Circular economy through plastic recycling process into 3D printed products: A frugal solution for schools

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Abstract

Plastic has a great number of benefits that have made it an essential material in our life, being one of the most used and produced materials around the world, over the past decades. In addition, its manufacturing is even going to increase in the next years. Consequentially, the fact of such a huge production is connected to an enormous waste generation. For this reason, it is important to take care of the environment through a green concept, circularity and recycling besides alerting the population in order to become aware of this problem and to change bad habits.

Circular Economy has emerged as one of the main concepts that can bring solutions on this matter enabling the reduction of the environmental damage. Therefore, 3D printing has emerged as one of the most scalable technologies to implement the concept of circular economy.

On the other hand, a successful solution must be affordable in order to encourage to develop these new practices. Within this context, it has emerged Frugal Innovation which intends to provide good results facing financial or operative restraints.

The goal of this Master dissertation is based on circular economy concept through plastic recycling (PET bottles) into 3D printed products in a scholar demonstration. Methodologies are employed with frugal concept as reference, trying to offer an inexpensive solution. Most of the difficulties come from extrusion and filament quality while some of the main results obtained are: avoid glue, take into account the appropriate parameters of the extruder or add a cooling system.

Keywords: Plastic Market; Plastic Recycling; Circular Economy; 3D Printing; Frugal Innovation

Abstrato

O plástico tem um grande número de benefícios que o tornaram um material essencial em nossa vida, sendo um dos materiais mais utilizados e produzidos em todo o mundo, nas últimas décadas. Além disso, sua fabricação vai aumentar nos próximos anos. Consequentemente, o fato de uma produção tão grande está ligada a uma enorme geração de resíduos. Por esse motivo, é importante cuidar do meio ambiente através de um conceito verde, circularidade e reciclagem, além de alertar a população para tomar consciência desse problema e mudar maus hábitos.

A Economia Circular emergiu como um dos principais conceitos que podem trazer soluções sobre esse assunto, possibilitando a redução dos danos ambientais. Portanto, a impressão 3D emergiu como uma das tecnologias mais escaláveis para implementar o conceito de economia circular.

Por outro lado, uma solução bem-sucedida deve ser acessível para incentivar o desenvolvimento dessas novas práticas. Nesse contexto, surgiu a Inovação Frugal, que pretende proporcionar bons resultados frente a restrições financeiras ou operacionais.

O objetivo desta dissertação de mestrado é baseado no conceito de economia circular através da reciclagem de plásticos (garrafas PET) em produtos impressos em 3D em uma demonstração acadêmica. As metodologias são empregadas com o conceito frugal como referência, tentando oferecer uma solução barata. A maioria das dificuldades advém da qualidade da extrusão e do filamento, enquanto alguns dos principais resultados obtidos são: evitar cola, levar em consideração os parâmetros apropriados da extrusora ou adicionar um sistema de refrigeração.

Palavras-chave: Plastic Market; Reciclagem de plástico; Economia circular; impressao 3D; Inovação Frugal

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1. Introduction

1.1 Background and Context

These days we have plastic as one of the most used materials. This happens due to the combination of great properties such as lightweight, being inexpensive and a high versatility in different applications. These features led to a rapid increase of their usage in the past half-century and even the prevision for the next 20 years is to duplicate (MacArthur, 2016). However, it exists an important disadvantage: plastics products are characterized for being waste after a short first-use cycle which means disastrous ecological problems. Plastic packaging is a remarkable application because after a single use only 5% of material value is retained for a subsequent use which results a loss between 80-120 billion USD per year. This is due to the plastic escaping from recycling systems besides the value losses in sorting and reprocessing. In addition, the production of such amount of plastics is connected with greenhouse gas emissions (MacArthur, 2016).

Due to the catastrophic consequences that the production of plastic has reached, new methodologies and technologies should be developed in order to improve the current practices and to promote a sustainable world. Related to this change, Circular Economy as emerged as one of the concept that propose a beneficial alternative way with the purpose of minimizing both natural resource utilization and pollution emission (Wu et al., 2014).

Additionally, new technologies have arisen to support circular economy in order to do this practice successful. 3D printing is a technology which has the tools to enable a reduction of cost and plastic waste as well offering versatility and being able to attain customers' demand (Berman, 2012). This technology has demonstrated to be able to extend the life cycle of the product , which it promotes new business models. 3D printing unlock value in Circular Economy because the production of product through plastic waste is an efficient and cost effective practice (Despeisse et al., 2017).

What's more, relating to the idea of reducing material and resources it has also emerged the concept of Frugal Innovation which intends to produce quality products but with financial spending restraints as well (Tiwari and Herstatt,2012). In this way, this concept is gaining importance to afford good solutions with reduction cost. In addition, frugal innovation is gaining importance if the project is expected to achieve is for an organization cannot do great expenses, for instance in the case of a project for schools. The different processes should be easy to manage and sustainable so adapted this concept is quite relevant.

This Master dissertation intends to interconnect the aforementioned concepts by proposing a frugal solution that encompasses from the collection of PET bottles, going through all the processes to make recycled filament until finishing by printing a product. This study aims to research and asses a viable and sustainable solution with the purpose to make demonstrations for scholars without many financial resources, where they can see the full cycle.

1.2 Problem Characterization

Researching about background and context of plastic material have proved that it is necessary to find solutions to improve the current situation. For this reason, having circular economy as reference it is proposed a solution based on a process of full cycle, what is means to start in the first stage (plastic waste collection) and after some operations, extract value of the waste by making a product, which is the final stage. This product could be discarded as well and afterwards the cycle would start again from the first step, saving resources compared to making new products. .

This concerning issue about the plastic production growth, plastic waste consequently, should be known by people as well as being aware of alternatives of circular economy and new technologies capable of solving the problem.

Alerting the population is a key factor in creating a more sustainable world. Therefore, it is important that children assimilate the concept and making demonstrations on which they can look what Circular Economy is based on, it would facilitate their understanding. As this type of demonstration will be accomplished by schools, it requires frugal solutions in order to be affordable. It is for that reason that it necessary to know what is the best technology taking account the restraints that proceed from a frugal solution and offering the highest possible product quality.

1.3 Problem Objective

The target of this project is interconnected the concepts of circular economy, frugal innovation and 3D printing with the purpose of raising awareness to children about the concerning topic of discussion, by reusing PET bottles (plastic waste) to produce filament which will be used in 3D printing. This filament will be made after several stages such as washing, shredding or extruding. Therefore, this project also aims to provide a complete theoretical basis on the concepts evolving the characterized problem to support the development of a methodology and to assess the technologies that provide a solution .

1.4 Project Structure

The following structure represents the study developed in this project. Chapter 2 presents a complete research of the context of plastic market because it is necessary an understanding of the situation and background of the topic is being dealt. Chapter 3 provides a state of the art on circular economy besides of incorporating the frugal innovation concept. Both concept will be related with the object of study of this Master dissertation. In addition, it also researches about the technologies and processes employed during the development of the solution. Chapter 4 presents the adopted methodology of each stage to reach the objectives. In Chapter 5, the results obtained during the project development were presented in detail. Finally, these results will be discussed and more information will be provided in the appendixes to support the conclusions.

2. Plastic market

This chapter introduces a general summary of the plastic context: Plastic market and plastic features. The first following section (2.1) is going to present the current situation of plastic production. It will show the advantages of this material as well as researching that packing is his main demand and China is the main world's leading producer. Besides, the following section (2.2) explains the context about recycling, including the different techniques used , the evolution of recycling over the years, balance of plastic production and definitively all related like best practises, benefits or market conditions demanded. At the end, last section (2.3) shows the idea of a project for schools and its solution .

2.1 Plastic market context

This material presents unrivalled advantages which make it special because it can be used in several applications. Their flexibility to adapt to the characteristics that the different products request, and a low price are the main benefits to become plastic as one the most used materials. Some of their applications range from the food industry, protecting and preserving the food, furniture or devices, batteries and even refrigerators, washing machines or iron (UNEP, 2014).

Plastics are those materials that, composed of resins, proteins and other substances, are easy to mould and can modify their shape permanently from a certain compression and temperature. As it is derived from different substances each one owning different features it is possible to create varied of products by the combination of them and treatment or additives which can modify their characteristics. In addition, it is remarkable to explain that each polymer type could be branched into a lot of subtypes which they can offer abounding different alternatives for use in explicit applications (Britannica, 2018).

The fantastic features that plastic possesses besides of being a really affordable material, have made plastic an overused material these days. Therefore, a plastic usage growth reports consequently a greater amount of plastic waste. Production estimation is not hopeful what is means not having a sustainable world. In fact, we are currently unable to cope with the amount of waste we generate, only a small fraction is recycled and around 13 million tons of plastic is dumped into the oceans. His versatility combined with a low acquisition price leads to a competitive advantage of this material comparing with the other ones used in similar applications and explains why plastics are growing into the market share so quickly. Besides, if consumption patterns and current management practices continue, by 2050 there will be around 12 billion tons of garbage in public spaces and the industry of this polymer will consume 20% of global oil production(UNEP, 2018). Over the last 50 years the plastic production has suffered a growth from 15 million tonnes (1864) to 311 million tonnes (2014) and it is expected to double in the next 20 years being plastic packing the largest application with almost 26% of the total volume (MacArthur, 2016). The main negative consequence of their production is that normally plastic products have a short life and an intensive use combined with non-degradation which cause disastrous problems to the nature. As the ENVI Commission of the European Union affirms: "*The solutions involve finding durable, reusable plastic materials that allow high-quality recycling*" (European Commission, 2018). Besides, the oil dealers emit greenhouse gases (CO_2) due to the combustion in the boilers that also result on devastating ecological problems which is a burning issue as well.

Due to the considerable growth of plastic production by the reasons explained previously, the management of that huge amount of waste is becoming in an environmental threat all over the world. There are several possible options that are able to be taken at the end of lifecycle like reusing, recycling, incineration or dumped (UNEP,2018). In Figure 1 it is showed the remarkable increase on plastic production over the last decades.

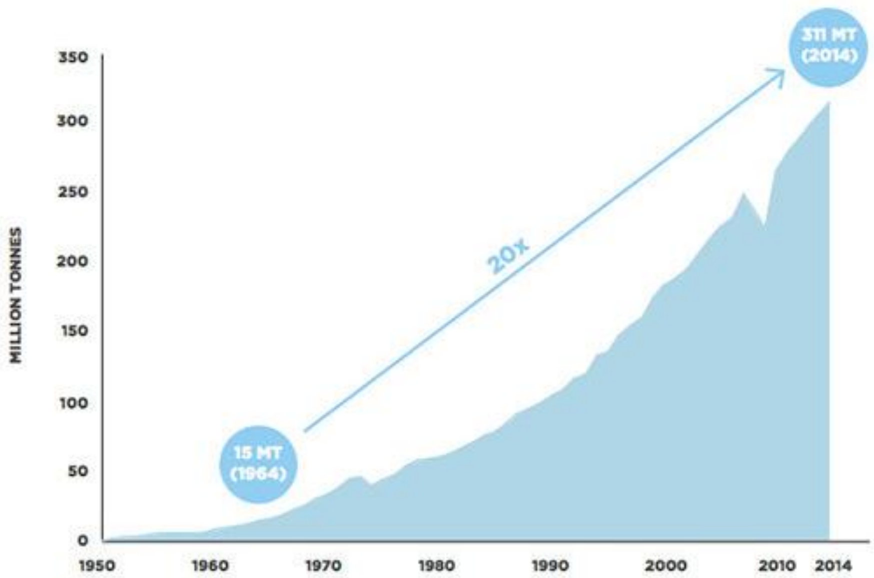


Figure 1 - Growth in plastics production worldwide 1950 - 2014 (PlasticsEurope - the Facts 2013)

For these matters, what we concern is to find solutions, to develop new technologies and define sustainable operations which circular economy is able to minimize production costs and serving efficiently an intensive demand because continuing as these days, our natural resources are not able to sustainable so amount of plastic. Countries have put efforts in government programs to achieve good recycling performances but most of them are still below the targets.

The following Table 1 represents a forecast of plastic volume growth and other externalities. Nowadays, it is leaked into the ocean 8 million tonnes of plastic every year and the expectation is quadrupling that amount by 2050 there being disastrously more tonnes of plastic than fish into the ocean (MacArthur,2016). The production of plastics come from fossil feedstock which over 90% of them are derived from virgin material and it represents about 6% of global oil consumption these days. If no action is taken, the plastic sector will represent a 20% of total oil consumption. Besides, there is a concept called carbon budget whose meaning is the amount of carbon dioxide that a country, company or organization must adhered to in order to achieve the common goal proposed by the committee on climate change to stabilise the global warming and just the plastic sector will account for 15% of global annual carbon budget by 2050.

Table 1. Forecast of plastic volume growth, externalities and oil consumption (MacArthur,2016)

	2014	2050
Plastic production	311 MT	1,124 MT
Ratio of plastics to fish in the ocean (by weight)	1:5	>1:1
Plastics share of global oil consumption	6%	20%
Plastics share of carbon budget	1%	15%

On the other hand, to understand the whole plastic context it is necessary to know the share of the total plastic production that corresponds to each market section. Figure 2 represents graphically how the plastic market is composed in Europe.

Figure 2 - European plastic demand divided by sectors in 2015 (PlasticsEurope (PEMRG),2016)

As shown in Figure 2, the European packaging applications represents almost the 40% of the total plastics demand, which is the largest share of the plastics industry. The second largest application sector corresponds to building and construction with a share of almost 20% over the total European demand. The next one is the automotive sector representing 8,9% of the total plastic demand. It would be followed by electrical and electronic applications with a share of 5,8% of the total demand and the last one which is not showed in the graphic, corresponds to agricultural applications with around 4%. Finally there are other applications like furniture, household and consumer products which includes all the European plastics demand remaining. Moreover, the six larger European countries cover almost 70% of the European demand in 2015 (PlasticsEurope, 2016).

Last but not least, it is important to know how plastic production is distributed around the world to understand the context of the current plastic market and conserve a big image about the leading producers. The distribution of global plastics production is illustrated in Figure 3, which includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives and PP-fibers.

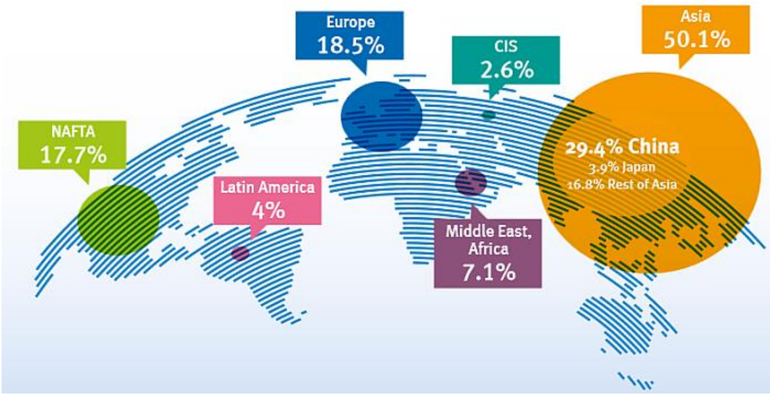


Figure 3 - Distribution of plastic production worldwide (Plastics the Facts,2018)

The world production of plastics in 2017 reached 348 million tons, 3.8% more than in 2016 being Asia the major producer with a 50.1%. In that region, it is important to highlight the leadership role played by China, which accounted for 29.4% of world production and leaving Japan in second place with 3.9%..

2.2 Plastic recycling context

Humans try to imitate natural polymers with synthetic polymers making up of repeating atoms connected to each other with covalent bond to form a long chain with some main characteristics such as durability, light weight, and low cost (Hopewell J. et al.,2009).

There are three types of polymers: elastomers, thermoplastic polymers, and thermosetting polymers. Elastomers are rubbers or rubber-like elastic materials. Thermoplastic polymers are hard at room temperature, but on heating become soft and more or less fluid and can be moulded. Thermosetting polymers can be moulded at room temperature or above, but when heated more strongly become hard and infusible (Gaurav S.Kulkarni, 2018).

Related to the fact that a product be easily recyclable, what's more important to know is that thermosetting polymers are not able or at least is more difficult to recycle, remould or reform due that their strong cross-linked structure shows resistance to higher temperature, which provides greater thermal stability than thermoplastics.

Plastic recycling technologies are divided generally into four types: primary, secondary, tertiary, and quaternary (Gaurav S. Kulkami, 2018) :

1. First group involves processing of a scrap into a product with almost the same characteristics than the original product.

2. Second type tries to process waste/scrap plastics into materials with different characteristics from those of original plastics product.

3. Tertiary recycling involves processing plastic waste of segregated waste or municipal waste stream into basic chemicals and fuels from plastics.

4. Last group uses the burning/incineration to retrieve the energy content of waste/scrap plastics.

Table 2 represents some valuable information about thermoplastic recycling. This table is divided into sections with the different kind of resins, whose recovery rate is shown. Besides, it provides other extra information such the applications where you can find this material or characteristics they possesses, some of them related to its recycling ease.

Table 2. Types of plastic, percentage recycled (2018) and common applications for the recycle (Gaurav S. Kulkami, 2018).

Resin	**Recovery Rate**	**Applications of Recycle**	**Extra information**
PET	27%	Fiber (clothing, carpet), film (balloons, packaging, thermal sheets, adhesive backing), bottles (pop, water), cosmetics packaging and food containers.	Clear, strong and lightweight.
HDPE	31%	Non-food containers (laundry detergent, shampoo, conditioner, and motor oil bottles) plastic lumber, pipe, buckets, crates, flowerpots, film, recycling bins and floor tiles.	Stiff and hardwearing; hard to breakdown in sunlight

PVC	3%	Packaging, loose-leaf binders, decking, panelling, gutters, mud flaps, film, floor tiles and mats, traffic cones, electrical equipment, garden hoses and mobile home skirting.	Can be rigid or soft via plasticizers. Often not recyclable due to chemical properties.
LDPE	7%	Shipping envelopes, garbage can liners, floor tile, plastic lumber, food wrapping film, shopping bags, compost bins, dry cleaning bags and trashcans.	Lightweight, low-cost, versatile. Failure under mechanical and thermal stress makes it hard to recycle.
PP	18%	Automobile battery cases, signal lights, brooms, oil funnels, brushes, ice scrapers, condiment bottles, margarine containers, yogurt containers, bicycle racks and rakes.	Tough and resistant; effective barrier against water and chemicals. Often not recyclable.
PS	2%	Thermometers, light switch plates, thermal insulation, egg cartons, vents, rulers, license plate frames, foam packing, take-out food containers and disposable cutlery.	Structurally weak and easily dispersed. It is rarely recycled.
Other	2%	Polycarbonate (refillable plastic bottles, metal food can liners, consumer electronics, lenses); nylons (clothing, carpets, gears); biodegradable resins (food and beverage packaging); mixed plastics and blends (electronics housing, plastic lumber), etc. Particularly in engineering sectors .	Diversity of materials risks contamination of recycling.

