Young Modulus [MPa]	639,22	55,38	8,66
Yield Stress [MPa]	40,39	0,61	1,52

The PLA mechanical properties obtained from the compression tests can be traduced as: **Young Modulus 639,22 MPa; Yield Stress 40,39 MPa.**

5.1.4 Best Printing Temperatures

Prior to the conclusions drawn for each material best printing temperature, it can be stated that the different used printing temperatures do not significantly influence and do not promote great differences in the overall values of the mechanical properties analysed, for the three different filaments.

Starting with ABS specimens, as observed in **tables 11, 12, 13, 14, 26, 27, 28, 29, 41, 42, 43 and 44** there were verified slightly differences on the mechanical properties, for each printing temperature, which do not represent a great variation on the material performance. However, the 240ºC printing temperature provided the overall best mechanical properties. The specimens printed at 240ºC produced the best overall values for the yield strength, tensile strength, shear modulus and yield stress. The maximum overall value for the young modulus was founded with the 250ºC printing temperature, still the difference for the overall value of specimens printed at 240ºC was approximately 40 MPa. Considering that the young modulus is scaled with intervals of approximately 500 MPa, the young modulus value for 240ºC printing temperature does not present great differences on the mechanical property. Thus, it was considered the **240ºC** printing the best temperature to produce products with this recycled ABS filament.

Regarding the PET specimens, as observed in **tables 16, 17, 18, 19, 31, 32, 33, 34, 46, 47, 48 and 49** there were also only verified slightly differences on the mechanical properties, at each printing temperature. Though, the 240º printing temperature provided the overall best values for the yield stress, young modulus, tensile strength and yield stress. The maximum overall value for the shear modulus was obtained with the specimens produced at 230ºC. The difference for the specimens printed at 240ºC was of approximately 50 MPa. The shear modulus is scaled with intervals of approximately 100MPa. This difference can produce slightly differences on the material stiffness, however it can be counterbalanced with the best values for the other mechanical properties. Thus, it was considered the **240ºC** printing the best temperature to produce products with this recycled PET filament.

Finally, in the PLA specimens, as observed in **tables 21, 22, 23, 24, 36, 37, 38, 39, 51, 52, 53 and 54** differences verified were similar to the differences reported for the ABS and PET specimens, except on the shear modulus where it was verified a greater variance at each printing temperature. Regarding this information, the 210ºC printing temperature produced the best overall values for the shear modulus and compressive strength. The young modulus, yield strength and tensile strength were provided with best overall values at the 215ºC, 205ºC and 205ºC printing temperatures, respectively. However, the difference verified for the young modulus obtained at 210ºC was around 40 MPa, which, following the reasoning made for the ABS filament, does not present significant mechanical differences. For the other two properties the differences verified with the results of the 210ºC printing temperature were almost insignificant. With this, it was considered the **210ºC** printing temperature the best temperature to produced products with this recycled PLA filament.

5.2 Mechanical Tests Results Discussion

In this section it will be provided the conclusions regarding the mechanical characteristics, for each studied recycled filament. Thereafter, as referred before, with the assistance of the software CES-EDUPACK, the three different recycled plastics analysed will be compared with the information disposed by the software, regarding the mechanical properties of the correspondent virgin material. The recycled plastics experimental properties will also be framed accordingly to scales relative to the mechanical properties, also available on the software. To conclude the material characterization, it will be suggested final product applications, with each type of plastic, accordingly the mechanical analysis performed and also information available on CES.

5.2.2 Recycled ABS Mechanical Properties Characteristics

Regarding the analysis of the recycled ABS mechanical properties, it can be compared the properties of virgin ABS presented in CES-EDUPACK with the recycled ABS properties, regarding the overall values obtained from all the ABS tested specimens. In **table 56** is presented the considered mechanical properties values displayed in CES-EDUPACK and the values obtained from the mechanical tests performed.

Table 56 – ABS theoretical values provided by CES vs Recycled ABS overall values achieved in the experimental analysis

Mechanical Properties	Virgin ABS Range Values	Recycled ABS Values
Young's Modulus [GPa]	1,1 - 2,9	0,793
Shear Modulus [GPa]	0,319 - 1,03	0,869
Yield Strength [MPa]	18,5 - 51	18,63
Tensile Strength [MPa]	27,6 - 55,2	21,21
Compressive Strength [MPa]	31 - 86,2	25,32

It is possible to verify that the recycled ABS filament presents lower mechanical properties values when comparing with virgin material properties. For the recycled ABS, the shear modulus and yield strength are the only values inside their correspondent range of values presented for the virgin ABS. However, the yield strength value is situated on lower bound of the virgin ABS values range. The tensile strength and compressive strength are out of the range, still the values are near the lower bound of the range for the virgin material. The young modulus is also out the range and with a more accentuate difference compared with the tableted properties of the virgin material. Looking to this comparison, it can be stated that the mechanical properties ABS suffer a reduction with this recycling and 3D printing processes.

Additionally, it is possible to frame the properties of the recycled ABS, obtained from the best printing temperature, with the available scales of CES-EDUPACK. In **figure 34** it is represented the scales provided by CES-EDUPACK. The blue line corresponds to a density line of all the polymers. The red mark corresponds to the value of the recycled ABS of the concerning mechanical property.