Once explained the plastic recycling market by types of plastic, it will be important to take into account how the plastic management context is working and the evolution that it has suffered. Earlier than 1980, it did not exist recycling and incineration being the total of the waste discarded. From 80's it started to change for incineration, and 10 years later for recycling, with an average growth of 0.7% per year each one reaching these days the highest values with a 25.5% and 19.5% respectively. What's more, if this trend continues in the same way the extrapolation would result reaching 50% of incineration rates, 44 per cent in recycling and residual 6% of discarded share by 2050, but this is just following the same tendency (Geyer et al., 2017).In Figure 4 is showed the global waste disposal from 1980 until 2015.

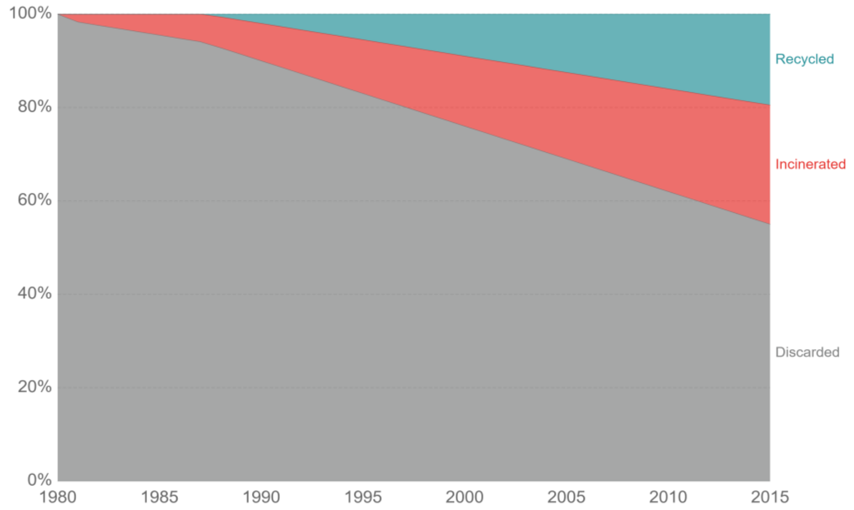


Figure 4 - Estimated share of global plastic waste by disposal method (Geyer et al.,2017)

Extending the previous explication, since 1950 8.300 million tonnes of polymers, synthetic fibers and additives have been produced, which almost a third part of the primary plastic production is still in use. Figure 5 below represents in detail a comprehensive global flow of the cumulative mass of plastics over the period 1950-2015, measured in million tonnes.

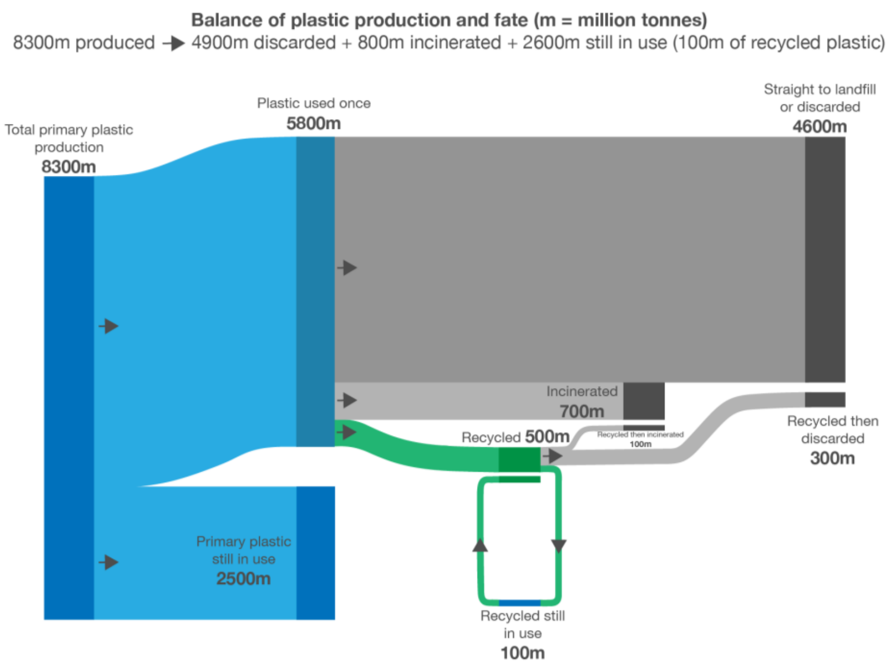


Figure 5 - Global plastic production and its fate 1950 - 2015 (Geyer et al., 2017)

On the other hand, plastic packaging is a remarkable issue due to its large share of production. These days, the 95% of plastic packaging material value or what is the same as $80-120 billion annually is lost to the economy after a short use and only 14% of plastic packaging is collected for recycling (MacArthur, 2016). The majority of recycled plastic is used for lower-value applications and their life is over after that use. Figure 6 below represents the previous explication and it shows as just a little part of the global plastic is collected and furthermore, from this plastic packaging the value yield is still low.

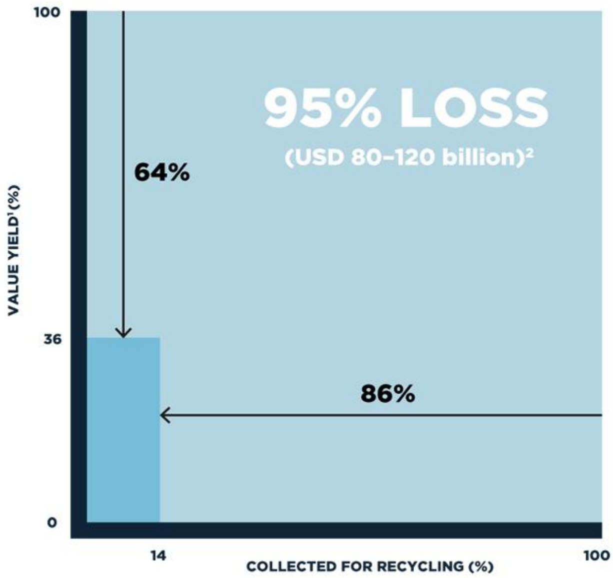


Figure 6 - Plastic packaging material value loss after one use cycle (MacArthur, 2016)

The recycling symbol was launched more than 40 years ago and only 14% of plastic packaging is collected for recycling, being this number a very low value. Despite being an alarming fact, the recycling rate for other plastic applications are even worse. The highest recycling rate comes from PET, a plastic used commonly in beverage bottles, but is still reaching only 50% of the global produced (MacArthur, 2016).

A part from the 14% of total packaging plastic production collected for recycling, there is other 14% from the total packaging plastic waste which is incinerated and/or converted into energy recovery process. These processes are quite good but they have some disadvantages such as losses of embedded effort and labour when the material is going into creating before combustion. Moreover, there is a shocking fact that 72% of plastic packaging is not recovered at all whose landfilled litter's share represents 40% and leaking out of the collection system is the remaining 32% (MacArthur,2016) .If we compare the three key options for handling plastic waste such as recycling, incineration or disposal in landfill, the best option from an environmental perspective is recycling because it has the lowest global warming potential and energy use. However, the problem is that plastic usually can be recycled for once or twice and finally it will end up in the others options. In addition, it results very difficult for recycling industry to compete with making new plastics when oil prices are low because oil is used as raw material and recycle could not be affordable in terms of money. Therefore, Figure 7 shows a comprehensive overview of global flows of plastic packaging material which represents the aforementioned information by classifying the total packaging plastic production into their practices employed concerning the management of plastic waste.

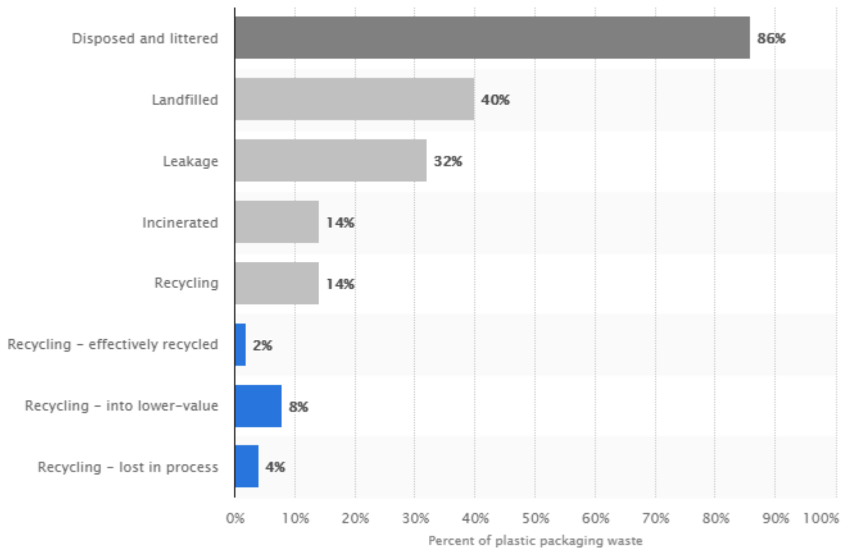


Figure 7 - Flow of plastic packaging waste worldwide in 2015 (McArthur,2016)

2.3 Project for schools

The project focus on the valorisation of waste through 3D printing technology to convert useless waste into value product. The conversion from plastic waste until a final product is made is not direct and, to achieve that, a series of operations will be developed as well as its implemented technology. There are several operations with the purpose to adapt the material to the requirements. Section below will describe the solution which is based on a full cycle divided into several operations.

By order, first phase is waste collection of plastic bottles where the plastic waste is carried into installations and then labels are removed. Apart from labels, it will also be assessed if is mandatory to remove the parts of the bottles containing the glue used to fix the labels. Besides, the volume of PET bottles should be reduced to the hopper size of the shredding machine, therefore, they are cut manually into smaller pieces. Afterwards, the shredding machine will be in charge to become these small plastic pieces into flakes whose size will be in connection to the employed bottom sieve. As the extruder requires a feed of feedstock with a specific size, it is necessary the cutting mill to convert and mill products into very small granulates.

Second process, washing will take place in the laboratory whereas sorting the PET material from others will be done as well in the station called plastic waste washing and sorting. This intends to improve the quality of the material by eliminating remaining dirt during its use and to separate the material is wanted to work, PET resin, from others. As after washing the flakes remains too wet, next station would be to dry this material as much as possible in order to have suitable feedstock for next stages due to deal with moisture is always a disadvantage.

Then, there is a phase called plastic waste extruding where pellets are molten into a machine and passed through an extruder which produces suitable filament for 3D printing. This process should be taken into high consideration cause it is highly connected with the quality of the printed product. Next phase is 3D printing where that filament elaborated previously is used now as feedstock for making new products. Finally, these products which are produced after several stages and show to children one solution of the circular economy, ends the circle with the valorisation of the plastic waste and the insight of the circular concept as reference. Figure 8 represents the closed cycle that it is created in the project.

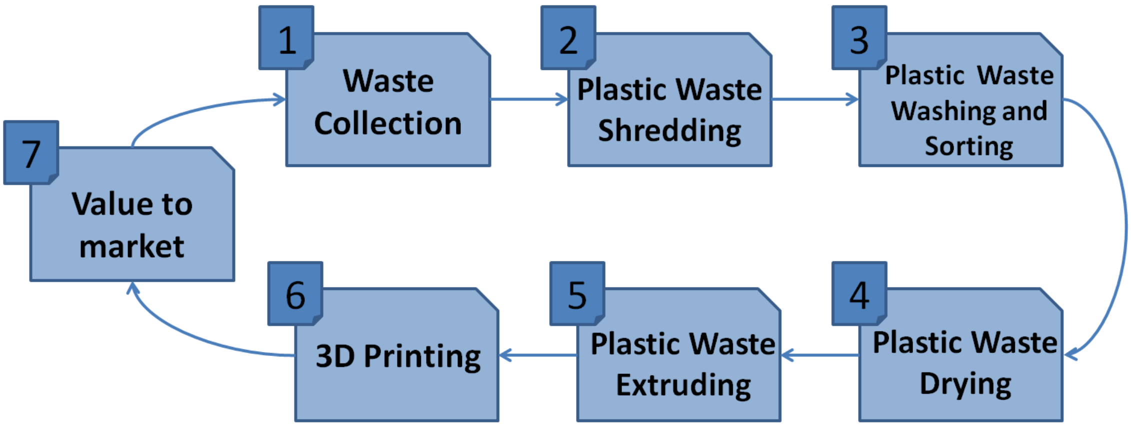


Figure 8 - Flow of the general process of the project's solution

The target of this project is to teach to children the circular economy concept in both entertaining and interactive way. Suitable activities for children and good demonstrations of taking profit of the waste which these days it is usually discarded and useless, it will become us aware and knowledgeable with the culture of recycling and care of the environment from an early age.

This project for schools is based on a closed loop which from PET bottles and going through a series of activities, it can be created some specimens made of this plastic waste. It would allow that the waste generation be back into value products, at least, in terms of making demonstrations and showing a final product which represents the circularity of plastic. Therefore as it is focused on schools, the solution must be affordable with no many financial resources because the funds at its disposal for a complementary activity are few. It is necessary to be appealing for schools to participate in this kind of demonstrations as well as being convinced that this type of activity is beneficial for the society and will help to create a more prosperous world. This project is needed to know the required tools to accomplish the objective, how is possible to introduce the technology that is going to employ in each of the stations and to understand, what method must be adapted. Apart from proposing a different solution of the circular economy concept the project will arrange all the matters that encompass if you want to develop it.

It has appeared as a solution in circular economy where plastics are used in some applications and afterwards, it is intended to integrate again in the market. Therefore critical points have to be identified and studied in order to know how to avoid them and find out if the conversion in second-use products could be sustainable. What is more, it should be studied the implemented technology as well as the know-how of the different processes and the technical requirements.

What refers to technology, the major complexity will be in the final stages using more complex machine such a extruder or 3D printer where a previous background is required in order to be able to use them.

2.4 Problem

As it has been explained throughout the Chapter 2, the massive growth of plastic production is matched as an intensive waste disposal as well. In addition, forecasts do not improve the current situation because world has become dependent of this material being plastic the most used worldwide. Nowadays, the damage caused to the environment is unsustainable and a huge quantity is leaked into oceans or other natural areas destroying their ecosystem. An ecological way of recycling the plastic waste should be found. To achieve that goal, a lot of countries have established some rules such as the concept of carbon budget, campaign of "Clean seas" and the global recycling symbol. Currently, the share of landfilling or discarding after a plastic first-use is too high and they should become in other treatments like incineration, reusing or recycling. For these reasons , circular economy's concept has gained importance and it intends to integrate the plastic more than one simple use in our lives. To fulfill the goals is necessary a cultural change in our society and improve the habits since we are children. In this way, education will take a key role making it essential the incorporation in schools of activities and teachings related to recycling. In order to incorporate these activities to schools, it is important to think the best way to include the circular economy of plastic waste through activities which should be affordable both financial resources and safety issue. As they are demonstrations for schools, the quality of the final product does not need to be too high. What is more, the different implemented processes should be performed with a small budget because as we know, schools do not have the same financial capacity as for example large companies, and it would be unattainable to realize the activity. In addition, one of the principles of the work is the interaction of the children to involve them in the project and that they are more interested in the topic we are dealing with. Therefore, processes will be realized with cheap material and easy to handle even for people with no knowledge of the subject. It should be taken into consideration these difficulties with the purpose to face them and to find inexpensive solution without great complexity. The focus of this study is to reduce plastic waste related to beverage bottles and give children the opportunity to create plastic specimens with 3D printers through the entire chain since we drink and use those bottles until they can see a final result in those objects created.

2.5 Conclusions

This chapter is mainly referred to a global overview of plastic market worldwide. It is subdivided in parts such as plastic market context, plastic recycling management and full cycle. Each part tries to provide a complete insight of this world identifying how it works and how we reached to the current situation. First part highlights the enormous evolution that world has suffered due to the massive production of products made by plastic being Asia the most global producer (China concretely) and, according to the largest EU share of plastic demand, packing is the number one representing almost the 40% of the total plastics demand which requires a deeper focus. Gaining awareness of the problem, it results unavoidable to research the plastic packaging flow and the other applications and taking account the global waste management. For these reasons, it is recommendable to know what could we do against the applications that produces more waste and moreover, which is the type of polymer used , because some of them present difficulties for a second-use. The goal is to identify the main characteristics of the plastics and where they are used according to achieve a green world as much as possible. Finally, sustainability should be tested and analysed in order to get successful implementation in final applications with the recycled plastics. In our case, it is dealing with the whole chain which includes all the processes necessary to produce plastic objects from discarded or unusable bottles. The purpose is to characterise the different processes in order to determine the best conditions to obtain good results, at least the manufacture of small specimens, and that in turn are feasible in a cheap way and without a high technological level. It is relevant to highlight that for a further successful implementation of the technologies used, children should be able to perform the different tasks with a global view in understanding the circular economy concept.

3. State of the art

This chapter will highlight the circular economy concept as the main focus by analysing methodologies and key points to apply the concept successfully. Besides, it will also illustrate how is composed the circularity and which considerations it should take account in the different perspectives and strategies taken to increase the scale, which it converts more or less circular level (section 3.1). On the other hand, section 3.2 will be based on a comprehensive overview of frugal innovation concept as well as the evolution of its definitions. This concept will be interconnected to circular economy and to the operations of the solution. Finally, this chapter will be concluded with descriptions of the several operations for plastic in circular economy, especially in the case of the project for schools mentioned during the previous sections. The ending aim of this research is to find sustainable methods to reconvert the useless plastic waste into value products. In this case, the product analysed will be the filaments used in 3DP which needs some particular characteristics and conditions in their manufacturing to achieve quality products. (section 3.3).

3.1 Circular economy

It is being generated a great amount of plastic waste which causes a big impact in our environment. For this reason, it is essential to prevent and minimize as much is possible the damages that waste can cause. It is also mandatory to think how we can formulate new methodologies and technologies in order to achieve the goal: to maximize the value chain of products and services (Despeisse et al., 2017).

Therefore, it is essential to integrate Circular Economy (CE) in our daily life. Different authors proposed different definitions of CE, however they are quite similar in their core. This concept intends to break the old linear model. Where the material is extracted followed by production and used for the customers, and finally, dumped. This flow model conducts to an unsustainable economic, social and environmental model (Frosch and Gallopoulos, 1989). Appropriately, circular economy tries to change the traditional system by a beneficial alternative way which is recognised for being regenerative and cyclical (Geissdoerfer et al., 2017).

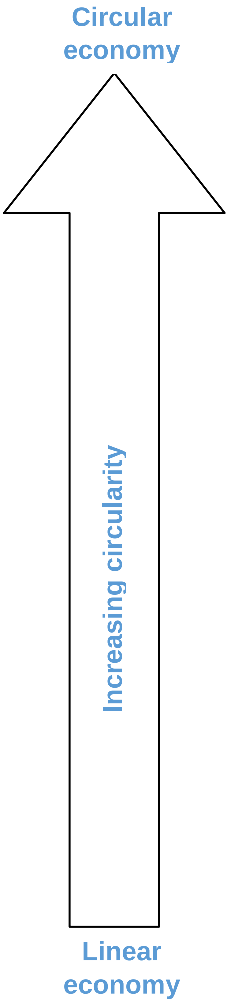
According with the wide range of scientific disciplines there are a big collection of concepts based on different fields such as industrial ecology, industrial ecosystems, cleaner production, the concept of zero emissions or others. For instance, Circular Economy could be defined as a purpose of achieving the ideal production by minimizing natural resource utilization and pollution emission as well, resulting a low amount of waste due to recycling and reusing (Wu et al., 2014). Other author express that Circular Economy has as a goal from the design to maintain products and materials at their highest utility and value by preserving natural capital and optimizing resource yields with a positive cycle and renewable flows (Moreau et al., 2017). Alternatively, CE could also be defined in economics' terms as a strategy that through the use of innovative ways it transforms the actual linear system of consumption into a circular one achieving sustainability with the material savings (Singh and Ordonez, 2016).

It is easily testable that CE has become trending these days because the growth of reviews is unstoppable from 2014 to 2016. The number of papers related on CE has more than triplicate (Geissdoerfer et al., 2017). However, most of the authors agree that this concept refers to a strategy of preserving the natural resources by establishing a restorative and regenerative system, which minimizes the material losses from the recycling, reusing and recovering.

A systematic assessment of definitions requires a coding framework with such a framework showing "*how verbal or visual data have been converted into numeric data for purposes of analysis*" (Bourque , 2004). Coding dimensions were being added throughout the coding process and it will be related to the core principles, aims and enabler (Dahlsrud , 2008). The first R framework was based on 3R's which simply refers to reduce, reuse and recycle. Besides, it was added a fourth principle used in several definitions and in the core of the European union framework directive as is 'Recover' (European Commission, 2008). Moreover, this R framework have been evolving from the most simple one until incorporating other new principles, that firstly it was the common 6R's and lastly, author refers to 9R framework which is the one with the most shading. In spite of this variety, all of them are characterised for sharing the core of their structure which is the first 4R's including 'reduce' (Potting et al. , Sihvonen, Ritola, van Buren, 2016)

In Table 3 illustrates the 9R framework showing all their principles with their respective meanings. As we can see, the gradations of circularity also clearly highlight that recovering energy from materials through the incineration of residual flows, is the final option for extracting value from resources. Originally, it was applied the linear economy where raw materials were removed and after a single-use it ended in waste material. Consecutively, a higher level based in recycling and energy-recovery is an economy with feedback loops where the loops are still not closed and raw materials continue entering as well as the generation of residuals. Lastly, the core of the circular economy is based in being more independent of raw material for production of goods and it tries to reduce the environmental damage produced by the huge residuals. Moreover, CE is an economic system on business models that through the principles mentioned before such as reducing, reusing, recycling and recovering materials in production and consumption processes, it has originated the replacement from the 'end-of-life' concept to a update one which intends to create economic prosperity, environmental quality and social equity (van Buren et al., 2016)

Table 3. The R9 Framework (Potting et al., 2017)



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore and old product or its parts in a new product with a different function
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

On the other hand, CE can be divided into three different perspectives according to their scale. Regarding the softest point of view micro-systems refers to the circularity of products, processes, companies and consumers. It follows a meso-systems level which emphasizes the importance of eco-industrial parks as systems in local stage and besides that, there is the biggest operated scale, called macro-system level, referred to modify the industrial composition and structure of the entire economy (regions or cities) as a target (Kirchherr et al., 2017). Besides, some performance indicators are used as being a vital part of quality management and essential for implementing and driving effective quality management. They are very useful because reflects measure achievement, reflect the changes associated to a performance and provide a comprehensive image of the CE's situation, allowing to determine the intervention of a development actor (Wisse, 2016). They have the capacity to highlights, focus and condensate the lack of simplicity of the changing environment. The European Environment Agency (EEA) categorised these indicators into 5 groups: 1) The descriptive indicators, which encompasses some variables and express values in an absolute scale such as state, pressure or impact. 2) The performance indicators which uses the same variables that the previous one but it measures how far we are until our goal. 3) Efficiency indicators that provide information about how good products and processes are running. 4) Policy effectiveness. 5) Total welfare indicators which asks *'Are we, in general, better off?'* (European

Environment Agency,2017) . Despite this classification there are other authors who proposed a different set of indicators. (G. Moraga et al., 2019)

This concept means to use the extracted raw materials as many times as possible by avoiding to end them up in a dump, but in a new product. This transition reports great potential for both the environment and enterprises due to get more value out of less by increasing recycling rates and using less materials. Moreover, government's plan of action should incorporate initiatives to support the transition to a more circular economy in order to pursue the 17 UN Global Goals. The following initiatives are proposed by the Danish government (The Danish Government, 2018):

- Strengthen enterprises as a driving force for circular transition. For instance, promoting circular business development and implementation in SMEs or expanding the access to financing these models.
- Support circular economy through data and digitalisation. Big Data and others economy platforms will provide valuable information to enterprises such a material flow or consumption.
- Create a proper functioning market for waste and recycled raw materials. To ensure high-quality recycling what it means that creates the lowest possible environmental burden and the highest value.
- Better design, new business models and innovative products that offer more sustainable consumption patterns.
- Get more value out of building. For instance, propagating selective demolition which separates the valuable parts of the waste

It is mandatory to take into consideration which will be the sustainable ways to implement the methodologies to establish successfully the CE principles in production processes, where one of their main shortcomings is the closing existing material flows. The aim is to implement a successful business model and aiming at keeping products at their highest utility and value always, preserving and enhancing natural capital by controlling finite stocks and balancing renewable resource flows, optimizing resource yields by circulating products, components, and materials and finally, promoting system effectiveness by revealing and designing out negative externalities (MacArthur, 2015). To achieve the desire target, it exists three types of re-design processes in order to consider barrier and prerequisites to establish the mentioned goals: one is the re-design of the provided services, considering necessary changes in the roles of products, users, service and infrastructure ; the second re-design is performed of the value chain relations up-stream to suppliers and down-stream to customers and users whereas finally is the re-design of internal business organization considering necessary changes in tasks, competences, structures and technologies (Michal Jorgensen, 2018).

A part from the benefits gained on the environment, circular economy will also contribute to economic growth and once it is completely implemented, CE will promote high value cycle instead of recycling only for low value raw materials (Ghisellini et al., 2016) which it could boost Europe's resource productivity by 3 percent by 2030, generating cost savings of €600 billion a year and €1.8 trillion more in other economic benefits (Mckinsey, 2017). Next chapter will introduce the frugal innovation's concept which is the basis to start with CE. This concept will try to find high-value solutions, but above all, without spending a lot of money on their development and optimizing resources to the maximum. After frugal innovation is developed, surely increase its scale and markets will be more focused on more complex and larger products.

3.2 Frugal Innovation

Frugal innovation was created as an idea of developing high-value solutions without many financial resources. It has begun to exploit its business applications and disruptive potentials (Rao, 2013) but it is still in an embryonic phase and the definition differs depending on the author. In addition, achieving solutions under limited resources, there are many papers that they have been published on similar concept than the previous mentioned. In spite of the different meanings that could have, everyone agree that this challenge wants to introduce something new or different (innovation) as well as saving financial resources (frugal).

Frugal innovation (FI) has recently become a relevant theme in the public domain, requesting further studies, since the phenomenon has been growing in relevance both in advance and emerging countries. It is considered as a new source of innovation mainly to meet the needs of low-income customers.

For a deeper comprehension, there are several representative definitions of frugal definition which explain the concept as these innovations are typically built on new product architectures that enable entirely new applications at much lower price points than existing solutions (Zeschky et al., 2014). Other authors (Hossain et al., 2016) define it "as a product, service or a solution that emerges despite financial, human, technological and other resource constraints, and where the final outcome is less pricey than competitive offerings (if available) and which meets the needs of those customers who otherwise remain un-served". Besides, recently Agarwal exposed that FI is coming to solve the problematic for those people with limited recourses who cannot cope with expensive products are able to afford new ones sufficiently good and they suffice the needs.

From the beginning of the concept of frugal innovations dated back to the term "frugal engineering", coined in 2006 by Carlos Ghosn, it has suffered an evolution which the existing definitions have been analysed over the years and classified into three big groups: First generation, Second generation and Third generation. Table 4 illustrates some remarkable definitions done by authors considering their generation and it highlights which is the respectively scope each group achieve.

Table 4 . The evolution of definitions (A. Pisoni et al.,2018)

First generation Years: 2012/2013 Product-oriented definitions	Second generation Years: 2014/2015 Market-oriented definitions	Third generation Years: 2016/2017 Criteria-oriented definitions
Frugal innovation seeks to reduce the amount of material and financial resources used in the complete value chain (development, manufacturing, distribution, consumption, and disposal) with the purpose of minimising the cost of ownership while fulfilling or even exceeding certain predefined criteria of acceptable quality standards (Tiwari and Herstatt, 2012)	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)	Innovations are frugal if they simultaneously meet the criteria substantial cost reduction, concentration on core functionalities, and optimised performance level (Weyrauch and Herstatt, 2016)
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)	A derived management approach, which focuses on the development, production, and product management of resource-saving products and services for people at the bottom of pyramid by achieving a sufficient level of taxonomy and avoiding needless costs (Brem and Wolfram, 2014) .	All resource-constrained innovations have the following features:cost-effectiveness, ease-of-use, prescriptive variable (Agarwal et al., 2017)
	Frugal innovation aims to provide the essential functions people seek to satisfy with a given product. For frugal innovators, scarcity is both fact (they cannot easily change the economic condition of their potential customers) and opportunity (Cunha et al., 2014)	Advanced Frugal Innovation (AFI) by leveraging advances in science and technology to capture the frugality inherent in a grassroots frugal innovation (Rao, 2017a)
	Frugal innovation refers to those innovative products and services which are developed under conditions of resource constraints (Agnihotri, 2015)	
	Process-oriented definitions	
	Frugal innovation as the means and ends to 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)	

In this way, a comprehensive overview has been done by collecting the main ideas and the basis of all the generations. First of all, the first block of definitions was called the first generation, which could be described as product-oriented too. It refers to product-based features of frugal innovation and focus on the characteristics of frugal products and services. The main purpose is reducing the use of material and financial resources being characterised by compact design, raw materials limited, low price, ease of use, and cutting-edge technology to achieve lower costs (Tiwari and Herstatt, 2012; Rao, 2013).

On the other hand, the second generation incorporates some new variables that describe differences and similarities among the various forms of resource-constrained innovations, and it differences between two criteria : market-oriented and process-oriented. According to the first sub-group, frugal innovation is developed to satisfy people at the bottom of the pyramid (Zeschky et al.,2014) focusing on the development, production, and product management of resource saving products and services by achieving a sufficient level of taxonomy and avoiding needless cost (Brem and Wolfram, 2014). However, process-oriented definitions have been suggested as the "*means and ends to do more with less for more people*" (Radjou and Prabhu,2015) or as well other authors consider that it is the whole design innovation process which properly includes the needs and context of citizens in developing world (Basu et al.;2013).

At the end, the third group represents a cut-out point. In fact, some authors who research this theme went back to the beginning of the frugal innovation concept and established three main characteristics both in emerging and developed market: substantial cost reduction, concentration on core functionalities, and optimized performance level. In addition, another remarkable research done by Agarwal in 2017, identified other three fundamental dimensions of constraint-based innovation: cost-effectiveness, ease-of-use, and prescriptive variables.

All this information and explanations helps us to understand this phenomenon and to accomplish the project for which we are working which is focused on circular economy in frugal way. Thinking about a solution based on the full cycle in the use of plastic (specially PET bottles), which the amount of waste produced currently is unsustainable and very difficult to eliminate due to the characteristics of the material, it is highly connected with the aforementioned definitions of Circular Economy cause it shows to children the whole process since we have discarded bottles until we are able to turn them into something useful.

At the end, frugal innovation concept will be very connected to this project because is characterised by low price, use of limited raw materials, avoiding needless cost and to satisfy with a given product. In this manner, the state of art both CE and Frugal Innovation concept will support the basis of the project.

3.3 Operations for plastic in circular economy

According to apply the concept of circular economy to discarded plastic waste, specifically PET bottles in his project, there is a set of operations that form the entire cycle. It will be explained for chapters which it will include mills, the washing process, drying, extruding and 3D printing. It is going to analyse each operation in order to understand its working and the rest of involved requirements. Implemented technology must also be considered as well as dealing with machinery cause every situation can need different working conditions.

3.3.1 Mills

The industrial grinders are able to shred the plastic waste collection into pieces of small size with the purpose to produce feedstock to extruders. Size reduction is known the fact to previously reduce the volume of the waste with the purpose to feed them right into the extruder machine's hopper (Toulupe, 2016). The plastic shredder incorporates a rotor with several blades that thanks to the power and speed of rotation, it cuts the plastic into the required flakes size, and these are then collected in a collection bin. Figure 9 below shows how it is composed a plastic shredder.

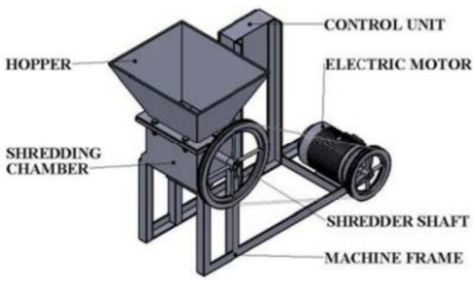


Figure 9 - Isometric view of the plastic shredder (Toulupe, 2016)

This process is key to help to reduce ostensibly large solid material objects into smaller products and it would thereby improve in waste management and disposal. However, it exists still limitations in developing countries where they cannot afford this expensive machinery and it blocks and stops the progress of the recycling activities (Ayo et al., 2017).

For this reason, facing this situation they had to invent a new shredder machine using available local materials that both reduced the price of the machine considerably and promote recycling activities and, what's more, it does not need too much ability to operate (Ayo et al., 2017).

On the other hand, there are a several design considerations in the design of the recycled plastic waste shredding machine which should take into account such as compactness, power requirement, safety, overall cost of productions and ease of operations (Ayo et al., 2017) whereas referring to material selection, characteristics like durability, availability, ease of fabrication and cost are considered as well. Toulupe (2016) published an article concerning the design procedure of this machine and establish their critical parts to develop a good philosophy of the design and adopting some considerations for a easy manufacturing or for a easy maintenance and assembly.

Another aspect to take into account is that moisture is a relevant factor that affects crushing performance. Siyi Luo et al. (2010) based their researches on the feed moisture cause its study was focused on a novel shredder for municipal solid waste. The breakage was proved with different amounts of water content inside feed which having more moisture, decreases the fine production in products. In addition, specific energy consumption showed an increasing trend when the moisture levels were higher.

3.3.2 Washing process

Washing process have the mission to eliminate from dirty flakes the remaining contaminants such as glue, very small PET particles or labels. Sorting or cleaning stages are some of the necessary steps to effectuate this operation. The flakes then washed with detergent in bins or tanks are followed by a classification based on floating or sinking to remove float caps ring (PP) and base cups (HDPE) (Nabeel, 2010).

It exists a standard practice that describes a procedure for washing dirty plastic. In this practice, room temperature wash step is usually utilized to facilitate separation of the labels and then, other washing at elevated temperature lets the separation of other contaminants by basing on densities (ASTM International,2009). ASTM International (2009) describes the different apparatus are needed to develop the process and the steps we should follow to achieve good results including the amount of detergent used or other standard like temperature and time like, for instance, to rinse the material in the strainer for 2 min with cold water while agitating the material with the manual rod is one of its guidelines.

However, washing plastic (PET bottles in our case) during recycling needs a huge demand of water. These days it is usually used fresh water in most plants for recycling plastics generating an extensive water demand. Despite not having many articles mentioning the amount of water consumed in the process of PET recycling, one study established that for each 3kg flakes washed is needed 80dm^3 of water (Santos et al.,2005). On the other hand, there is a great amount of systems which are used to recycle water such as coagulation (e.g. Girczys and Caban-Pabian, 1999), membrane ultrafiltration (Loganathan et al.,2015), flotation (e.g. Zaneti et al.,2012) and other more innovative as photocatalytic treatment technology under artificial and solar illumination (Tsoumachidou et al.,2017). New technologies are often required for water reuse in technological processes and the reduction of wastewater (Güyer et al.,2016). Obviously, this will increase the initial costs but it reports ecological and economical benefits in the end as consequence of the water saving.

Regarding legality concerns, there are strict regulations on environmental protection for these industrial plants that use fresh water in technological processes. Europe has no uniformity in the required quality of the recycled water (Bożek et al., 2013) but many legislation acts are in favor of the reuse of treated wastewater (e.g. Council Directive 91/271/EEC) and they determine key factor such as permissible values for contaminants or pollutants (U.S. EPA,2012; WHO,2006).In addition, depending the branch of industry the water is used for, the quality requirements could suffer modifications with the goal to ensure suitable quality of the final product.

For providing a more in-depth analysis, some companies that recycle PET bottles wash the flakes produced during grinding with detergents at 90°C, with it removes the glue, dirt, paper and other impurities.

3.3.3 Drying

After the washing process, the remaining material should be dried. PET is a material characterised for being hygroscopic, what it means that it tends to absorb water from its surroundings of a natural way. This part is quiet important because if PET is heated while is slightly wet, the water hydrolyzes the material decreasing its resilience. Therefore, as much moisture as possible must be removed from the resin before it is processed in a moulding machine (Nabeel, 2010).

To achieve the drying, it is common the use of dryers or desiccant before the PET is fed into the extruder machines. The process is produced in a closed loop inside the dryer where the dry air is pump into the bottom of the hopper removing moisture and, the hot wet air leaves the top of the hopper (Nabeel, 2010).

After uncontrolled growth of the usage of PET bottles, the recycling of this plastic waste has become a fundamental need. For this fact, there is an increasing demand to refine the recycling process and it is considerably important to achieve being cost and time effective. Kennedy (1999) tried to establish which were the best conditions to elaborate this process with the objective of obtaining the best possible product with the highest quality. Time and temperature were being varied in order to determine the best results which were showed at 177 degrees and time around six hours. Increasing or decreasing the drying time, it would degrade the material according to Kennedy (1999).

Regarding the dryer residence time, it should be longer than four hours. It is due to the fact that if material is dried in less than 4 hours would require a temperature above 160 °C and pellets could not be properly dried out because of hydrolysis. Moisture levels in the resin should not be more than 5 parts per million (parts of water per million parts of resin, by weight) before processing (Nabeel, 2010).