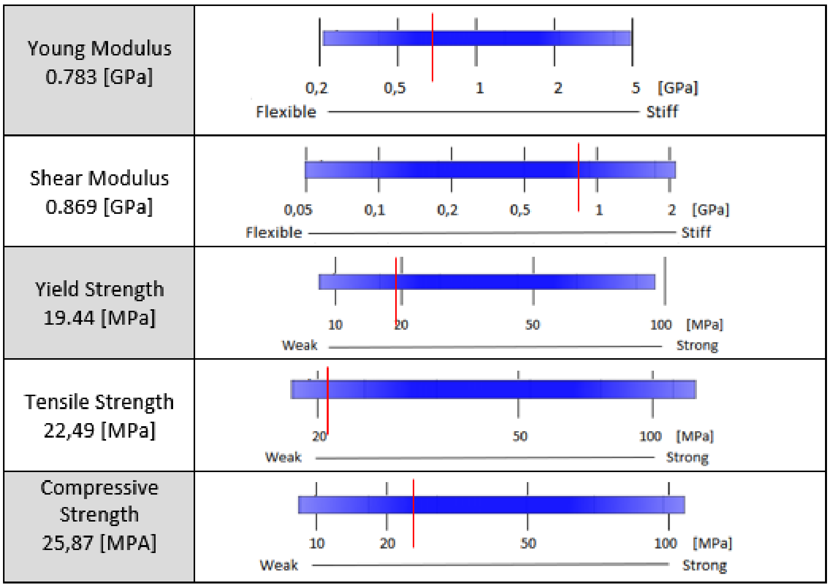


Figure 34 – Mechanical Properties Framework with Recycled ABS highlighted by a red mark

Regarding the young modulus, with the best printing temperature (240ºC), this recycled ABS presented a value slightly lower from the medium term between a flexible or stiff material. The shear modulus presented a value corresponding to a stiffer material. These two properties present values near the densest zone of the polymer's density line. The yield strength presented a value in the weak zone of the scale, corresponding to low resistance to absorb elastically a tensile load. The tensile strength presented a value also in the weak zone, in bottom of the scale, corresponding to low resistance to tensile loads. The compressive strength presented a lower value present in the intermediate term between a weak or strong material, corresponding to a medium resistance to compressive loads. In general, these three properties presented values in more isolated zones of the polymer's density line. This framework can traduce this recycled ABS as a material with a weak resistance to tensile traction, a medium resistance to compressive loads, more flexible to tensile traction and with a stiffer property regarding torsion resistance.

Finally, with information provided by CES-EDUPACK, it is possible to allocate this material into best scenarios for its utility. CES-EDUPACK suggests final applications related to automotive instruments and other interior components, home-security devices, communication equipment, business machines and luggage shells. Thus, and regarding the properties obtained, it is recommended to use this recycled ABS for products which do not require great and continuous resistance to tensile and compressive loads. However, regarding the verified factures on the tensile tests, and the correspondent weak properties, this material can be useful to produce mechanical fuses. This recycled ABS can be suited for production of functional products, to serve simple applications. Cases for equipment's or recipients to store oils can be a possibility for final applications of this filament.

5.2.3 Recycled PET Mechanical Properties Characteristics

Regarding the analysis of the recycled PET mechanical properties, it can be compared the properties of virgin PET presented in CES-EDUPACK with the recycled PET properties, regarding the overall values obtained from all the PET tested specimens. In **table 57** is presented the considered mechanical properties values displayed in CES-EDUPACK and the values obtained from the mechanical tests performed.

Table 57 - PET theoretical values provided by CES vs Recycled ABS overall values achieved in the experimental analysis

Mechanical Properties	Virgin PET Range Values	Recycled PET Values
Young's Modulus [GPa]	2,76 - 4,14	0,762
Shear Modulus [GPa]	0,994 - 1,49	0,89
Yield Strength [MPa]	56,5 - 62,3	28,97
Tensile Strength [MPa]	48,3 - 72,4	33,87
Compressive Strength [MPa]	62,2 - 68,5	31,53

It is notable that the recycled PET presents a considerable downgrade of the mechanical properties when comparing with the virgin material properties. For the recycled PET, all the values of the properties are out the range of the values presented for the virgin PET. Considering the shear modulus scale presented in the recycled ABS characteristics section, this is the property, that even though it is out of range, presents the nearest value to the theorical range with a lower variance. The yield strength, tensile strength and compressive strength present values with substantial differences of approximately 30 MPa to the lower value of their correspondent virgin PET range values. The young modulus is the property which presents the greatest difference of approximately 2 GPa to the lower value of its correspondent virgin property range. With this, it can be stated that the PET mechanical properties suffer a accentuate reduction with this recycling process.

Furthermore, identically to the analysis done for the ABS mechanical characteristics, **figure 35** presents the scales provided by CES-EDUPACK.

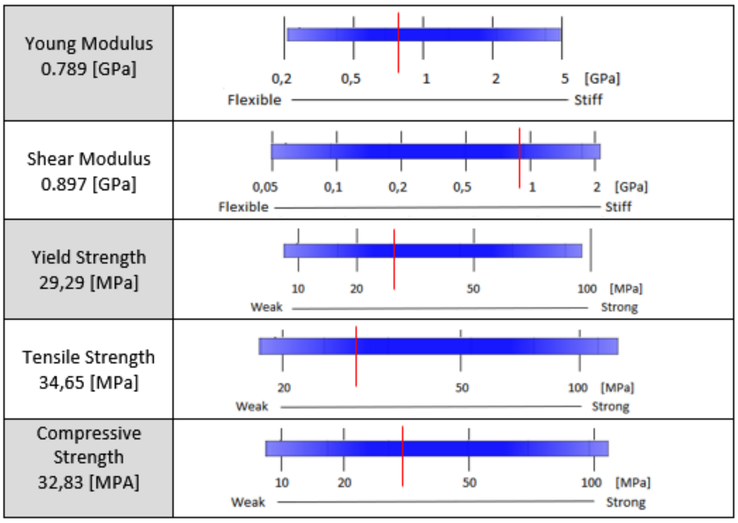


Figure 35 - Mechanical Properties Framework with Recycled PET highlighted by a red mark

Starting from the young modulus, with the best printing temperature (240ºC), this recycled PET presented a value near the medium term between a flexible or stiff material. The shear modulus presented a value corresponding to a stiffer material. The yield strength presented a value slightly lower from the intermediate term between the weak and strong zones of the scale, corresponding to the average polymer's resistance to absorb elastically tensile loads. The tensile strength presented a value corresponding to the medium zone between a weak and medium strong material, corresponding to a material with a medium tensile resistance. The compressive strength presented a value a slightly lower from the intermediate term between a weak or strong material, corresponding to the average polymer's resistance to compressive loads. In general, these three properties presented values with better properties from the ABS properties. This framework can traduce this recycled PET as a medium strong material resistant to compressive and tensile loads, more flexible to tensile traction and with a stiffer property regarding torsion resistance.