The proposed residence time and the temperature vary from author to author. It will be explained the values that other authors have determined to dry PET recycled in similar cases than ours in order to be closed to the best solution we should established: Hao Wu et al. (2019) dried the PET pellets at 140 °C in an oven for 8 h to remove moisture; Torres N. et al (2000) did the drying process in a dehumidifier drier with a values of 5h at 160°C for virgin PET and two phases of 2h at 120°C more 4h at 140°C for recycled PET, respectively. This happens because recycled PET possesses a softening temperature inferior to virgin PET, since it is less crystalline ;Paci M. and La Mantia F. (1998) did the procedure in a vacuum oven at 170 °C for 4h.

From this data, it could be concluded values of time will be around 4-6 hours whereas temperature between 130-170°C (some recommend less up to 160°C). For this reason, 5h and 150 degrees would be good standard conditions to do the process. To support this statement, other literature review describes that PET should be dried at a temperature between 137,8 and 160 °C (280-320 °F) using a drier that reaches a dew point of -28,9 °C (-20 °F) or below and for the drying time, virgin pellets should be at least four hours and whereas recycled flakes at least five to six hours (CWC, 1998).

3.3.4 Extruders

Plastic extrusion is the traditional process, which usually follows the shredding and make suitable filament in order to deal with polymers and composites other products. Extruders are the machines that provides the plastic recycling filament. They are used to create a wide range of items, including plastic tubing, trims, seals, plastic sheets and rods from a selected type of plastic resin. The most widely used extruder, screw extruders, are divided into two groups: single screw and multiscrew extruder. First group is most popular for their simple designs, reliability, ruggedness and low cost. On the other hand, if you want to mix different ingredients such as additives, fillers, and liquids, twin screw extruders are more efficient (A. Shrivastava, 2018). Considering final shapes, extrusion screw design has been improving over the years, with new innovations and ideas that help in perpetually adjusting the process so as to meet the needs of specific applications (Ravi et al., 2011; Singh et al., 2017).

An extruder machine is usually compounded by a barrel segmented into three zones which they differ by having different temperatures. They are called solids conveying, melting and melt conveying. Generally, each temperature zone is assembled by a couple of heaters, but sometimes small experimental extruders are using only one heater. The polymer which has been previously shredded into small pieces is entered in the barrel through a hopper. Afterwards, it has increased the temperature of the material up to the polymer melting temperature while passing through the temperature zones. Finally, extrusion process ends pushing the material to the die zone, where it will be shaped in the desired form. Generally, the final solid form is in a cylindrical shape (Ravi et al., 2011; Singh et al., 2017).

There are several factors that influences in the final result of the plastic extrusion process. What it is wanted to achieve is to control all of them in the best possible way to make a good extruded polymer. The quality of the filament will be a very important issue and it is associated with a controlled and uniform distribution of the temperature in the different zones. What's more, relating to filament quality there are other important aspects to take into account such as time of cooling, speed of rolling through the barrel or the physical property of the polymer. In addition, some authors discuss that the efficiency on the extrusion process is mainly related with the precision in the control of the temperatures in all the zones (Ravi et al, 2011; Singh et al. 2017).

At the end, we should know how it will be the filament made after modifying the different key factors. It is important do not set the temperature too high for the material because of could cause degradation and burning of the materials and the release of toxic gasses VOCs. Besides, it might appear bubbles in the filament, it is not round and is too thin. On the other hand, when the temperature is too low the material will be too solid and might push the nozzle out of the machine or even the filament cannot be pulled (3Evo).

In figure 10 it is schematized a possible single screw extruder. As we can see, polymer powder or granules is fed via the hopper and conveyed and melted along the screw and forced out through a die to achieve the desired form. During this process, the polymer undergoes complex thermal–mechanical transformations along with a change of the physical properties. In extrusion process, the screw takes a main role and it is composed by three main functional/geometrical zones: solids conveying, melting and metering. (Abeykoon et al., 2011)

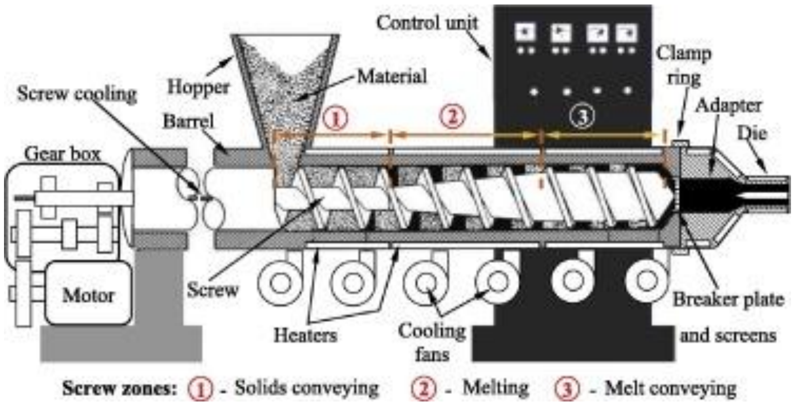


Figure 10 - The basic component and functional zones of a single screw extruder (Abeykoon, 2011)

3.3.5 3D Printing technology

3D Printing has result to have a great scalability in terms to integrate it in the circular economy atmosphere which promotes sustainability and improvement of the resources usage, providing new optimised characteristics to manufactures and responding to the flexible demand. 3D Printing is a good tech trend to begin defining sustainable operations and both costs and waste reduction. This technology is capable to develop affordable solutions, offering quality in services and products while promoting a sustainable and profitable business strategy (Despeisse et al., 2017).

3.3.5.1 Additive Manufacturing

Additive Manufacturing (AM) processes produce physical objects from digital information piece-by-piece, line-by-line, surface-by-surface or layer-by-layer (Gibson et al., 2010). AM technologies has experienced an extraordinary evolution and a large range of materials are allowed for the processing being an opportunity of recycling.

Until relatively recently, three were the main techniques that were used in the manufacture of objects: gradually remove matter until forming the final piece (for carving, cutting, milling, drilling...), combine various materials (fabric, sintered ...) or deform the material to give it the desired shape. The manufacture of an object usually combines these three procedures, which requires the use of numerous tools and the use of different materials (Bertier Luyt & Mathilde Berchon, 2016).

3D printing works in a completely different way: the formal name of 3D printing in the industry is additive manufacturing, which is quite descriptive of the operation of these machines. Firstly, *additive* refers to the fact that 3D printing methods manufacture depositing objects or pouring thin layer by layer, at an average rate of a few centimetres in height per hour; to shape a solid three-dimensional object that takes shape when the layers solidify. The created object can consist of internal mechanisms (such as ball bearing), woven and interlaced forms, or even hollow and curved. On the other hand, *manufacturing* refers to the fact that 3D printers create these layers according to some type of predictable and repetitive systematic process as it is illustrated in Figure 11.

Figure 11 - Schematic representation of the printing of an object by layers (Emaze)

3D printers, given that they are generally used in cast-wire filing technology, are composed of four indispensable elements: a print bed, an extruder (through which the filament is slowly passed), a thermal head and a plastic filament. The several variants of these four elements significantly influence the technical characteristics of the machine. Depending on the model, the printer could be faster, more compact or even more accurate These four pieces are installed on a solid structure and are controlled by a 3D positioning system (Bertier Luyt & Mathilde Berchon, 2016).

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- The different 3D positioning systems

The 3D positioning system defines the way the print head will put the filament out on the print bed. The x and y axes correspond to the lateral displacement of the system; the z axis, to the vertical displacement (Bertier Luyt & Mathilde Berchon, 2016).

- Crane: the extruder moves in the axes x and y, and the print bed, in the z axis.
- Mobile bed: the bed is the one that moves, and not the extruder. This model has the advantage of being simpler from the mechanical point of view. Maintenance is easier and costs are less expensive. In contrast, printing is slower because of the print bed is heavy.
- DeltaBot: Three mobile control sticks direct the print head. This type of model allows to increase the speed and precision of the impression, but it requires of a more complex motor.

3D printers can have different sizes and aspects, and it is always linked to various computer programs that are essential for the process, since they allow us to prepare the 3D file of the object that we are going to manufacture and control later. A 3D printer, therefore, is a machine capable of manufacturing a physical object from a 3D model (Bertier Luyt & Mathilde Berchon, 2016).

On the other hand according to Circular Economy, the use of waste materials in additive manufacturing would reduce cost and increase sustainability, providing a high-value output for used plastics. Polyethylene terephthalate bottles can be used for additive manufacturing methods like fused filament fabrication and what is the most relevant is that they do not need additives or modification to the polymer (Zander et al., 2018).

Fused filament fabrication (FFF) is one of the most cost-effective AM methods. Recently, there has been much interest in the use of recycled plastics in FFF to increase sustainability and reduce cost. For a suitable recycling should be carried out some processes which the material is cleaned and dried and it is tested and analysed for knowing the thermal, chemical and mechanical properties. In that scenario, virgin PET which is a non-biodegradable plastic and one of the most widely used and important engineering plastics is also one of the easiest materials to recycle. As conclusion, recycled PET has been shown to be a suitable material for FFF printing (Zander et al., 2018).

The waste plastics are recoverable resources that can give rise to products of commercial value. The plastic, when it becomes waste, can be valued so that it can become useful again. In this regard, the polymer can also be considered an environmentally friendly material because it encourages the use/recovery of waste that, in addition to the environmental advantages in economic terms, can aid in the production of lower cost materials by reducing the cost of construction (Suganti et al., 2015).

- Rapid prototyping (RP)

It is important to point out rapid prototyping as a key application within the many under the AM umbrella. It is the technology of making three dimensional (3D) models utilizing CAD models with minimum human intervention without any tooling requirement within reasonable time and cost (Mahindru and Mahendru, 2013). RP applications include the development of prototypes quickly within the time constraints (Pham and Gault, 1998). The major advantage of additive manufacturing (AM) processes is the manufacturing of intricate geometries in an efficient way manufacturing process of creating a solid part combining plastic layers (Levy et al., 2003) .

3.3.5.2 The materials of the 3D printing

Nowadays, the main materials used in 3D printing are divided into two large families: plastics and metals, which must be added ceramics and organic materials. Of course, not all of them are compatible with all 3D printing techniques.

The commonly used 3D printing filaments are acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA), but they are very expensive and not environment friendly (Berman B., 2012). There is a great interest about how the filament should be made from recycled materials and be eco-friendly. In addition, there has been extreme growth and excitement about the possibilities of using 3D printing technology to boost world economy. However, it should be taken into account that mechanical properties vary from virgin plastic to recycled material so experimental work is important for the production of new generations (Kemmish et al., 2011).

3D printers need plastic filament and most of it produced is from virgin generated by petroleum which ends in big amounts of waste and carbon emissions contributing to environmental damage. For this reason, it results a great opportunity to integrate recycled plastic as filament which PET could be key because is an easy and good material to print and has become well know from plastic beverage bottles. The target market for recycled PET filament can be either businesses and/or individual consumers (Feasibility studies, 2016).

In addition, there are other opportunities for encouraging existing SMEs (or to stimulate start-up enterprises) to create, develop and commercialise 3D printed products such as recycling fishing nets and ropes. There are a number of relevant case studies in order to compile a desk-based review of the potential opportunities and challenges to FNRs (fishing nets and ropes) being successfully recycled into valuable products using 3DP *(*Oxvig & Jansen, 2007*)*.

Anyway, according to the project is coursing which is based on the production of specimens through 3D printing technology from the recycling of PET bottles, it is especially important to know the background of this type the material and his sustainability. There are some studies that experimented to process PET bottles into filament used for additive manufacturing methods as our project for schools, without varying the polymer or use of additive (Zander et al., 2018). Rheological data showed the polymer's viscosity increased after drying the recycled PET, however, tensile results such as injection molded part (3.5%) and tensile strength (35.1 ± 8MPa) has similar values to commercial filament.

In this way, it is encouraging that this recycled filament will be able to replace the printing of a large range of plastic. Companies like Refil and B-PET, sell filament generated from recycled PET (Zander et al.,2018). However, it remains to be tested if this could occur in a frugal way and with both financial and resources restraint.

3.4 Conclusions

Literature review has highlighted Circular Economy as an important emerging concept whose purpose is to reduce the great amount of plastic is being generated and its impact to our environment. It was defined by many authors but having similar meaning which it tries to break the old linear model. Government's strategy intend to support this transition with initiatives by emphasizing the prevention of the generation of plastic waste and the increase in the recycling of plastics, as well as stimulating new business, production and consumption, intelligent and circular models that cover the entire value chain. It addresses the challenges posed by plastics throughout the value chain and taking into account their entire life cycle and, as a consequence, resources are used as long as possible maximising their value whereas pollution and wasted is reduced**.** Throughout new plastic economy, where the design and production of plastics fully respect the needs of reuse and recycling, promoting more sustainable materials, it will encourage innovation. Another concept has been emerged under this umbrella: Frugal Innovation. Researches proposed a comprehensive overview by collecting the key ideas whose main meaning is to reduce the use of material and financial resources but finding competitive solutions. Literature review also shows the different processes in connection with the project for schools: its machinery, setting the parameters, its technology. Thus, it encompasses 3D printing technology which has appeared as a technology easily scalable offering benefits to producers by reducing both material consumption and waste. State of the art proved there is a via where is possible to find efficient ways to make products using the recycling plastic resins. From all the different types of products, it will be developed those ones which could offer quality overcoming the resources constraints. Exploring on these matters has opened an opportunity to interconnect the aforementioned concepts and to offer an innovative solution. As a target, this Master Dissertation has as purpose to produce sustainable and quality products in spite of the financials limitations.

4. Methodology

The literature review was conducted in order to propose an operational process for filament and printed product production from plastic waste in a frugal way. This process is intended to be applied in schools in order to increase the knowledge about how the world of plastic waste recycling works, namely amount of plastic waste, applications for valorisation of plastic waste, how this problem is growing or solutions to avoid it. Therefore, from that previous research and all the literature review, the theoretical basis has been established with the purpose to achieve the next objectives: To determine the operations management of the process for plastic revalorisation, which can be done for schools. The process will be established in a frugal way by assessing the different possible options in terms of financial and technology constraints and most frugal options.

Figure 12 shows an overview of the proposed operations:

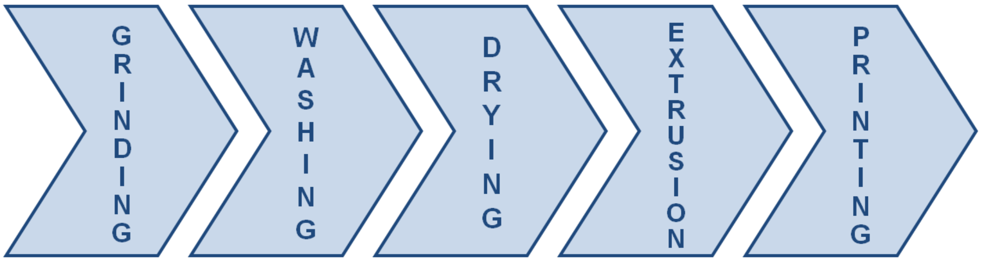

Figure 12. Scheme in order of performance of all the proposed operations

Summarizing, this work will define how each operation should run, which frugal equipment should be selected in order to have a reliable operation and costs of the solution will be presented.

4.1 Grinding

4.1.1 Description

After collecting the bottles, which are the PET plastic waste used to work with, first stage is grinding the bottles, in order to shred the material into pieces of small size, so that they are a suitable feedstock for extruders. This operation is necessary because extrusion operation needs to be fed with small flakes. Therefore, thanks to the cutting mill is possible to crush different types of materials and to reduce them to the specified size according to bottom sieve. In addition, as the bottles do not fit in the entrance of the mill a pre-step is required, where manual cut of the bottles should be done.

In order to characterize this operation, there are some relevant date to measure, such as the time we need to spend on grinding the material, weigh material (before/after and the difference), size of the mesh and gather any occurrence could happen (for instance, a blockage on the machine).

4.1.2 Equipment and material

This section describes the machinery used in this stage which basically is compounded by the cutting mill whose function is to grind material. In order to have a deeper comprehension, Figure 13 comes to illustrate how works this equipment.

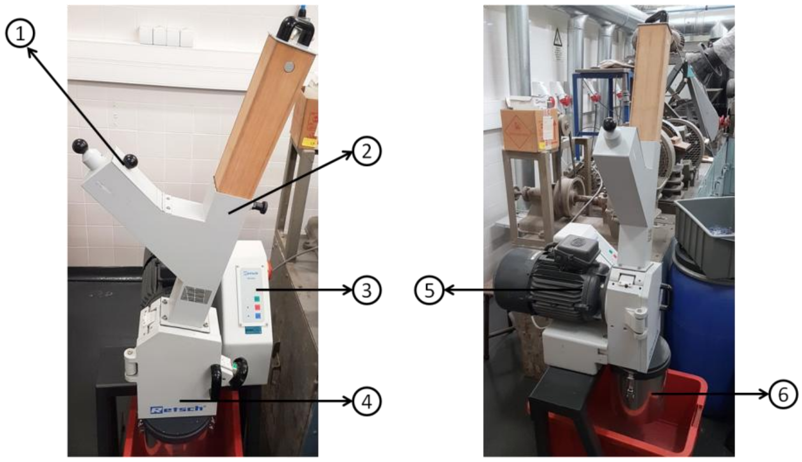

Figure 13. Scheme of the SM 2000 cutting mill

Each number refers to a different part of the cutting mill and the purpose of each one will be described separately to understand the complete working operation of this machine.

Point 1) Where is the material feed. Thanks to the support of a big metal spool, the material is fed in small pieces through this place. Due to the characteristics of this machine and for proper operation, feed size must be up to 60 x 80 mm.

Point 2) This structure is hopper and, in that case, this is a standard hopper. This kind of hopper is used for a universal use for bulk and lumpy material.

Point 3) This is the control panel. It has by three buttons: green, red and blue. Green button called Start is used to initialise the grinding. On other hand, red button is used to stop the operation. At the end, blue button is a safety switch that prevents the mill from being switched on when the door is open.

Point 4) It is the door which has been patented as a central locking system for quick access and simple cleaning. It is useful to access easily to grinding chamber when the operation is over and you want to leave it clean and, in addition, when there is a blockage and the material inside the chamber has to be removed.

Point 5) This is where the motor is located. The motor controls the rotor. The pieces are connected because motor is in charge to supply the necessary force to turn the rotor and crush the material. Therefore, when you do the feeding of the material, it passes through the hopper until arriving to grinding chamber where is production the grinding. The rotor speed can be operated to 750 or 1430 r/min.

Point 6) It is the receptacle where you receive the material. During the operation, the grinded material is being accumulated in that deposit and once the process is finished, you can take and close the receptacle with the tap besides of transporting it easily. In that case, the vessel capacity is 5l.

Another remarkable material is bottom sieve which according to its aperture size modifies the size that the material is cut. It is introduced a mesh size of 4 mm whose magnitude works properly as feedstock for extruders. Related to the type of this material, bottom sieve is made of stainless steel as well as the hopper, rotor, motor flange, door insert and 5l collecting vessel. On the other hand, the mill casing is of aluminium.

4.1.3 Experimental procedure

The procedure of the grinding process will be described in the following steps:

1) Pre-grind the bottles in order to reduce the size of the material and to be able to feed the mill. This is done because of bottles size is higher than hopper capacity, which just allows a feed size up to 60 x 80 mm . The pre-grinding process is done through the use of scissors. With the scissors the bottles are cut into small pieces with a size lower than 60x80mm. It is an inexpensive operation done in a frugal way, moreover, students will have the material available and will be capable to easily execute the operation.
2) Pre-set the grinding machine. Set a rotor speed of $750 min^{-1}$ cause the amount of material is low therefore the process will be fast, and it will avoid forcing the rotor. Use a 6-disc rotor, which is compound of reversible cutting plates of hard metal and for universal use.
3) Grind the plastic pieces obtained in the pre-grinding process. Flakes cut in step 1 are fed into the hopper. Once all the material is cut this procedure should stop.
4) Remove the cut material from the vessel and to put into bags to store it
5) Clean the rest of material that has been left inside the grinding chamber.

4.2 Washing

4.2.1 Description

Research on this operation has been useful to know how by companies or other authors do the plastic washing process. For this reason, this Master's Dissertation proposed various scenarios where the conditions of the processes executed were changed with the purpose to assess the difference between each operation. Characteristics such as temperature (room, 40°C, 65°C), the agitation type according to employ glass bar or net bag, washing phases and the idea of reusing rinse water.

However, to assessment the wash quality of each variant has been become a real challenge due to the difficulties to find a suitable tool for this task. There are international standards organizations that have published technical standards for a wide range of materials, products, systems and services. Specifically, ASTM international (2009) published a standard practice for separation and washing of recycling plastics prior to testing that are supporting and guide some patterns from which we should get the best washed.

Figure 14 shows in an illustrative mood the washing tests that have been performed according to consider the different variables.

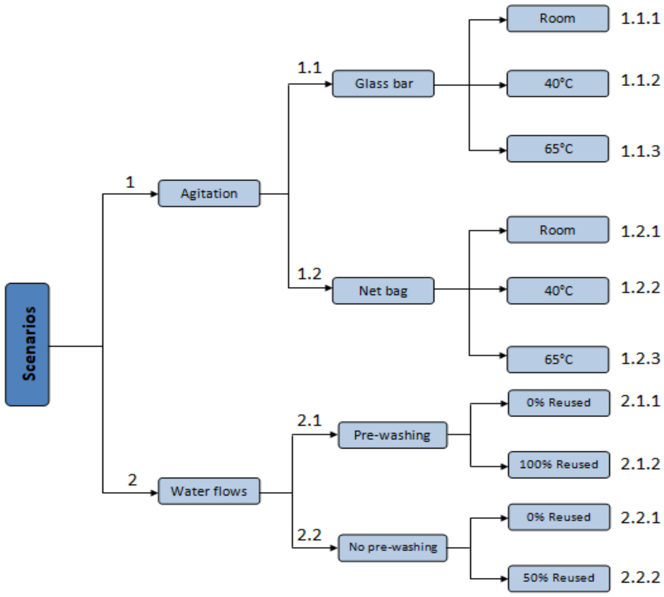

Figure 14. Schematic representation of the different washing scenarios

First of all, it was incorporated the agitation scenario (1) whose purpose is to increase the contact of the material with the water, which is mixed with detergent to reduce the impurities of the flakes. In this scenario, two different options were considered: agitation with glass bar (1.1) and agitation with a net (1.2). These are two frugal options because it is thought to interact between the tools and the students who should conduct the washing process. This agitation can be produced by a glass bar or a net bag.

Another parameter to take into consideration is the temperature of the water. Literature review (ASTM international, 2009) highlights that increasing the temperature of the fluid, will improve the removing of dirt. For this reason, washing process is operated in three different modes to evaluate if the results are better with a higher temperature. Room temperature water is called the scenario (1.1.1 and 1.2.1) where you do not warm up the water coming from sanitation network. In the other two cases, a device is used to increase the temperature until it reaches the set point.

On the other hand, saving the maximum possible water is another point to consider. Usually washing process takes three steps: pre-washing, washing and rinsing. Pre-washing is included at the beginning to improve the process by mixing clean water with the material and to eliminate the surface dirt from flakes. Afterwards, washing is performed thanks to the incorporation of detergent and the consequent agitation. Finally, rinsing with clean water is done to eliminate the rest of detergent and dirt water remaining into the flakes. Therefore, rinse water could be used again in the following washing saving part of the water. Moreover, if pre-washing step is skipped it will consequently lead to a reduction in water use. It will be followed by the two scenarios of water flows where water is reused. Figure 15 represents the Scenario 2.1.2 of pre-washing with 100% rinse water reused.

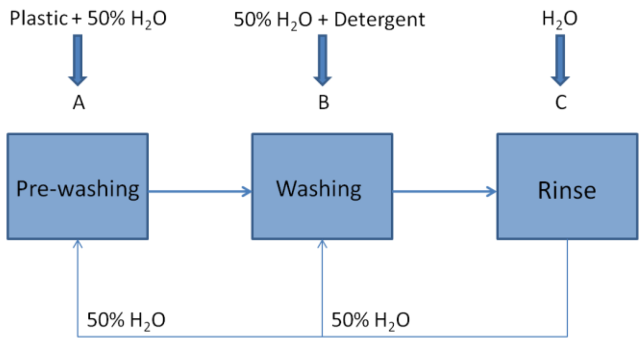

Figure 15. Water flow scenario with 100% rinse water reused

All material will be washed in different batches because a large amount of flakes is not possible to wash them at once with the tools that we have. Thus, this scenario has the objective to profit in each washing the rinse water of the previous batch in order to reduce the water usage. By this way, it is assessed if reusing all the rinse water presents good results. It is considered that rinse water has mainly remaining detergent because dirt should have been cleaned both in pre-washing and washing steps. In that procedure the two first steps reduce the amount of water in half what reports a saving of 33,3% of the total in comparison with the scenario that remove all the water (Scenario 2.1.1). On the other hand, Figure 16 illustrates the Scenario 2.2.2 where it is reused the 50% rinse water but pre-washing step is skipped.

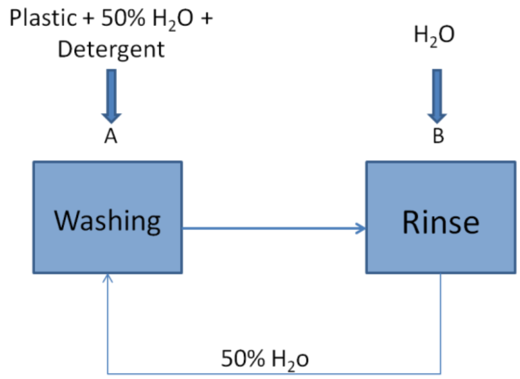

Figure 16. Water flow scenario with 100% rinse water reused and without pre-washing

This Scenario 2.2.2 follows a similar procedure than the others but presents the feature that pre-washing step is skipped. It saved a 25% of the global water in comparison with the flow that has three steps and reuses the rinse water (Scenario 2.1.2).

Between Scenario 2.2.1 and 2.1.1 there is a usage decrease of 33%. Table 5 illustrates a summary of the water usage according to water flow and taking as a reference a use of 2l water in each of the three steps. The values are calculated per wash batch and starting after the second wash because the first batch uses all clean water. Saving water is calculated compared to Scenario 2.1.1.

Table 5. Water usage according to water flow scenario. It has been taken as a reference a water usage of 2l in each of the three steps.

Scenario	Pre-washing (l)	Washing (l)	Rinse (l)	Total usage (l)	Saving (%)
2.1.1	2	2	2	6	-
2.1.2	1	1	2	4	33,33
2.2.1	-	2	2	4	33,33
2.2.2	-	1	2	3	50

The quality of washing will be assessed by checking carefully all the flakes and to test if glue or other dirt particles are still remaining. If it is impossible to evaluate the different scenarios and to visualize if dirt has disappeared, the validity of each scenario will be assessed in the next operations, with the extrusion process. Thus, if the flakes of a determinate option is able to produce filament of high quality this means that at least their washing specifications are valid.

4.2.2 Equipment and material

This section aims to illustrate the equipment and tools used during the washing process. It is important to highlight that the material to accomplish this stage will be though in a frugal way. This means to be inexpensive and non cutting-edge devices.

First of all, it is going to show equipment related to agitation scenario. Figure 17 represents the tank where is dumped the water as well as the glass bar.

Figure 17. Plastic tank and glass bar

In this plastic tank are performed the three operations of the washing process: pre-washing, washing, rinsing. It is recommendable to account with at least two deposits to be able to pass from one step to other. The tank capacity is 5l, more than enough to wash each batch. Moreover, Fig. 17 shows a glass bar used to agitate the product inside the water. On the other hand, Figure 18 illustrates the net bags used in the second scenario of agitation.

Figure 18. Net bags to do the agitation

This kind of bags are characterized by allowing the water to pass through itself. With this tool is aimed to work with material that usually you will not find in a laboratory besides of increasing the interactivity of children and be more appealing for them. The flakes are put inside the bag followed by moving the bag inside the water as if it were shaking.

Another material to take into consideration is the detergent. Dish washing detergent is used in the washing step by mixing the product with the water inside the tank. Figure 19 shows a glass tank which can be utilized to scale the amount of detergent you want to use. It is used because we want to measure the quantity of liquid detergent to insert subsequently into the tank with water (Washing step).

Figure 19. Scaled glass tumbler

Figure 20 illustrates two useful tools to remove the flakes.

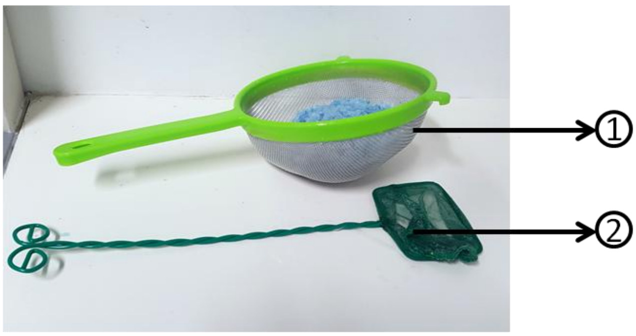

Figure 20. Colander and net

It can be observed that these two tools respond to the idea of frugality whose price is low and it will be easily manipulated for students. It has been already explained that it will be essential the student's participation during the processes because it will increase their interest in the activity and will enhance the adoption of the proposed solution. For instance, these two objects are quite simple to manipulate, and students could find them in its everyday life which become more familiar.

Number one is a colander, a common kitchen tool used to drain the water. Its function in this process is to decant the flakes from one tank to another when your pre-washing is ended and you want to start washing, or when washing is finishing and you have to rinse. Number two is a small net which is mainly used in fish tanks. In that demonstration it will be utilised to separate all the remaining material floating at the top of the water after the agitation, which produces a classification based on floating or sinking depending on the type of the material whose density is different: Float caps ring (PP) and base cups (HDPE) are floating whereas PET material is sunken (shown in results Fig. 35).

Another aspect to consider is the management of the scenarios working at different temperature. Dealing with the temperature variable, it will be used a water boiler machine to warm the water. This a common device usually used to cook and whose introduction in the experiment is under frugal characteristics because is not expensive and besides it is easy to manage even for children, just putting the water inside the machine and switching on the button.

Related to water temperature is the sensor capable to calculate it. As it can be seen in Fig. 21, to calculate the temperature of the water it simply needs to put the thermometer sensor inside the tank and automatically it will be calculated its value. Figure 21 illustrates a tool usually used in labs. Anyway, we just need to measure the temperature of a liquid thus it can be a simple thermometer for frugality able to calculate this parameter.

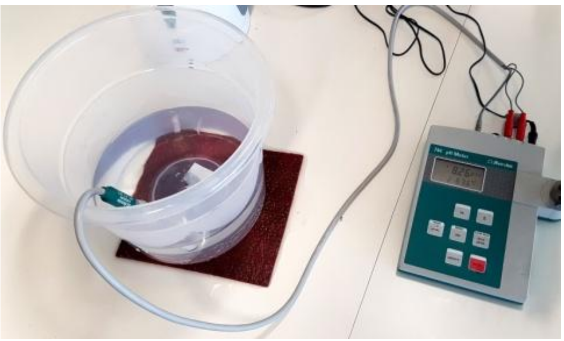

Figure 21. Equipment to calculate the water temperature

4.2.3 Experimental procedure

The procedure of the washing process will be described in the following steps:

1) First step is to weigh the quantity of flakes to wash according to each scenarios with its respective conditions through using the balance of the laboratory and separating the right quantity from the big bag that contains all the material previously grinded. Each batch will be around 200g weight whose amount is enough to assess the validity of each washing scenario. What it means that with this quantity is possible to make enough filament to print later and evaluate the results.
2) The material is inserted into a tank full of 2 litters of clean water to do the pre-washing phase as well as floating process of non- PET material. The content is agitated by moving the tool to an approximate speed of 200r/min and taking around 1min30s.
   **Depending on the method, the material is shaken by a glass bar or a net bag*
3) The water temperature of the washing stage is prepared by a water cuisine boiler. The temperature is monitored by a sensor to reach the right value.
   **When the scenario is cold water, third step is skipped and water is used directly from the tap.*
4) Material is decanted from the pre-washing tank followed by the washing process with clean water. 2,5ml of detergent is mixed with another 2l of water. At the beginning it was tested with 5 and 7,5ml of detergent but it creates too much foam during stirring with the consequent growth of water to rinse accurately and it did not improve the quality of the washing process. However, this amount of detergent avoids the foam problem and leaves the product enough clean. The mixture is agitated for 2min. This time could be longer but as it is working manually in a frugal way, it is a enough time if you want to realise a vast number of experiments in a short space of time.
   **If you are in a scenario skipping the pre-washing step, the same water that is used to separate the different kind of material, it is used to do the washing putting detergent inside.*
5) Rinse the material. Washed material of the fourth step is decanted into another plastic tank full of clean water in order to procedure to the rinsing stage to remove the foam and the rest of detergent that has been mixed during the washing. This step takes 2 minutes (ASTM international, 2009).
6) Finally, the material is decanted for last time trying to remove all the remaining water as much as possible and put it inside a box getting ready for the operation, drying. These boxes are accurately identified according to the scenario in study, highlighting the conditions that have been set such as agitation, water temperature and water flow, to test which flakes produce a better filament (extrusion stage).

In order to justify the amount of water used in the washing process, a consideration should be done with the purpose to clarify the amount of water used. According to Santos et al. (2005) , they published a study that established that for each 3kg flakes washed is needed 80dm^3 of water. Therefore, if it is going to wash 200g of flakes it is necessary approximately 5,3l of water. Scenario with pre-washing and without reusing water is using 6l whereas if in the same type of procedure, it is eliminated the pre-washing step it would use 4l. For this reason, the proportion chosen falls within the parameters.

4.3 Drying

4.3.1 Description

The third operation of the circular economy process, is the drying process. This is essential due to the characteristics of the PET material as it tends to absorb water from the environment because of hygroscopicity, which is a tendency of a solid substance to absorb moisture from the surrounding atmosphere. The total amount of water, which can be taken up by the hygroscopic material will be a function of the temperature and humidity of the atmosphere in which it is located. Moisture could cause problems in the manufacture of filaments whose quality will be decreased. Thus, if it is not correctly dried, it will appear bubbles inside the filament and to make the 3D printing will not be able.

In addition, it is important to take into consideration that this operation is done after the washing process with the consequent use of water. Therefore, flakes are completely wet, and it is mandatory to dry the material as much as possible.

Thanks to literature review, which describes similar drying processes for PET or Virgin PET (Torres N. et al., 2000 ; Hao Wu et al., 2019) ,it is easier to establish the suitable condition of the several processes to make best possible product. Features such as temperature or operating time are important to determine.

4.3.2 Equipment and material

Due to the importance of having the material as dried as possible, oven is used in order to minimise the moisture. As it has been explained throughout the Master Dissertation, the quality of the filament is very connected to this feature and it is important to be able to make 3D printing in order to end the circle.

Figure 22 illustrates the oven that has been used, which is the main equipment in this stage. The operation of this machine is quite simple so scholars would be capable to turn on the oven and use the device.

Figure 22. PET flakes are dried in the oven

First arrow points a monitor where you can visualize the current temperature inside the device. Number two is a switch where you can turn on/off the oven while with the potentiometer of number 3 the working temperature is being regulated.

Relating to material, few are the necessary tools to accomplish this process. On the one hand, aluminium paper is used to as a container to hold the flakes inside the oven. Due to the different washing operations, each piece of aluminium paper has been accurately classified and separated with the purpose to identify all the flakes. On the other hand, it is recommendable the use of gloves when the material is putting inside the oven due to its high temperature.

4.3.3 Experimental procedure

1) The oven is turn on besides with a setting of 150ºC, because this value has reported good results to other similar projects accomplished (Torres N. et al,2000). It takes around 45min until this value is reached so it is important to leave it on while the next step are being prepared.
2) Pieces of aluminium paper are cut to use as a container inside the oven. Each one will be identified according the type of flakes that contains. This type is referred to their performed washing scenario.
3) Around 200g of flakes are placed on top of each piece of aluminium paper. Once the oven has a temperature of 150ºC, all the material is put inside for 5 hours. For further clarification on the assumption of this value see section 4.3.1.
4) After 5h the material will result correctly dried and with almost all the moisture removed. It is taken off the oven and placed into dried bags and closed. These bags are identified according to their conditions during the washing process.

4.4 Extrusion

4.4.1 Description

After doing the aforementioned processes the material should be cleaned and dried and ready to procedure to the extrusion. This dissertation pursues to develop a suitable methodology to produce a recycled filament as feedstock of 3D printing. It will take as a basis the research of the literature related to this topic in order to get results closer to optimal cause there are several parameters that influence the results and what is intended is to know them and control with the objective to get a good extruded filament (Ravi et al., 2011).

It is important to analyse the features of each filament with the purpose of assessing the validity of previous stages such as washing process besides of taking into consideration that this process is followed by printing and whose quality of the final product will be completely connected to extrusion . On this way, adopting a solid method to take the best characteristics of the resins will be fundamental to extract the value of the plastic waste which is based the circular economy solution.

At the extrusion operation will be noted if the differences in the washing operation will influence in the extruded product. For instance, if you want to assess the impact of the temperature, you will test the results of extrusion Scenario 1.2 (see Fig. 23) using flakes washed in Scenario 1.1.1 and Scenario 1.1.3 (see Fig. 14). Otherwise, if you want to analyse differences between type of agitation, it will be tested the results of extrusion Scenario 1.2 performing twice by using flakes washed in washing Scenario 1.1.1 and 1.2.1. Therefore, to infer any conclusion about if there is any improvement comparing washing scenarios, it is necessary to extrude different washed flakes but under the same extrusion scenario, in order to avoid the introduction of more variables such as percentage of recycled material and not be able to evaluate results.