Finally, with information, provided by CES-EDUPACK, regarding PET typical uses it is possible to allocate this material to best scenarios for its utility. CES-EDUPACK suggests final applications related with packaging film, electrical fittings and connectors, ovenproof cookware and carbonated drink containers. Thus, and regarding the properties obtained, it is recommended to use this recycled PET for products which require some resistance to loads and fractures. This recycled PET can be suited for production of functional products, with the need of flexibility and robustness.

5.2.4 Recycled PLA Mechanical Properties Characteristics

Finally it come the analysis of the recycled PLA mechanical properties. Following the same methodology done for the other two types of plastics, it can be compared with the properties of virgin PLA presented in CES-EDUPACK. In **table 58** is presented the considered mechanical properties values displayed in CES-EDUPACK and the values obtained from the mechanical tests performed.

Table 58 - PLA theoretical values provided by CES vs Recycled ABS overall values achieved in the experimental analysis

Mechanical Properties	Virgin PLA Range Values	Recycled PLA Values
Young's Modulus [GPa]	3,3 - 3,6	0,849
Shear Modulus [GPa]	1,2 - 1,29	1,13
Yield Strength [MPa]	55 - 72	19,02
Tensile Strength [MPa]	47 - 70	21,18
Compressive Strength [MPa]	66 - 86	40,39

Once again it is notable a downgrade of the PLA mechanical properties when comparing with the virgin material properties. This PLA downgrade is similar to the one verified for recycled PET. For the recycled PLA, all the values of the properties are out the range of the values presented for the virgin PLA. However, the value of the shear modulus is near the theorical range and, accordingly the shear modulus scale, the variance is not accentuated. The yield strength and tensile strength present values with substantial differences of approximately 30 MPa bellow the lower bound of the range. The compressive strength present a value bellow the lower bound of the range of around 25 MPa. Identical to the pattern verified in the recycled PET analysis, the young modulus is the property which presents the greatest difference of approximately 2,5 GPa. It can be concluded that the PLA mechanical properties suffer a accentuate reduction with this recycling process.

Moreover, identically to the analysis done for the ABS and PET mechanical characteristics, **figure 36** presents the scales provided by CES-EDUPACK. The blue line corresponds to a density line of all the polymers. The red mark corresponds to the value of the recycled PLA of the concerning mechanical property, obtained with the best printing temperature.

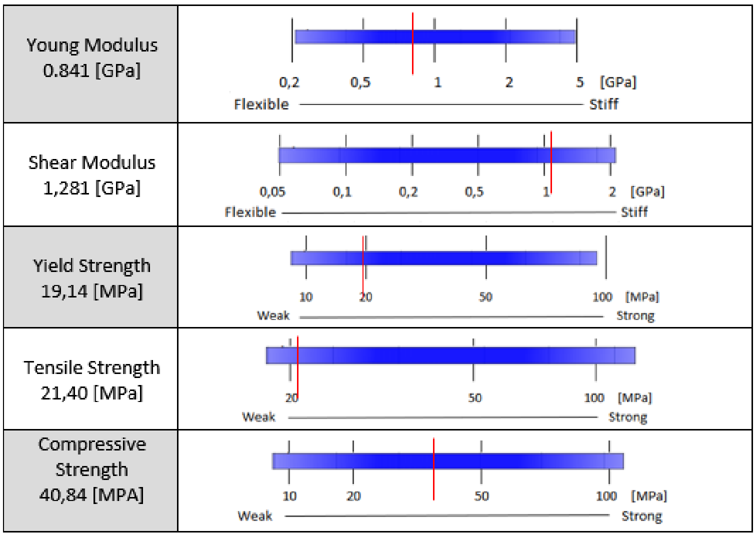


Figure 36 - Mechanical Properties Framework with Recycled PLA highlighted by a red mark

With the best printing temperature (210ºC), the young modulus of the recycled PLA presented a value near the medium term between a flexible or stiff material. The PLA shear modulus presented the highest value, corresponding to a stiffer material. In fact these two properties presented similar characteristics to the PET properties. The yield strength presented a value in weak zone of the scale, corresponding to a weak resistance to absorb elastically tensile loads. The tensile strength presented a value in the lower bound of the range, corresponding to a weak tensile resistance material. The compressive strength presented a value corresponding to the intermediate term between a weak or strong material, corresponding to a medium resistance to compressive loads. In general, the recycled PLA presented the first two properties of the scale with similar values to the recycled PET properties and the yield strength and tensile strength presented similar values to the recycled ABS respectively properties. This framework can traduce this recycled PLA as a material with weal resistance to tensile loads, however stronger than ABS, presenting a balanced flexibility and stiffness regarding tensile loads and stiffer concerning torsion loads.

To conclude this analysis, with information, provided by CES-EDUPACK, regarding PLA typical uses it is possible to allocate this material to best scenarios for its utility. CES-EDUPACK suggests final applications related with pencil sharpeners, rulers, plant pots, trays for fresh food packaging and sanitary products. With this, and regarding the properties obtained, it is recommended to use this recycled PLA for products which do not require great resistance to tensile loads. Considering the robustness of the produced specimens and all the analysis done, this recycled PLA filaments can be suited for production of simple functional products, similar to the ABS filament, but offering a strongest resistance compressive and torsion loads.

5.2.5 Recycled ABS, PET and PLA Properties Comparison

A final comparison of the three different plastics can be done, using the obtained properties with the best printing temperature. This comparison can be attractive to provide a clearer vision on the differences between each type of plastic, in order to better allocate each material to its corresponding final applications/products. **Table 59** represents this comparison between the properties obtained for the tested recycled filaments.

Table 59 – Recycled ABS, PET and PLA mechanical properties comparison

Mechanical Properties	Recycled ABS Values	Recycled PET Values	Recycled PLA Values
Young's Modulus [GPa]	0,783	0,789	0,841
Shear Modulus [GPa]	0,869	0,897	1,28
Yield Strength [MPa]	19,44	29,29	19,14
Tensile Strength [MPa]	22,49	34,65	21,40
Compressive Strength [MPa]	25,87	32,83	40,84

Starting by the young modulus, the recycled PLA presented the highest value for this property. The recycled ABS and PET presented similar values for the young modulus. Though, considering the presented scales regarding the stiffness variance in the young modulus values, the difference of the recycled PLA value and the recycled ABS and PET values is not accentuated.

Regarding the shear modulus, the recycled PLA presented, again, the highest value for this property. The recycled ABS and PET presented identical values, and, as described for the young modulus, the difference verified for the young modulus recycled PLA value does not reflects great property alterations. However, it can traduce a slightly stiffer capacity, regarding torsion loads, from the PLA filament.

The highest value obtained for the yield strength was from the recycled PET filament. The ABS and PLA presented identical values, with a considerable reduction, comparing with the PET yield strength value, of approximately 10 MPa.

The highest value obtained for the tensile strength was obtained from the recycled PET. The recycled ABS and PLA presented similar values. The difference comparing with the PET value is, once again, considerable and can traduce stronger capacities, to resist to tensile loads, for the PET filament.

Finally, the recycled PLA presented the highest value for the compressive strength. The recycled PET presented the intermediate value, while the recycled ABS presented the lowest value with a notable reduction when comparing with the value for the PLA filament.

In general, the recycled ABS seems to be the weakest material, presenting low values for the considered properties, comparative with the PET and PLA filament. The recycled PET appears to be the strongest material to resist to a set of compressive and tensile loads, presenting values that characterize an acceptable capacity at all these three properties. The recycled PLA seems to reproduce a weak resistance to tensile loads, similar to the ABS filament resistance, and a strong resistance to compressive loads, slightly stronger than the PET filament. However, for the properties that evaluate the stiffness capacity, this recycled PLA presented the highest values for the tensile and torsion loads. Considering the evaluated mechanical properties it can be considered the ABS recycled filaments the weakest material. The PLA and PET can be considered the recycled filaments that provide a stronger capacity, the PLA more resistant to compressive loads and the PET more resistant to tensile loads.

5.3 Conclusions

This chapter is composed by two main contents. Firstly, it is presented the results obtained from the performed mechanical tensile, torsion and compression tests. Thereafter, it is presented an analysis on the obtained mechanical results. This analysis takes an important role in this section, since it gives content to provide conclusions on the mechanical properties obtained in the experimental tests. This content is extremely important in this master dissertation, given that it will provide knowledge and tools to compose possible product applications for these types of recycled filaments. It also intends to, with the selected printing parameters, define the best printing temperatures for each recycled filament. For the ABS, PET and PLA filaments it was defined as 240ºC, 240º and 210ºC, respectively, the printing temperatures that provided the best mechanical properties for each filament. Regarding the conclusions drawn concerning the mechanical characteristics of each filament, the PET filament seemed to be the strongest material to resist to a set of compressive and tensile loads. It can be an interesting filament to produce a variety of simple products which have the need to offer flexibility and robustness at the same time. The PLA filament presented a weak capacity to resist to tensile loads, but with a better capacity to resist to compressive loads. It also presented good properties concerning the stiffness and flexibly capacities. This filament can be adequate to produce products with the necessity of presenting a moderate capacity to compression loads. The ABS filament seemed to be the material with weakest properties considering the overall of the studied mechanical properties. This filament can be used to produce simple and functional products, which do not require to present a great mechanical resistance.

6. Frugal Products and 3D Printing

In this section it will be, firstly, presented in section 6.1 the three Frugal Products chosen to be produced with the recycled filaments. In section 6.2, it will be presented the decisions made to decide with which type of filament would the chosen to produce the different products. Finally, in section 6.3 the 3D printing quality will be assessed as well as the usability of the printed products.

6.1 Frugality of the produced products

As referred in section 3.3, frugal products look forward to satisfy essential needs with simple products and designs, making them affordable for the majority of the people. This concept can be even more attractive when it compromises simplicity and functionality with a development, of a production process and a delivery process, which minimize the use of resources. In the following section it will be taken under consideration the characteristics presented in **table 10** to identify the ensure frugality of the selected products to be produced.

6.1.1. Arm Cast

Additive manufacturing has been recently taken under consideration as an effective and efficient tool to provide solutions for the medical sector. One of the best advantages is to provide rapidly customized patient designs. Thus, it has been explored the possibility to produce patient customized casts, allowing patients to live their daily life with reduced impact on their abilities (Trauner, 2018). Regarding casting bracing, 3D printing offers a considerable amount of advantages such as: offer breathability, adaptive fitting for swelling, windows for wound care and modularity. Basically, this innovative design allows to better apply fracture care techniques. Therefore, with low temperature thermoplastics it is possible to accelerate production times, turning this new casting and bracing concept in a real distributed manufacturing of 3DP medical devices in physical offices (Fitzpatrick, Mohanned, Collins, & Gibson, 2017; Trauner, 2018). Thus, it seemed interesting to produce a 3D printed arm cast, regarding the enthusiasm and rise of attention concerning the application of 3DP in medical innovations. It was selected a 3D printed arm cast available on the web platform Thingiverse. This arm cast is produced with thermoplastics and, basically, it just need to be heated and then moulded to the patient arm. When the arm cast cools down it becomes solid and performs its essential function.