On the one hand, in Figure 23 is showed the several proposed extrusion scenarios to make filament with the 3Devo-Composer 450 and then it will be proceeded to test the different results to determine their quality.

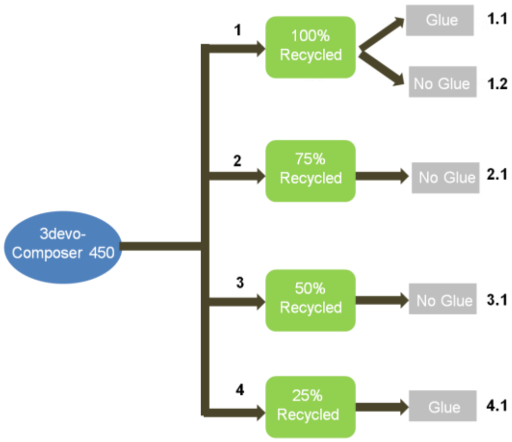

Figure 23. Scheme with the different scenarios performed in extrusion with 3Devo-Composer 450

In this way, every different scenario presents filament of different quality and characteristics. The mechanical properties of each one will be analysed and compare with the purpose to make the highest quality product.

On the other hand, it was also proposed a semi-industrial extruder to make recycled filament. As was done with 3Devo extruder, Figure 24 illustrates a scheme of the different implemented scenarios in the extrusion corresponding to characteristics such as the percentage of recycled material used or the implemented cooling system on the extrusion. Mixture between virgin and recycled PET is done because recycled material reports problems frequently whereas than virgin material works better so these scenarios mixing both material are proved the evaluate its difference of quality and if virgin PET must be incorporated in case of disastrous results in the first scenario. On the other hand, the variable of producing filament with dirt flakes containing glue was just proved with 100% recycled because due to its results and background they were not necessary more tests to conclude its invalidity.

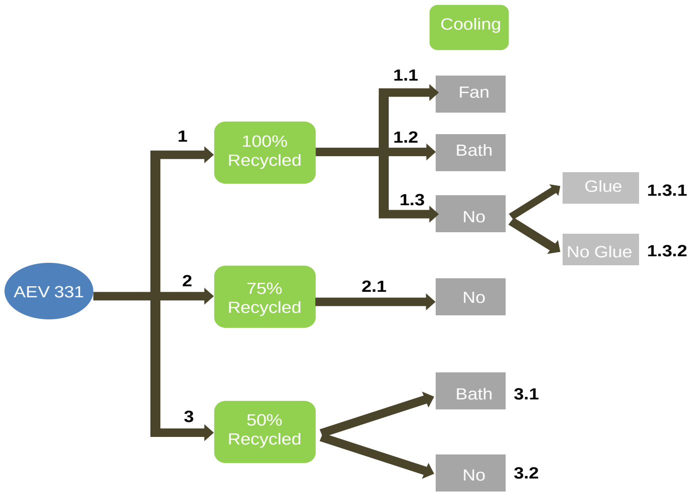

Figure 24. Scheme with the different scenarios performed in extrusion with AEV 331

Another issue to take into consideration was the use of virgin PET at the begging of each extrusion. This is realized because the amount of recycled PET is limited and as both material present similar working conditions like extruding temperature, it supports to calibrate the machines with the consequent saving of recycled material.

4.4.2 Equipment and material

It purposes to reach a several rules and guidelines that should be followed and adopted to make filament of good quality. To establish some of the steps is important to analyse the product is making in order to go modifying and get it right. On the one hand, this process was intended to realise by the extruder for scholars 3Devo Composer 450 which has a specific way to operate. Figures 25 and 26 illustrate this equipment.

Figure 25. 3Devo Composer 450 (1)

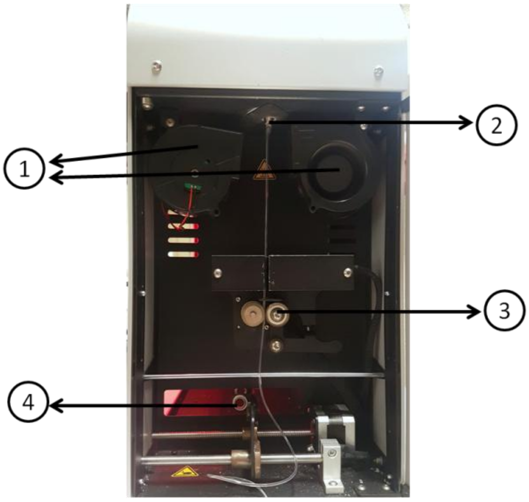

Figure 26. 3Devo Composer 450 (2)

Point 1) Indicates the two heaters. This is a cooling system whose method is to provide air directly to nozzle of the device from material is coming out, and to reduce its temperature faster.

Point 2) Nozzle. This is the part of the device from material is coming out.

Point 3) These two rolls have the function to fit the filament by passing through the middle of both. They press the filament and provides it enough tension to take good shape.

Point 4) Through this hole the filament reaches the spool.

The majority of the common materials used to extrude have their settings of extrusion (heater temperatures, screw speed, etc.) predefined in the memory of the device. These are usually the recommendable values to extrude a good filament according to the different type of material. You can load the values saved in *Material presets*. Anyway, it is possible to change the different values during the extrusion or even before of it. The settings that have to be determined are the temperature of the heaters, the diameter size, fan speed and screw speed. Afterwards, the feedstock is inserted into the hopper of the extruder and the extruder can be started. When the current temperature of the heaters reaches the value predefined it will begin the operation. Figure 27 shows the control panel of 3Devo Composer 450. It is also possible to observe the spool at the bottom of the figure.

Figure 27. 3Devo Composer 450's monitor

If it works correctly the filament will be extruded automatically with the diameter that previously has been determined. Sometimes it is difficult to get it right and can take even 30min (Experimental results), however, modifying screw speed helps to reach it faster. When the diameter size is being produced is stabilised on the target value, the operation of spooling can be started with the intention of making some meters of filament with no interruptions.

As aforementioned, It is also necessary to pay attention with what material is going to work and effectuate a right changeover that for instance, it is used virgin PET before recycled material with the purpose to clean the axis of the extruder and to eliminate remaining particles without spending the material that provides from plastic.

Regarding to AEV 331 extruder, it is more complex to control the operating of the machine. Firstly you have to set the temperature of the heaters and, once have been reached , it is ready to start the extrusion putting the feedstock on the hopper and turning on the motor that activates the rotation. In addition, this machine includes one belt with a roll which is connected to the grid and must be located following the exit of the nozzle. This belt is used to shape the filament by passing the filament under the roll. All this equipment is shown in Figure 28.

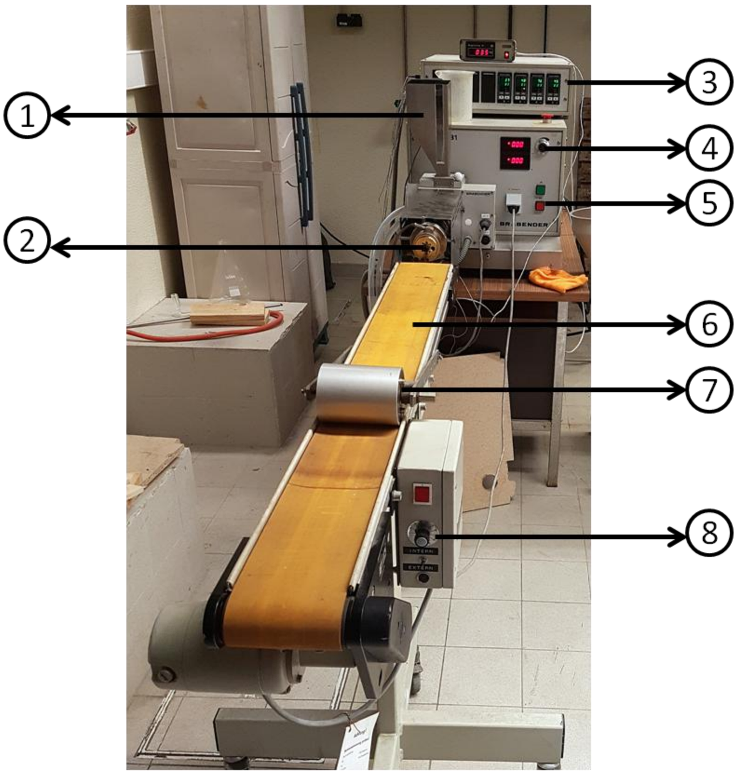

Figure 28. Brabender single screw extruder, model AEV 331.

Point 1) Hopper. Where material feed is produced. It has a vibration mode that helps the feedstock inlet.

Point 2) Nozzle. This is the part of the device where material is coming out.

Point 3) Monitor to control the temperature of the four heaters. Each one have two buttons to decrease or increase the degrees, respectively. There is also a screen where is shown the established set-point and the current temperature.

Point 4) Potentiometer to regulate the screw speed measured in r/min. To increase this parameter means more material coming out ,otherwise, a speed decrease means a reduction of output material.

Point 5) Two switches to turn on or off the extruder respectively. The colour of the buttons are green and red respectively.

Point 6) Conveyor belt. The material is coming out from the nozzle and go to this equipment. Filament is cooled down along the belt. Belt conducts the filament under the roll.

Point 7) It is a roll. Filament passes under this tool. Its function is to shape the material.

Point 8) It is a potentiometer. It controls the belt speed and is highly related to the diameter size of the filament. A speed increase means a reduction in the filament diameter.

The semi-industrial AEV 331 extruder presents some peculiarities in spite of having a quite similar methodology compared to 3Devo's device. After connecting the extruder on the grid and the intern cooling system based on water, it is necessary to turn on the heating motor in order to set the desired temperature in the four heaters before of activating the rotation in the screw. This is important because if the axis begins to rotate having material inside that has not yet melted, it could cause the fracture of some part as a result of great tensions.

Both extruders are compounded of four heaters. These heaters are located along the screw of the extruder. Heater referred to number one is the closest to nozzle while Heater 4 is in the part of the screw next to the hopper. The other two are in the middle of the screw.

Regarding the set temperature, it varies the thermo-mechanical properties of the filament and, each type of material is performed under different values. The suitable heater temperature working with PET material is normally between 260 and 275 degrees. Heater 1 has more influence on the fluid state with which the material comes out. Therefore, usually it is set the highest temperature to avoid occurrences such as clogging and blockage at the exit. Relating to the speed, they are mainly determined in order to achieve the diameter size into the limits (All data shown in Appendixes Fig.89). The screw speed, measured in rpm, is related to the amount of material per time coming out from the nozzle. An increase of this parameter means a thicker diameter. Otherwise, if that speed is reduced, the diameter size becomes thinner. Related to conveyor belt speed, it also influences to the final thickness. From the combination of both speeds will decisive to control the size of the diameter. It is very important to calibrate this parameter because thickness should be around between 1,35 and 1,90 mm to be appropriate to make the 3D impression.

As the results of the filaments made by brabender single screw extruder require the incorporation of cooling system with the goal of improving its quality, new equipment were utilized. Thus, scenario 1.1 incorporates a fan to the operation. On the other hand, scenario 1.2 and 3.1 used a device full of water through is going the filament and cooled down. This equipment is shown at the section 5.3 .

4.4.3 Experimental procedure

Despite the two extruders work differently the methodology that must be followed is quite similar. Then it is going to describe some general guidelines commenting on some appreciations:

1) Connect the extruder to an electric network. Then set the temperature in each heater.
2) When the temperature is achieved, to enter the material through the hopper and start the extrusion.
3) Calibrate the suitable speed. At 3Devo Composer 450 is possible to vary the thickness by setting the screw speed although the diameter size is supposed to be automatically calibrated. In addition, screw speed influences in clogging problem. In the case of the AEV 331 extruder, the thickness is controlled completely manual and must be measured with a measuring instrument. Both screw and conveyor belt speed should be adjusted in order to achieve the correct diameter, at the same time you are measuring.
4) Once the diameter size is right, it is the time to start the spooling to prepare the filament for the next stage: the printing. Scholar extruder do this step automatically whereas in AEV 331 this step is also manual.
5) To finish the process properly it is mandatory to remove all the remaining material inside the screw.

4.5 Printing

4.5.1 Description

After accomplishing all the previous operations the filament is ready to be used in the printer. This filament will be the feedstock of the 3D printers which have the function to effectuate the printing operation. Therefore, from digital information this device is capable to transform the recycled filament into a physical object through the 3D printing technique. Students could participate in this operation by fitting the filament through the printer and setting the right parameters under the supervision of a specialist. Moreover, they can observe the entire process while the product is making layer by layer.

4.5.2 Equipment and material

This section describes the machinery used in this stage which basically is compounded by the 3D printer whose function is to print a product from both filament and digital information. In order to have a deeper comprehension, Figure 29 comes to illustrate how works this equipment.

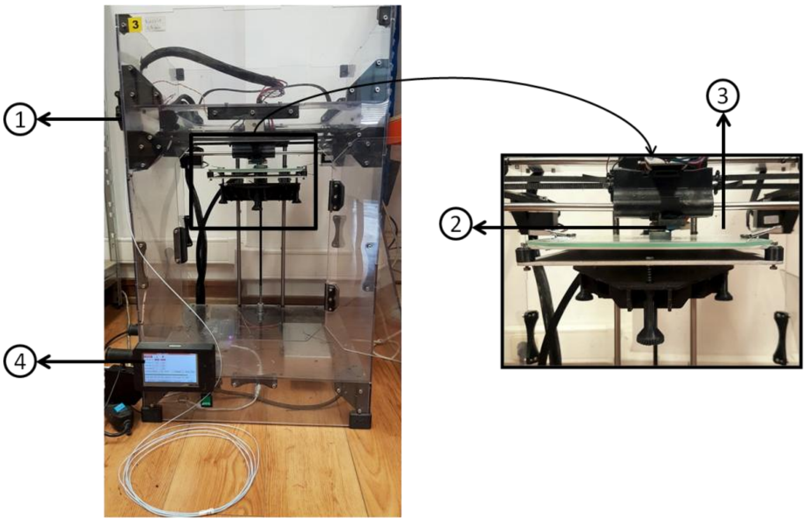

Figure 29. W300 3D printer

Point 1) 3D printer feed. It is located the inlet of filament into the 3D printer. It is compounded by two holes followed by a black tube. This tube conducts the filament until the nozzle (Number 2). If the diameter size is not right, for instance bigger than the allowed limit, you realise that is blocked and that means an inappropriate filament

Point 2) Nozzle. The part of the 3D printer where the build material is extruded from. Nozzles are interchangeable, and come in various sizes; 0.4 mm is the standard value, while you might use a smaller nozzle for finer detail or a larger nozzle to print faster.

Point 3) Print bed. It is where the extruder deposits the filament to form a solid object. For high-temperature materials, a heated print bed is a must in order to cut down on warping issues, improving the overall print quality. In this case, it is made of glass.

Point 4) Control panel. Where is determined the printing parameters. In that panel you are able to change the different value before and during the operation. It includes a port to insert a pen-drive and to load the drawing (3D model). 3D printed is linked to a computer program which provides the information of the object is going to manufacture. Figure 30 represents the monitor of the printer is working with and the value of the different settings.

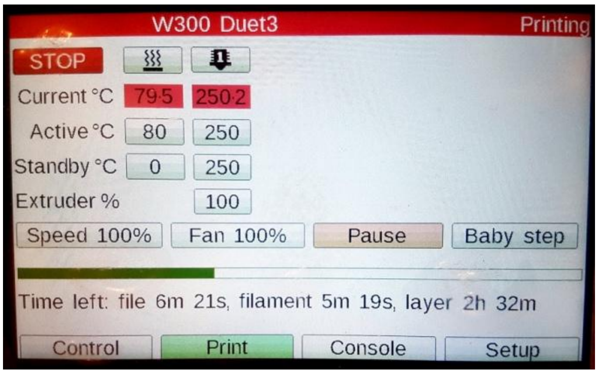

Figure 30. 3D printer monitor

Other material to take into consideration is the gloves used as a safety barrier against the high temperature both inside the machine and the glass print bed. In addition, it is necessary a trowel to take the specimen from the print bed because the specimen remains completely fixed. Besides, if the product is manipulated manually it could be dangerous because of its temperature and even sometimes the specimen could break or deform according to the fragility it has. For this reason, this tool helps to take the product by pressuring between the piece and the print bed being careful not to crack it.

On the other hand, the cleaning of the print bed is other aspect to highlight. At the beginning and end of each printing, 3D LAC spray is used as a tool to remove the remaining dirt. It is a useful product to clean the print bed because during the printing the plastic comes out molten and hooks to the glass. As next printing is doing in the same place, dirt could cause problems and to decrease the quality of the product as well as adopting non-desired forms.

4.5.3 Experimental procedure

1) Create a 3D model with one of the software available for 3D printing. Extract this model and save in format .STL .In this case, the drawing is a small cylinder.
2) Connect the 3D printer to the electric network and turn on the equipment.
3) Set the temperature of the print bed besides of the nozzle temperature. In this case, it is 80°C and 250°C respectively (Resource: 3dways).
4) Insert the filament into the machine. You have to manually pass the filament through two holes connected to a tub. Pass the filament along all the tub until it reaches the end. Subsequently, fit this tub into the part connected to the nozzle.
5) The button 'Extrude' has to be pressed to be sure that the filament is put it right. If the result is positive, it would be coming out material from the nozzle. You decide the batch of material you want to extrude, anyway, as it just a testing step of checking is not recommendable to spend too amount.
6) Insert the pen-drive. Select the drawing you want to print. Then, the data file is loaded on the monitor.
7) At this time printing could be started by pressing 'Print'. After some minutes the product is made. In case of study, as it was printed a small specimen the operation takes around 10min.
8) Once the printing is done, the product has been produced on top of a print bed which must be removed from the printer with the intention of taking the product and to leave the print bed available for the next printing. It this step is incorporated the 3D LAC spray whose purpose is to support the cleaning of the print bed.
9) To change the filament and start another printing it is necessary to press on the monitor the button 'Retract'. Once this filament has been extracted it is possible to put a new one and start the process again for the first step.

In order to justify the drawing selected in 3D printing, it has to be considered a 3D model easy to assess. The cylinder is formed by a flat face, the base, and another curved surface, the height. It allows to assess the density of the mesh and if the structure is strong besides of testing the union between the two parties. The size of the 3D model is small because we simply want to infer its quality without spending large amount of material. Moreover, printing simple products will also be the target at school demonstrations.

5. Results

In this chapter the results extracted from the different operations are presented in separate sections. These results will show the evolution of the plastic waste after each stage whose shape and properties will experiment variations. Depending on the point of the cycle we are, we will have the product in the form of PET bottles, flakes, filaments or printed product. Thus, it will be fundamental to approve each working procedure because all are highly related within the chain and influence the final success. Figures will provide more information supporting what is happened during the experimental work as well as helping to obtain a comprehensive view of the entire process.

5.1 Grinding

Regarding the grinding process, Figure 31 presents the collection of plastic bottles which is the first step of all the experimental work. The plastic waste coming from water bottles are made of PET polymer despite belonging to different brands. Nevertheless, rings and taps, which are not removed, come from others polymers (PP and HDPE). Labels were removed, however, glue is still remaining in part of the bottles.

Figure 31. Collection of PET bottles.

Subsequently, as it was reported a pre-grinding step was required. Two possible scenarios were considered: to remove the part of the bottles, where glue was still there or to leave it to assess its influence on filament quality. Thus, bottles were cut one to one taking into account the previous consideration and using a simple scissor. The tool complies the requirements that we have established related to frugality and the participation of children. It will be mandatory for children to wear safety glasses with the purpose to protect from risk hitting. In Figure 32 can be seen the results of the aforementioned steps. These pieces were cut in around 50x50mm size to manage to be within the limits (60x80mm).

Figure 32. Plastic bottles reduced to smaller pieces

Related to the form of material we have, it is completely different in comparison with the product coming from, bottles, whose volume has been experimented a great decrease. In Figure 33 could be noted the volume reduction through grinding process whose size flakes are 4mm according to the employed bottom sieve.

Figure 33. Flakes after grinding operation

Once flakes have been produced, they are put into bags to use in the next steps. One recommendation is to close accurately this bag with the purpose to avoid the entry of dust or other impurities. Figure 34 shows where the flakes are carried besides of appreciating how the many bottles of Figure 31 have been converted into a small product. Therefore, we have achieved a suitable product in both terms of size and shape used as a feedstock of the extruder.

Figure 34. Storage of recycled flakes

The weight of the bottles cut into small pieces (Fig.32), the weight of the flakes after grinding (Fig.34) and the operating time where measured. Subsequently, it was calculated the loss of material during the operation, which is the difference between the input and output of material, and finally mass flow, calculated from dividing the amount of flakes at the end of the operation by the operating time. These results are presented in Table 6. Each experimental test was done using 10 plastic bottles. We can see from Table 6 that test number 3 has higher values in some of its parameters in contrast with to the other two. This was because a blockage occurred during that experimental test due to the presence of material that the cutting mill was not able to shred and the central locking system had to be accessed with the consequent loss of time. This test has been kept, since this can happen to the kids while doing the tests. By contrast, experimental tests 1 and 2 were performed without interruption. On the other hand, the yield of the grinding operation was calculated from the following equation (1) .

$$Y(\%) = \frac{(\mathrm{Wi} - \mathrm{W_l})\mathrm{x}100}{\mathrm{Wi}} \qquad (1)$$

Where,

Y(%) = The conversion rate, expressed as a percentage, of the grinding operation efficiency

W_i = Amount of material that enters to the cutting mill (g)

W_l = Material weight losses during grinding operation (g)

The last row in the table highlights the average over the three essays to support which are approximately values of the working parameters: 96,16% of yield in grinding operation (Y) and a net mass flow (m_f) of 13,83 grams of flakes produced per minute. As the value of the other parameters are presenting amount of time and weight based on the use of 10 plastic bottles, these results could be used as an orientation and extrapolation to another number of bottles.

Table 6. Parameters under study for the grinding process: material weight input grinding (W_i), material weight output grinding (W_o), loss of material in the operation (W_l), yield operation (Y), operation time (t) and net mass flow (m_f)

	W_i (g)	W_o (g)	W_l (g)	Y (%)	t (min)	m_f (g/min)
Essay 1	396	387	9	97,73	26,8	14,44
Essay 2	401	391	10	97,51	27,2	14,38
Essay 3	415	387	28	93,25	30,5	12,69
Average	404	388,33	15,67	96,16	28,17	13,83

Regarding to future process undertaken at schools, pre-grinding step could be achieved in its entirety by students but always wearing the appropriate safety clothing such as glasses and lab coat. As cutting mill requires a high level of expertise and could be dangerous for children, the operation will be in charge of an expert and students will observe from a safety zone.

5.2 Washing process

As it was reported in the methodology chapter, the washing stage has been performed considering different scenarios whose way of proceeding experiences modifications with the purpose to infer the best operating solution.

Thus, from the wet flakes after washing we obtained that is was impossible to infer any clear conclusion. Just it could be noted that remains glue in form of small brown particles. Therefore, results referred to the quality of the product will be presented after extrusion regarding the characteristics of the filament.

Regarding the washing process, the following figures will illustrate the results of each procedure step. When the quantities of flakes have been weighed the flakes are dumped into tank full of clear water whose result is shown in Figure 35. It can be noted as at the beginning all the material is floating at the top of the water.

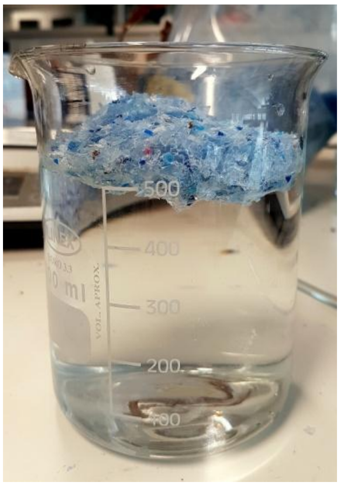

Figure 35. All the material floating at the beginning of the pre-washing

Figure 36 presents what occurs after agitating of the material. This the second step of the procedure which could be performed in the pre-washing stage or, in that scenarios whose pre-washing has been eliminated, before starting the washing stage. Part of the flakes are floating whereas others are sunken whose phenomenon can be explained because there were materials with different materials, PET, PP and HDPE, which have different densities. The removal of the floating flakes is performed by the small net (Section 4.3) and afterwards, all the PET material should be underwater at the bottom of the glass vessel.

Figure 36. Flakes separated by density

On the other hand, previous step is followed by the washing stage which is performed the washing of the material by mixing detergent with water and do agitation. After weighing the amount of detergent, this blend is shaken with a glass bar or a net bag depending on the scenario while increasing its contact and producing foam at the top of the water.

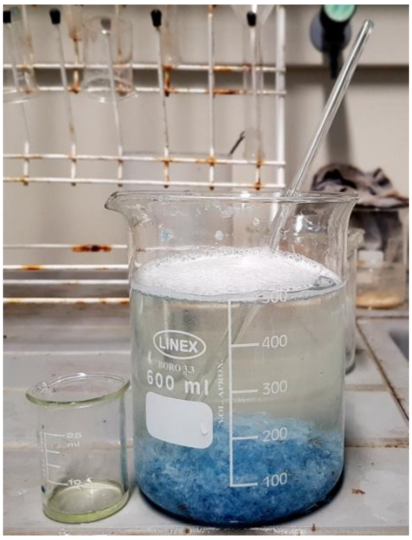

Figure 37. Washing step

By contrast, in Figure 38 is presented a intermediate step where material is decanted into a kitchen colander which is a tool to perform under frugal conditions: cheap, easily manageable and accomplishing the purpose. It can be noted how is separated the material from the water.

Figure 38. Decanted flakes between the steps of the washing process

Last step will be to put the washed flakes inside transparent plastic bags accurately classified by the employed scenario. As preceded by the water washing process, material remains completely wet being a disadvantageous feature for the fabrication of filament.

In reference to the recommendations for the future projects, analysing both employed tools and procedure it can be inferred that student could perform this stage in its totality. As were possible to note, this process does not have complex equipment or a high degree of know-how thus it is just needed a comprehensive explanation to follow the guideline such as quantities of employed products (for example, detergent), operating time and how to procedure.

Regarding the safety issue, it always will be an important matter to take into consideration to protect children of any occurrence. Wearing a lab coat to avoid the contact with dust and dirt particles besides of not getting wet is one of the few recommendations we should take avoiding cause really there is no great risk in this stage.

Definitely, washing process could be one of the most interactive steps of the full cycle. It can become in an appealing activity where children deal with the plastic waste as well as the tools involving themselves more in the proposed circular economy solution.

5.3 Extrusion & Printing

This chapter will present the results on the extrusion and the printing stages which are the most important because any previous operation is focused on achieving the suitable feedstock for both extruders and 3D printers with the purpose to make a good product and demonstrating that the circular economy related to the material is being dealt, PET bottles, makes sense to extract value when it is waste.

Regarding the proposed extrusion scenarios, these are classified into four main groups, according to its percentage of recycled material used in feedstock to extrude, which is also mixed with virgin material. Results proved a lower quality of recycled material compared to virgin whose resins have different characteristics. This effect can be supported by Hu et al. (2009) who highlighted different thermo-mechanical properties between recycled and virgin PET. This behaviour in the 3Devo Composer 450 could be explained by the decrease in the molecular weight of recycled PET or other parameters related to the processing whose quality is impossible to be matched to industrial processed flakes.

As it was reported, virgin PET was used at the beginning of each extrusion in order to save recycled material whose extraction is more difficult and the amount available the project has is more limited. Therefore, thanks to this step we can calibrate the settings of the device before using the produced recycled PET. Filament made by flakes of virgin PET presents more stability than recycled material in terms of having a homogenous diameter and avoiding the clogging matter, which is described below. Figure 39 illustrates the behaviour of this device extruding the virgin flakes which originates a solid filament besides of noting the fact that even was possible to pass the filament through the hole that conducts to the spooling step.

Figure 39. Extrusion with 3Devo-composer 450 using virgin PET

By contrast, Figure 40 presents what occurs when recycled PET is being introduced. It can be noted that diameter size is varying along the diameter what does not allow to use to the following stage, printing. This operation was performed under the same conditions as in the last Fig. 39. Besides, it was intended to change the value of the parameters such as the temperature of the four heaters, screw speed or fan power but it was impossible to solve. It can be inferred that this phenomenon is induced by recycled material.

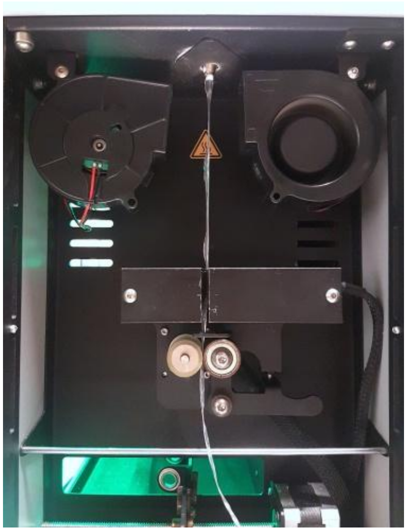

Figure 40. Instabilities in the diameter using recycled PET

Fig. 40 demonstrates that the diameter of the filament is continuously changing when is working with the recycled flakes. However, it was not the only occurrence that appeared. There is another concerning issue shown in Figure 41: the blockage at the nozzle. Fig. 41 illustrates how the nozzle is completely blocked leading to a bigger obstruction whereas the machine is still running. This fact causes also difficulties to restart the process because while this blockage is not removed, it is also cooled down material inside the device. Therefore, there is some material attached to the exit inside the machine and that is quite more difficult to remove.

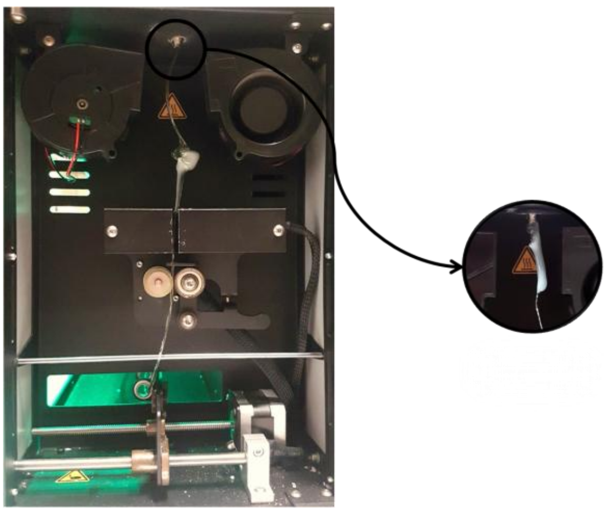

Figure 41. Clogging problems on the extrusion process

So, it is important that when the filament is coming out from the extruder, it presents a fluid state running with no interruption in order to avoid the accumulation of material. There are some aforementioned parameters that can help to control this problem and reduce its frequency. However, the behaviour of the extruder using recycled material became almost uncontrollable. This concerning matter brings the consequent big waste of material that is shown in Figure 42.

Figure 42. Discarded filaments due to clogging problem

This context about virgin and recycled PET, 12 tests in total (you can see more information in Appendixes), has served to know the behaviour of the device with each material and deduce that the scenarios with a higher percentage of recycled flakes will have more possibilities of quality problems and producing filament with a lower quality.

The results will be presented taking into account each employed scenario as well as providing figures to support a better detailed description. Firstly, Scenario 1.1 was performed under conditions of completely recycled material and flakes whose glue was not removed in the grinding stage. Due to the clogging problem it was necessary to do 5 tests to produce analysable filament. The purpose was, when the problem of blockage allowed, to extrude a product performed under these conditions to draw conclusions about the validity of the material in spite of facing the aforementioned occurrence whose origin was unknown. After wasting a great amount of feedstock it was possible to infer a problem related to its quality: a critical variation in the size of the diameter is derived from small hard balls because of glue. The following Figure 43 mainly shows what occurs when we were making filament using flakes containing glue.

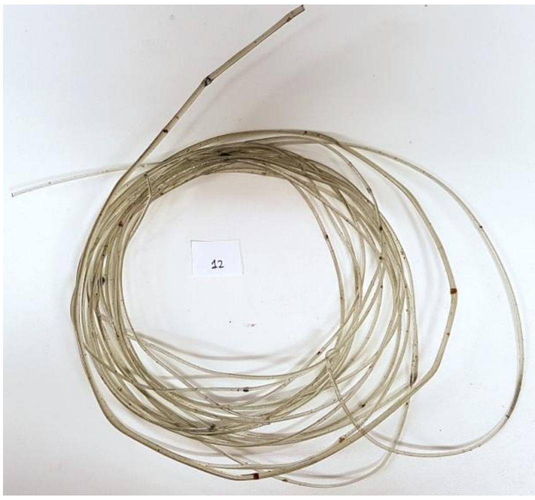

Figure 43. Filament extruded in test 12 (Scenario 1.1. 3Devo)

Filament used as feedstock for 3D printers requires a diameter size around 1,75mm. However, in Fig. 43 can be noted that there are parts with small hard balls, glue, whose diameter increases to values higher than 2mm, which are outside the allowed diameter limits. Therefore, leaving the glue in the bottles do not allow to obtain good quality filament.

In Scenario 1.1, out of the 750g of flakes used in the experimental test it was only possible to extract 60cm in which there was no glue. Thus, it was intended to make the printing with the goal to test a 100% recycled product. Results shown in Figure 44 illustrate that the quality of the specimen is not as bad: structure quite uniform, high impact strength and not holes in spite of having some thinner layers. However, the main issues are two: work with recycled material lead the appearance of occurrences (calibrate the diameter size and clogging) while not removing glue makes impossible to print any sample. In that case working with 100% recycled material the clogging frequency is even higher. This effect can be verified by the Scenario 1.2 whose feedstock was not mixed with virgin PET either and it was impossible to extrude as well as printing consecutively.

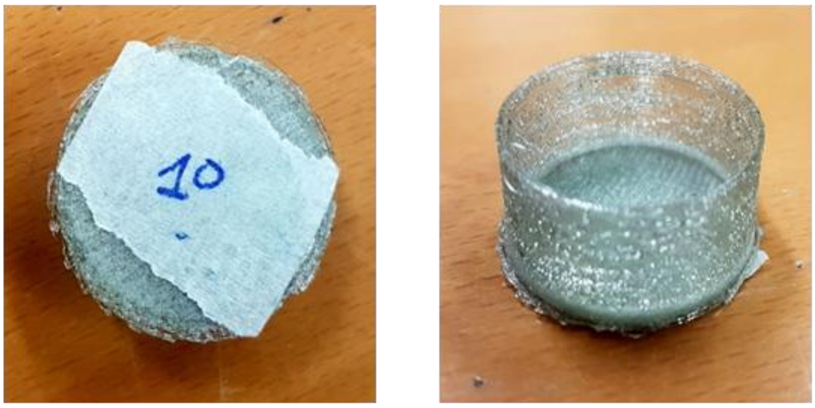

Figure 44. Printing with filament referenced to test 10 (Scenario 1.1 3Devo)

Likewise, Scenario 2.1 was performed under similar conditions but adding an amount of virgin PET. In this scenario, it was not possible to make neither filament nor printing. Therefore, it is possible to conclude that working with a higher percentage of recycled flakes will lead to clogging problems.

On the other hand, Scenario 3.1 mixes a considerable quantity, 50% of the feedstock used, of processed industrial material and results are highly improved. This filament has quiet good qualities such as not appearance of bubbles, be elastic and have a diameter size quite stable. These characteristics can be noted in Figure 45.

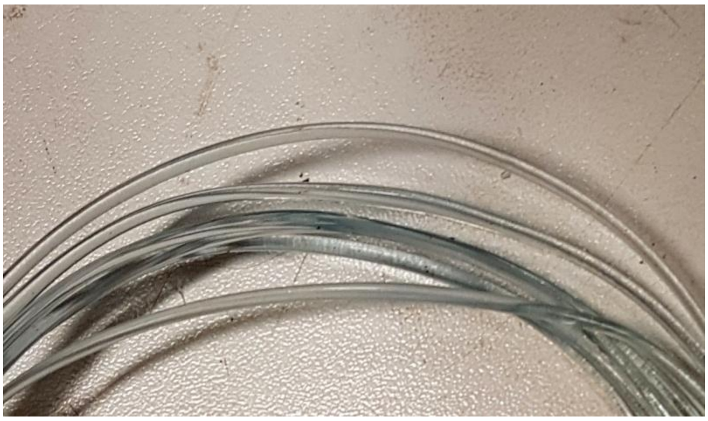

Figure 45. Filament extruded in test 8 (Scenario 3.1 3Devo)

Printing with this filament lead to a good product being highlighted by its solid structure and an acceptable tensile strength. However, it presents a thin structure, noted by its transparency, and micro holes.Figure 46 illustrated the printed specimen under the conditions of Scenario 3.1.

Figure 46. Printing with filament referenced to test 8 (Scenario 3.1 3Devo)

Regarding the Scenario 4.1 whose percentage of virgin PET was higher, both operations presented good results with certain peculiarities. The colour of the filament is whiter besides of being the most transparent and elastic. We could infer that virgin material tends to transparency and elasticity (shown in Appendixes Fig. 78)

After performing all the scenarios and analysing the results it is possible to conclude that 3Devo Composer 450 with recycled material will not lead to filament and products with the required quality. Moreover, the equipment is not stable and reliable. In many test the equipment was clogging and the operation were interrupted. It was proved that varying parameters such as extruder speed, fan speed or the temperature of the heaters in order to avoid clogging was not solving the problem. This instability implies a great loss of material as a consequence of not being able to make proper filament and deal with the interruptions. On the other hand, it was noted an improvement when the recycled flakes were mixed with virgin material.