Regarding **table 10,** which concerns the frugal characteristics**,** this 3D printed arm cast is for sure an exciting product to prove the usability of the analysed recycled filaments to produce frugal innovations. Starting by the first two frugal characteristics, this 3D printed arm cast is a product that improves the traditional arm cast concept, serving medical essential needs more efficiently, as explained in the previous paragraph. Concerning the third, fifth and sixth characteristics, it turns the process of wrapping the cast much simpler and more accurate, as it uses high precision design techniques to reproduce the patient's unique anatomy. It is also significantly lighter, with improved water resistant and air circulation properties. Considering that this arm cast would be produced using waste plastic as resources (recycled plastic filament), it opens the path to an affordable product which spares the use of resources. **Figure 38** presents the arm cast presented on the web platform Thingiverse.

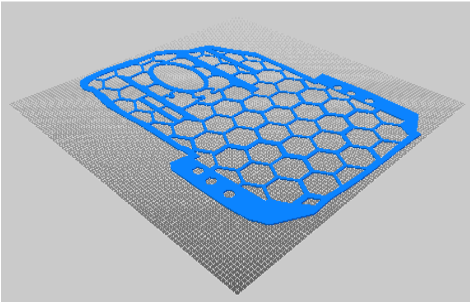


Figure 38 – 3D Printable arm cast (Thingiverse, 2019)

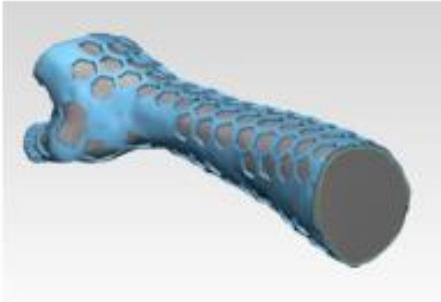


Figure 39 – 3D Printable arm cast concept (Thingiverse, 2019)

6.1.2. Fork and Spoon support for disabled people

As aforementioned in the arm cast presentation, addictive manufacturing is proving to meet the requirements to offer a significant contribution on the medical sector. Regarding the prosthetics and orthotics, 3DP allows to connect modern industrial design and mass customization. Thus, allocating 3DP to this medical sector can be an enthusiastic union to unlock design free and individual preferences. 3DP can remove traditional manufacturing methodologies by offering efficient design for prosthetics (Trauner, 2018). Therefore, in the context of this dissertation which intends to prove feasibility of a product production methodology based on sustainable and innovative concepts, it was considered a simpler product that aims to improve a daily task of a disabled person. It was selected an item from Thingiverse, which corresponds to an eating support for disabled people. In this support it is possible to attach a fork, a spoon or a personalised tool, that allows a person with reduced mobility/sensibility in his/her hand to use this eating tools much more effortlessly.

Regarding **table 10,** this support is also an excellent simplified product to serve essential needs of disable people, which fulfils the first frugal characteristic. Also, it seems a proper tool to reinforce the feasibility to allocate plastic waste into frugal products. Considering the third and fifth characteristics, the simple geometry attributes to this product a functional usability and simplifies the production process. Thus, it is considered a user-friendly product, since it just need to be attached to the user hand, which completes the second and fourth characteristics. Finally, regarding that this is a small support compounded by recycled plastic waste, there are not verified great costs to produce this tool, making it an affordable product. **Figure 40** presents the fork and spoon support available on MyMiniFactory.

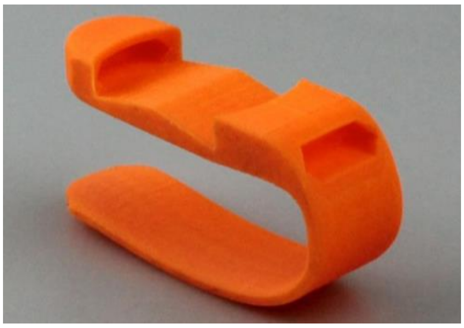


Figure 40 - Printable Fork and Spoon Support concept (MyMiniFactory, 2019)

Figure 41 – Printable Fork and Spoon Support concept (MyMiniFactory, 2019)

6.1.3. Waterlock

The observed increase of the connection between economies worldwide has risen awareness to attack the necessities of emerging markets. However, it is important to take in consideration that to efficiently tackle these markets, it is necessary to effectively analyse existent challenges in such emerging countries. In fact, there are an enormous range of problems, where the most common pass through limited purchasing power, incomplete infrastructure and resource constrains. Thus, producing products to tackle these challenges comes up as an exciting perspective to test and explore the functionality and acceptability of frugality. An opportunity to explore this sector can pass through the development of Frugal Products, which its usability promotes clean and sustainable actions. Clean technologies are seen as a great tool to face environmental issues, such as water pollution, waste water and environmental resource consumption. Introducing this concept in the conceptualization of a Frugal Product can be interesting to promote the Frugal concept itself and at the same time sustainability (Kuo, 2017). Thus, this product was chosen a simple product to serve two purposes: promote a reduction on waste water; allow people with low sanitary and pipe conditions to have a mean to better personal care quality. Basically, this product is a waterlock which can be inserted in a used bottle with water. This waterlock has a holder to attach a cable which, in turn, attaches the soap and a load. With the load, the bottle can be turned upside down and the waterlock obstructs the water. Then, basically, as the waterlock is a floating body, the user just needs to lift up the soap and the load, which will immediately trigger off waterfalling to allow the user to wash users' hands. As soon as the user drops the soap, the load waterlock will obstruct the water again. With this system it is possible to save water and easily assemble a sanitary product.

Considering **table 10,** this product intents to serve basic personal needs of a human which lives in poor conditions, which achieves the first and second frugal characteristics. It is a functional product which serves an essential need and at the same time promotes a sustainable using process. Considering that it is just necessary to print a simple product to work with a used bottle, this waterlock also trims down many processes, which fulfils the third characteristic. These processes can be, for example, the need to construct pipes in suburb areas, where this can be an extremely difficult process. As explained in the previous paragraph, using the waterlock does not requires any type of specialized knowledge and can be easily installed in every bathroom or kitchen, which complete the fifth and sixth characteristics. Finally, it is a product with a simple geometry and it is produced with waste plastic, which traduces the affordability and spare use of resources. **Figure 42** presents the waterlock printed with recycled ABS, in 3D Ways.

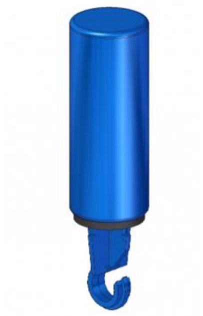


Figure 42 - Printable waterlock (MyMiniFactory, 2019)

Figure 43 – Waterlock concept (MyMiniFactory, 2019)

6.2 Selection of recycled materials

After the selection of the products to be produced, the best plastic for the production of each product needs to be defined. It is important to take into consideration the final application of the product and the different actions that they undertake. These actions determine the possible type of loads submitted to each product and necessary resistance to traduce a good performance. Obviously, the objective is to choose the material, regarding the obtained properties and the information presented relative to their usual final. To better clarify the features provided by each material, **table 60** presents the conclusions drawn from the comparison between the three different recycled analysed plastics. It takes under consideration the scales presented in materials characterization and the values obtained from the performed mechanical tests.

Table 60 – Recycled ABS, PET and PLA flexibility and mechanical resistance comparison

	ABS	PET	PLA
Young Modulus Stiffness	Flexible/Stiff	Flexible/Stiff	Flexible/Stiff
Shear Modulus Stiffness	Medium Stiff	Medium Stiff	+ Medium Stiff
Resistance to Tensile Loads	Medium Weak	Medium Strong	Medium Weak
Resistance to Compression Loads	Medium Weak	Medium Strong	+ Medium Strong

Regarding the arm cast, it is suggested in the file available in Thingiverse to produce it with PLA. The printed arm cast is a product that needs to have a good relation between stiffness and flexibility, since after the modulation to the patient arm, which requires flexibility, it needs to be stiff to perform the final intention of correct the broken arm structure. Accordingly the information provided in **table 60,** the recycled PLA filament presents good proprieties to be used in the production of this product. Regarding the young modulus, this material presents an acceptable capacity to be either flexible or stiff. Considering the shear modulus, this recycled ABS presents the stiffer capacity of the three tested filaments. Finally, it has a good capacity to resist to compressive loads, which can be interesting in case of eventual unexpected loads that can be applied against the patient arm. Thus, it was decided to produce the 3D printed arm cast with the recycled PLA filament.

Regarding the fork and spoon support for disabled people, there is no suggestion concerning the production material in the platform MyMiniFactory. Since this support was design to adapt to people's hands, it requires to be a stiff flexible product in order to adapt and fix to a disable people hand. Considering the cases where this product is used to support a fork, it seems important to provide some resistance to loads and forces inherent in the act of eating a meal. Regarding the data stated in **table 60**, the recycled PET filament seems to be adequate to fulfil this objective. Considering the young modulus, this materials presents similar acceptable capacity to the ABS filament to be either flexible or stiff. Taking under consideration the shear modulus, this PET filament presents a medium stiff characteristic. The union of these two properties appears to be exactly what this product essentially needs as mechanical properties. Finally, it has a medium strong capacity to resist to tensile and compressive loads. Therefore, it was decided to produce the fork and spoon support with the recycled PET filament.

To conclude it was decided to produce the Waterlock with the recycled ABS filament. Also, it was not presented any information considering the production material in the platform MyMiniFactory. Considering the final application of this product, it is notable that is does not requires great mechanical properties to perform its function properly. Basically, this product does not need a great capacity to resist to tensile loads, since soaps are not heavy objects and the load to pull the lock downwards is also of small dimensions. Thus, since the ABS was the material that presented the lowest mechanical properties values it was decided to produce the Waterlock with the recycled ABS filament.

6.3 Printing Quality and Products Usability

Printing Quality

Recently, with the verified growth of FDM machines, it has been verified a development of researches to address the best dimensional capability and geometrical accuracy of such machines and used feedstock. It has been developed benchmark objects to test this dimensional and geometrical accuracy, where one of the most common used is the well-known *benchy* artefact. The 3D printers are challenged to perform a well-structured shape and size of the 3D model. The objective is to check on dimensional accuracy, tolerances, warping and deviations regarding different printing parameters and material type (Tronvoll, Elverum, & Welo, 2018). To complement the visual critic on geometrical accuracy of the printed *benchy,* it can be done a comparison of the tableted dimensions and the obtained printed dimensions to check the dimensional accuracy. **Table 61** presents the mentioned comparison per each type of material.

Figure 43 - Printed PET benchy

Figure 44 - Printed PET benchy

Figure 45 - Printed ABS benchy

Figure 46 - Printed ABS benchy

Figure 47 - Printed PLA benchy

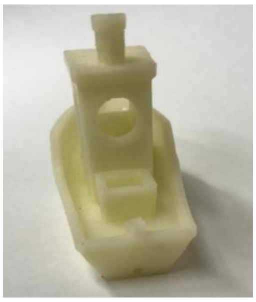
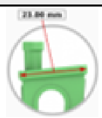
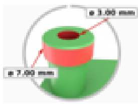
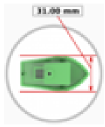
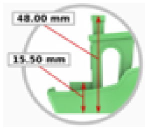
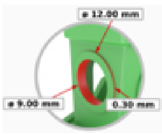
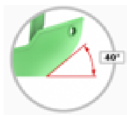


Figure 48 - Printed PLA benchy

Table 61 – Comparison between theoretical benchy dimensions and the PLA, PET and ABS printed benchys

Measurement Test Description	Measurement Test Illustration	Theoretical Dimensions	PLA Benchy Dimensions	PET Benchy Dimensions	ABS Benchy Dimensions
Front and Rear surface of the roof parallel		23.00 mm	22.50 mm	22.20 mm	22.60 mm
Cylindrical hole ad outer top part of the chimney		3.00 mm 7.00mm	2.00 mm 6.70 mm	2.70 mm 7.00 mm	2.40 mm 6.90 mm
Horizontal overall-length from bow to stern		60.00 mm	61.00 mm	61.50 mm	60.40 mm
Horizontal overall-width from port to starboard		31.00 mm	31.30 mm	31.10 mm	31.30 mm
Vertical overall-height from top to bottom measurement and top of the box		48.00 mm 15.50 mm	48.30 mm 15.50 mm	48.40 mm 15.90 mm	48.10 mm 15.70 mm
Cylindrical stern window diameter and flange's depth		12.00 mm 9.00 mm 0.30 mm	12.00 mm 9.90 mm 0.10 mm	12.70 mm 8.90 mm 0.10 mm	11.90 mm 8.80 mm 0.30 mm
High-cain spoon bow overhang angle to the horizontal plane		40°	44°	43°	38°

In terms of visual critics, the three benchys made from the three different recycled filament have a good structure, however there were verified some differences concerning each type of material. These printed benchys are presented from **figure 43 to figure 48,** where it is possible to visualize the benchys structures. Starting from the PLA benchy, it was probably the 3D printed artefact with the most concise in almost his entire structure, with exception of the chimney. This PLA benchy presented a good definition of all the boat details, with only small imperfections in some curvilinear boat structures. Concerning the PET benchy, it also revealed a concise definition of almost all the boat details with more clear imperfections in the structures which required a curvilinear movement from the printer. The ABS benchy also presented an interesting definition of the boat structure and details, however it was benchy with the most notable imperfection, which was verified in the stern window. Finally, the comparison between the real dimensions and the theoretical dimensions of the benchy revealed a good printing precision. It was verified only small differences from the theoretical measurement values, with almost every variation within the millimetric decimal magnitude. Thus, it was achieved a good printing precision using the best printing temperatures, for each recycled filaments, with the printing parameters selected in section 4.2.2.

Usability of the products

Regarding the usability of the arm cast, it was not accessed to tests with real people, since it was necessary to involve injured people and that requires other levels of bureaucracy. Thus, it was accessed to a research done by Fitzpatrick et al. (2017) on this printed arm cast, which tested the product and obtained some interesting feedback. The fit and the stiffness of the cast was considered excellent, however there were some concerns that proved space for improvement. The first and main concern was on the methods to closure the cast, which require a more robust and strength fixation and at the same time it needed to be thinner. Another problem was related with some restrictions in the ability to pinch and movement of the thumb. Finally, there was verified an interesting circumstance. The thumb joint diameter was not taken under consideration when modelling the product and it was not fitting well on the patient's hands. However, this problem was effectively solved by heating and soften the plastic, which allowed to modify the structure to widen the opening. This revealed the capacity to produce small modifications to the cast, which is not provided by the traditional methods (Fitzpatrick et al., 2017). Finally, as presented in **figure 49**, the 3D printed arm cast produced in this dissertation revealed a robust and clean geometry with the solid desired design. The product was tested to adapt to an arm of a children and it effectively responded to the arm adaptation desired format, as exposed in **figure 50.**

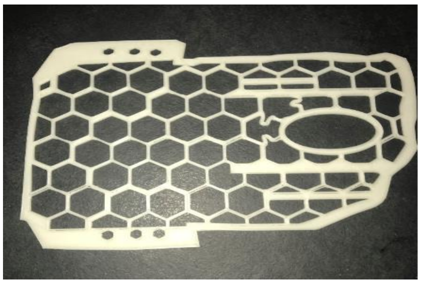


Figure 49 – 3D Printed arm cast with recycled PLA

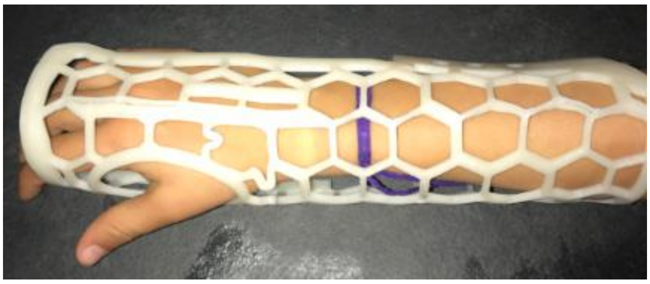


Figure 50 – Printed arm cast molded to a children arm

Regarding the usability of the fork and spoon support for disabled people, it was asked to a group of five users to perform three different tasks. The first task was to eat a soup with a spoon attached to the support. Thereafter, it was defined to the users eat a pasta and rice with a fork attached to the support. Finally, it was asked to users eat meat and fish with also using the fork in the support. **Table 62** presents the tasks assessed by the users and their success percentage.

Table 62 – Tasks assessed by the users and respective success rate

	Task descripition	Attached cutlery	Sucess
Task 1	Eat a soup	Spoon	100%
Task 2	Eat a pasta and rice	Fork	100%
Task 3	Eat meat and fish	Fork	100%

The feedback concerning the usability of the support given by the users was positive, with a fully successful task's performance. In general, the users described this support as comfortable robust product, with the potential to help disabled people. However, there are some aspects that need to be taken under consideration regarding this product evaluation. Firstly, unfortunately it was not possible to assess to people with hand mobility problems, which would give a more realist feedback on the product usability. Although, it was asked to the users to simulate as possible a hand mobility handicap. Secondly, the cutlery provided was of a unique size, and, given the numerous cutlery's designs and sizes, it seems important to develop an adapter to turn this support universal as possible. To conclude this overview on the support quality and usability, it is important to refer that the geometry of this support was not the most appropriate to work with PET filament as feedstock to the printer. As presented in **figure 51,** the support presented some imperfections in the geometry due to the accentuate curvature, which could be redesigned to a rectilinear shape. However, these imperfections did not influence the product usability performance and comfort. Thus, the PET filament seemed to be adequate to produce this product.

Figure 51 – 3D Printed support with recycled PET

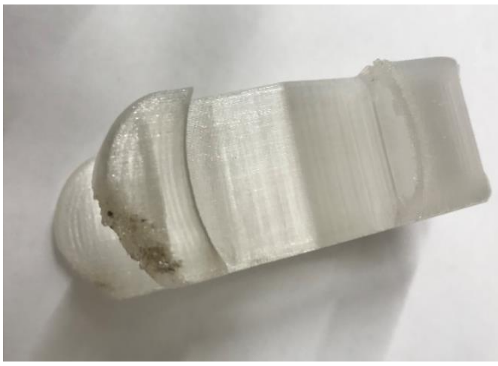


Figure 52 – Imperfections verified on the support

Figure 53 – Support with a spoon attached

Regarding the usability of the waterblock, it was asked to the users perform only the task of washing hands, as this is the unique purpose of this product function. This task was also performed with a fully successful rate, and, again, the feedback given by the users was truly positive. This product allowed users to wash their hands with a used plastic water bottle and, at the same time, saving water in this daily personal care task. However, there are some details, concerning the product design, that can be upgraded in this product. Firstly, it can be produced a complementing support to grab the bottle, allowing to attach a cable that makes possible to hang the bottle to any structure. Secondly, the necessity to drill a bottle lid is not interesting, since this product is directed to help people living with scarcity of resources. So, it seemed interesting to produce a bottle lid, already with this hole, making this product more functional and promoting its ease of use. **Figure 54** presents the product design, which presented an acceptable printing quality with negligible imperfections and, so, the ABS filament is adequate to produce this product.

Figure 54 – 3D printed waterlock with recycled ABS

Figure 55 – Waterlock with the soap attached

6.4 Conclusions

This chapter presents the final application of the research done to the recycled filaments, to the circular principles and methodologies studied and to the connection between frugal products and 3D printing. Firstly, it was selected three different products considered to be frugal. It was selected a 3D printed arm cast, fork and spoon support for disabled people and a waterlock to provide sanitary needs, such as wash hands. Afterwards, the type of plastic filaments to produce the products was decided. This decision to allocate the filaments to the products was based on two main aspects: the final applications of the products, which influence the type of loads that the products can be subjected; the mechanical characteristics of each type of filament. With this information, it was decided to produce the arm cast with the PLA recycled filament, the fork and spoon support with PET recycled filament and the waterlock with ABS recycled filament. To conclude this chapter, it is presented a quality assessment to the 3D printing quality of the recycled filaments and the conclusions taken from usability tests performed to the produced products. The three recycled filaments presented a good dimensional accuracy with the printers and printing parameters used in this dissertation. Regarding the products usability, although there was find space for improvement for each product, the usability tests revealed a good feedback from the experience of the users. Thus, this dissertation proved the functional feasibility and connection of an entire process, starting from recycling plastics to produce 3D printing filaments and ending with the production of frugal products with the recycled material.

7. Conclusions, Limitations and Future Work

This master dissertation presents in several aspects a possible innovative concept. Firstly, it exposed the necessity to improve the methods and resources to response to a critical situation currently affecting our planet, the poor plastic recycling rates. Secondly, with an extensive literature review it is provided quality information regarding circular economy principles, 3D printing industry and technology and frugal products. It was exposed the possible connections between these concepts, which can provide a convenient methodology regarding methods to recycle and reuse plastics, taking advantage of the 3D printing technology. Furthermore, this theoretical content was used to put into practice an opportunity to explore possible applications of recycled plastic material, using this innovative technology to the produce frugal products. The developed theoretical research alongside with the experimental research, provided a document that accomplished interesting objectives.

- The statement of the verified reduction of five important mechanical properties, triggered by the plastic recycled method and 3D printing technology.
- A functional interpretation of what the values of the approached mechanical properties define in terms of product mechanical performance.
- A mechanical resistance comparison between recycled ABS, PLA, two main types of plastics used in the plastic 3D printing industry, and recycled PET, one of the plastics that have the most armful impact on our ecosystems, which has recently raised the attention to explore it in the 3D printing industry.
- An analysis on the 3D printing temperature parameter, to provide information to define good setups to produce plastic 3D printed recycled products with the most reliable quality.
- A real demonstration of possible frugal products applications, based on the concepts studied and experimental data collected, proving the functional feasibility of an entire innovative methodology, which starts from recycling plastics and ends on producing frugal products using circular economy principles and 3D printing.

Although this dissertation can achieve its main objectives, some limitations, which were identified should be highlighted. Firstly, it was not possible test the support for disabled people with people which really suffer from this incapacity, which would be interesting to produce even more reliable conclusions on the product usability. Secondly, and following the same reasoning of the support, it was not possible to test the 3D printed arm cast with people with broken arms. Finally, given the wide range of concepts approached, it was not possible to the provide an entire analysis on all the material properties variations triggered by the recycling and 3D printing processes.

To conclude this master dissertation, it is important to mention possible future work on this research. To produce quality products, it seems important to explore other material variations, such as structure changes and the degree of contamination and traduce it into possible product applications. It also arises the possibility to combine different types of plastic to produce 3D printing filament, to understand if it is possible to take advantage of the best properties from each type of plastic, producing an even better recycled filament solution.

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Appendix A

Table 63 – Tensile Tests variables dimensions

Variables	Dimensions
W	13 mm
T	3,2 mm
A0 = W*T	41,6 mm
L	57 mm

Table 64 – Compression Tests variables dimensions

Variables	Dimensions
W	12 mm
T	12 mm
A0 = W*T	144 mm
L	12 mm

Table 65 – Torsion Tests variables dimensions

Variables	Dimensions
L	50 mm