The summary of the results of each scenario is presented in Table 7.Test numbers corresponds to the sample performed in the extrusion operation under the conditions specified in Fig.89 (Appendixes) .

Table 7. Description with the results obtained in the different scenarios with 3Devo-Composer 450

	Test	Filament	Printing
1.1	4,5,10,11,12	Crystalline. Good elastic properties. Not bad quality but dirt becomes the filament unavailable. ✗	Printing of some filament without dirt was OK. Some thinner layers but quite uniform. Neither holes nor fragility. ✓
1.2	1,2,3	Not able to extrude something. ✗	No printings ✗
2.1	9	Not able to extrude something ✗	No printings ✗
3.1	8	Good properties. Crystalline, elastic and with no bubbles. ✓	Solid structure and acceptable characteristics. Sometimes layers a little thin. ✓
4.1	6,7	Stable diameter. Crystalline (more white due to higher virgin PET's %). No bubbles and quite good the parts with no dirt. ✓	It is not fragile but mesh a bite thin. It seems transparent but OK anyway. ✓

The first idea was to intend the extrusion by using the extruder for scholars 3Devo-Composer 450 to make filament through both frugal and affordable process. This machine is ten times cheaper than a semi-industrial extruder (AEV 331) and much easier to manage. However, 3De presented problems dealing with PET material as already described. Therefore, It makes no sense to try to demonstrate the extrusion process and nine times of 10 to have to stop the demonstration because is not working and only was possible to profit a small amount of recycled flakes with a consequent waste of time, material and money. 3Devo was no reliable and therefore an semi-industrial extruder turned to be a solution for filament production.

AEV 331 extruder was used with the purpose to improve the 3Devo extruder's results increasing the quality of filament and infer if the recycled material is the problem or if the problem is from the equipment. As well as it was done with the 3Devo extruder, experimental tests were done under different conditions corresponding to variation on variables such as the percentage of recycled material used , implementation of cooling system which this extruder does not incorporate and a sample proving with material with glue to experiment if that semi-industrial extruder can eliminate by its melting process. Testing with flakes containing glue was only done in Scenario 1.3.1, because after checking its results and what we inferred from 3Devo, no further tests were necessary to conclude its invalidity.

Thus, it was proved AEV 331 with the same recycled flakes in order to check if the results were different. It is important to mention that due to the characteristics of this machine, a bigger nozzle and more rotational power as well as upper limits of extruder speed, leads to a significantly reduction on the clogging problem. Figure 47 illustrates a view of the extruder and the result of many meters of filament produced without interruption ,what proves that this machine is a good option for equipment. By contrast, when we were working with the 3Devo extruder, it was very difficult to produce a reliable filament.

Figure 47. View of AEV 331 extruder while is working

At the beginning, 100% recycled flakes were extruded without a cooling system because this machine does not incorporate a refrigeration system as 3Devo did. The material extruded presents a great fragility and a loss of elasticity, which are two properties where PET is characterised for. Besides, the colour of the filament is completely opaque. If within the scenario of 100% recycled flakes (Scenario 1.3), we have add the variable of not removing glue, its quality is even worse due to the appearance of hard balls inside the filament. As was reported, it was tried with flakes with glue to prove if AEV 331 was capable to melt and remove these particles that causes a problem. Figure 48 shows the aforementioned features (Scenario 1.3.1).

Figure 48. Filament extruded in test 15 (Scenario 1.3.1 AEV 331)

Subsequently, in Figure 49 the printing results of this filament are presented. It is possible to verify the fragility of the material and the lack of quality in the printing process. This fragility is mainly related to recycled material whose crystallinity is higher. It can be noted that the product below is completely broken cause it has low impact strength. Besides, its structure is very thin and some holes have appeared. The other samples of Scenario 1.3, based on 100% recycled flakes use, are attached in Appendixes (Figures 72,73,81,82,83,86,87).

Figure 49. Printing with filament referenced to test 15 (Scenario 1.3.1 AEV 331)

Afterwards, experimental work continued the procedure by mixing recycling material with virgin PET in order to try to avoid this fragility. Testing Scenarios 2.1 and 3.1 can be noted a slightly improvement related to the fragility problem, but still not good enough. It could be concluded higher amount of virgin PET turns the product more elastic and its colour becomes whiter, however, it should be proved the incorporation of cooling system to test a qualitative leap. Following, Figures 50 and 51 are showing one sample of extrusion and printing coming from a mixed feedstock (Scenario 2.1). You can also see the other samples in the Figures 74 and 85 (Appendixes).

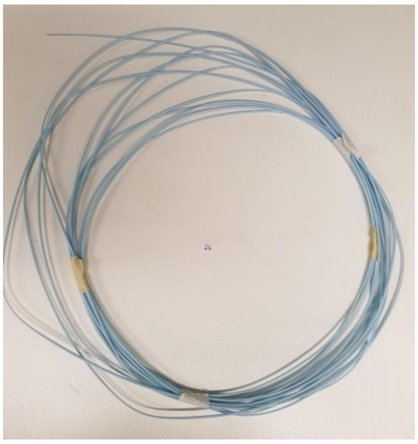

Figure 50. Filament extruded in test 26 (Scenario 2.1 AEV 331)

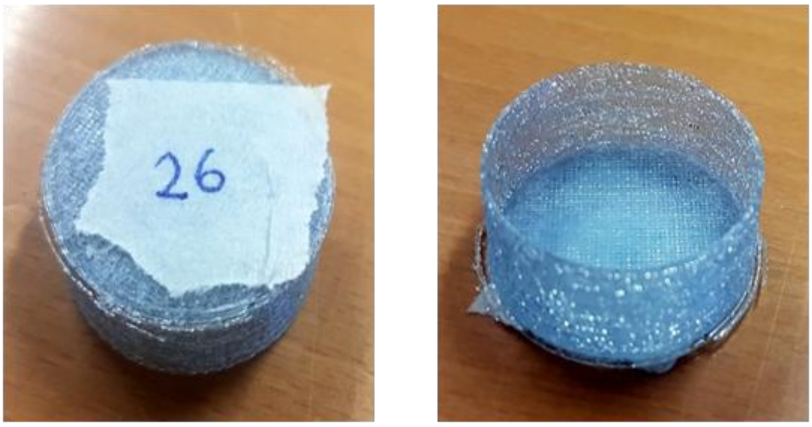

Figure 51. Printing with filament referenced to test 26 (Scenario 2.1 AEV 331)

The problem was not solved, in Fig. 50 can be noted the opacity of the filament what means a high crystallinity that results to be a brittle material. Moreover, the product of Fig.51 presents a low impact strength. As using virgin flakes did not eliminate the problem of fragility leading to a slightly improvement, it was incorporated different refrigeration systems at the exit of the nozzle in order to cool down faster the material (see Scenarios 1.1, 1.2, 3.1). Two mechanisms were considered to accomplish this task: i) water bath cooling ; ii) inclusion of a fan.

The water bath cooling, performed in Scenarios 1.2 and 2.1. The system is based on a tank full of cold water, which it is constantly renewing itself by feeding through the network. So, the filament is coming out from the exit of the extruder and it goes directly to the cold water what it reduces his temperature much faster. Figure 52 below shows how the water bath was installed in the extrusion line. It is located between the exit where is coming out the filament and the belt where it runs with tension and takes shape.

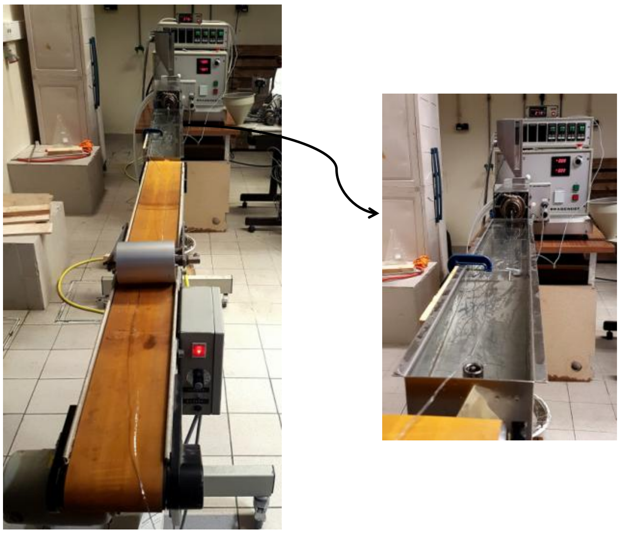

Figure 52. Views of the water bath cooling

This type of mechanism presents turn difficult to get the correct diameter size because in contrast to the extrusion without water bath, the filament does not go straight to the conveyor belt that provides the force to run the product until the roll and shape it. In that case, when the filament goes straight to the water it adapts immediately a random form. For this reason, the filament is accumulated in the tank and does not have the enough tension to run through the belt.

Once the filament was being produced with the water bath as cooling system, it was possible to observe that it had different characteristics in comparison with extrusion without cooling. First of all, the material presented a clear improvement about fragility concerns. Their features are much more similar to virgin PET after cooling the material with water: transparent , clear, elastic (see Fig. 53).

Despite the improvement of the fragility, it appeared another quality problem: bubbles. This is always a concerning issue that is tried to be avoided because the 3D impression will reduce quality. Therefore, it was concluded that using a water bath for cooling, is highly related to the moisture inside the filament, because PET absorbed fluid before condensation. Figure 51 illustrates that bubbles emerged along the filament made in Scenario 1.2. You can also see in Appendixes Fig. 75, results of Scenario 3.1 which is performed under the same system just differing of using a higher percentage of virgin PET.

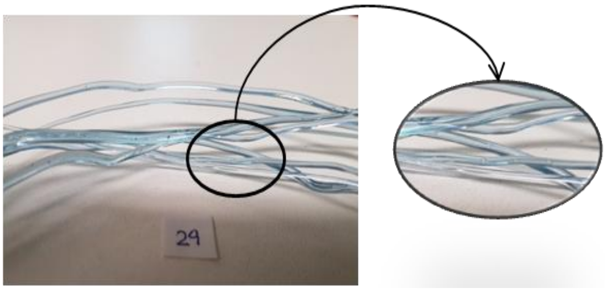

Figure 53. Bubbles emerged after this type of cooling system (Scenario 1.2 AEV 331)

Apart from that occurrence, it could be noted that filament presents a high transparency and a clear aspect. In addition, its degree of crystallinity has suffered a decrease because you could fold the filament without breaking it, which means that fragility has decreased. The target was to obtain a filament of 1.75m cooled under these water bath conditions in order to procedure to the 3D printing stage and to test the quality of some printed sample. So, facing the difficulty to achieve a diameter size within the limits, it was intended to extract a short filament able to proceed to the printing ,with the purpose to analyse how influences water bath in the mechanical properties. Figure 54 corresponds to the printing of recycled filament (Fig. 53) from the AEV 331 extruder incorporating the cooling system of a water bath.

Figure 54. Printing with filament referenced to test 29 (Scenario 1.2 AEV 331)

It was possible to verify that the quality was better in comparison to other scenarios that presented results with cracks, big holes or super thin structure, but anyway it presents certain particularities. One remarkable feature is that in the cylindrical part the piece presents some small hole which are might be caused due to the aforementioned problem of the bubbles. Moreover, it can be noted some clear parts derived from a lack of solidity.

The colour of the printed product was blue and presents transparency as his original filament. An additional consideration is that was solved the characteristic problem of fragility corresponding to other printing samples from filament made without any cooling system. For instance, compared to Fig. 49 which broke easily, its impact strength was really improved with the incorporation of this cooling system.

It could be inferred that work with this type of cooling system decreases the crystallinity, which improves the quality of printing product. However, the emergence of holes decreases the quality of the specimen and it could not pass in quality tests. Consequently ,it would be good to prove other methods with the purpose to avoid these holes related to bubbles but keeping the others aforementioned good features.

Regarding the Scenario 3.1, the extrusion is performed under the same cooling system than Scenario 2.1, water bath, but it was provided with a mixture of virgin PET and recycled flakes in order to test if the quality of the filament improved. It was proved if the combination of water bath cooling besides of the introduction of virgin PET brings results more favourable.

Products of Scenario 3.1 present characteristics quite similar to Scenario 1.2. The main remarkable phenomenon is the bubbles occurrence, which has not disappeared in this case either. Therefore, we can verify that this mechanism brings moisture that appears inside filament in form of bubbles. According to its mechanical properties, the filament produced in Scenario 3.1 is elastic and the tensile strength is lower. The colour is more transparent and tends to be whiter (shown in Appendixes Fig. 75).

The results of the printing operation with the filament of Scenario 3.1 shows a structure quite stable in spite of presenting some thin parts. It appeared some micro holes. Printed product has a quite uniform mesh. Concerning fragility, it shows a high tensile strength. It could be concluded that the results are better, however, it could be highly improved. A more dense mesh and the elimination of micro holes are the main issues to face (shown in Fig. 88 Appendixes).

In Scenario 1.1 the fan was applied as cooling system. This allows to cool down the filament once it is coming out from the nozzle. This cooling system is quite simple and therefore frugal innovation concept is respected. In Figure 55 is possible to visualize how the system of fan cooling is composed.

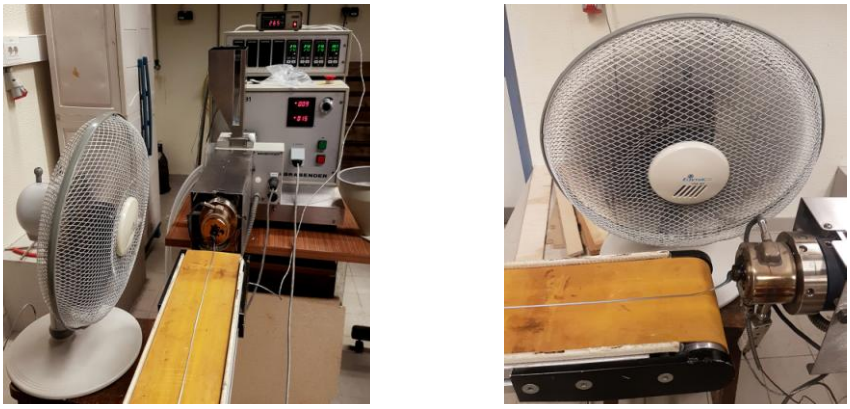

Figure 55. Fan used as a cooling system (Scenario 1.1 AEV 331)

The fan is still in the same position providing air with the appropriate power directly to the machine outlet. By this way, this scenario runs as usual by adding an innovative solution.

Therefore, it will be used to test if with a faster cooling down through this device, the quality of the filament is improved.

This type of mechanism allows an easier calibration of the filament diameter, which is better than the water bath system. The filament coming from this extrusion, it was possible to obtain a clear filament of blue colour with no bubbles besides of having great mechanical properties. Two concerning problems have been solved: it has been improved the fragility compared to scenarios with no cooling system (1.3, 2.1, 3.2) and moisture has been removed in contrast to water bath scenarios (1.2, 3.1). Moreover, the filament process become more reliable being possible to produce more meters of uniform filament without interruptions. Figure 56 below shows the filament cooled down by a fan and using 100% of the flakes from recycled PET bottles, Scenario 1.1. It is possible to appreciate that the quality of the extrusion is better.

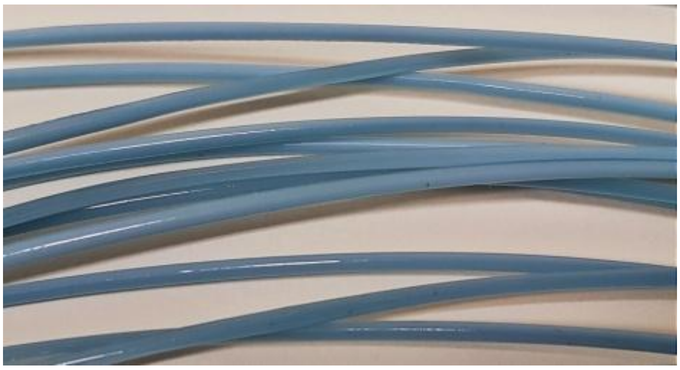

Figure 56. Filament extruded in Scenario 1.1 AEV 331

Printed product done in Scenario 1.1 supports what it was reported before: extrude with a fan cooling brings an efficient solution and a higher quality of specimens. First of all, the most remarkable feature was the dense mesh that compounds the basis of the specimen creating and strong structure difficult to break. The plastic solidifies properly after printing and the rest of the piece have good characteristics as well. Regarding the colour is blue in the same way as the filament from which it comes ,100% recycled material. It presents a good texture without any particles of dirt inside the piece. Besides, the problem about fragility has disappeared and the figure presents a rigid structure but conserving elasticity, what it means is not splitting it. These features can be noted in Figure 57.

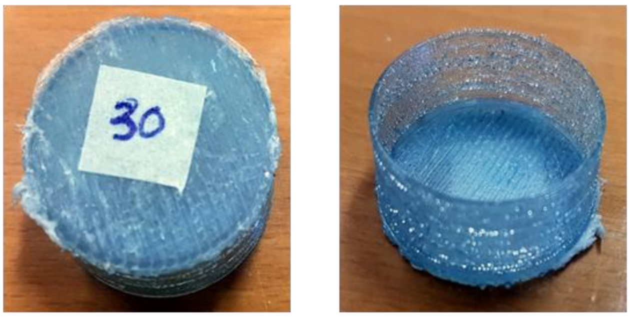

Figure 57. Product printed in Scenario 1.1 AEV 331

Once it has been described all the employed scenarios, Table 8 summarizes the conclusions extracted into each type of experimental work. It shows which are the best solutions and the main reasons to support them.

Table 8. Description of the obtained results in the different scenarios with AEV 331

	Test	Filament	Printing
1.1	30	It has a great quality. It is elastic, clean, without bubbles and able to make a lot of meters of filament with no interruptions. ✓✓	It presents the best quality. It has a stable strong structure with a dense knitting. No holes and a good blue appearance. ✓✓
1.2	29	Good elasticity and clear appearance. Problems to get the right diameter and a lot of bubbles inside the filament. ✗	It presents a weak mesh and appears holes in the specimen. ✗
1.3.1	15,16,17,18,19,20,21	Very fragile, it breaks too easily. It is opaque and glue is bigger than the diameter size limit. ✗✗	Same fragility in printing. Prone to breaking easily. Good composition of layers and no holes but very cracked. ✗✗
1.3.2	13,14,22,27	Stable diameter but problems with fragility. It seems to lose the PET properties. Opaque colour. ✗	Structure too fragile. Requires more cooling down time once it is made. Mesh is so weak and appears holes as well. ✗✗
2.1	25,26	It was able to make a lot of meters with a stable diameter. It is fragile but less than 1.3.2 .Colour blue opaque. ✗	Has easy to break. Bottom support of the specimen was dense but fragile. Weak structure and with holes. ✗
3.1	28	Similar than 1.2 . Characteristics according to PET patterns, good elasticity and manageable. It is transparent but a lot of bubbles appear which decrease quality greatly. ✗	Structure quite stable. Some layers are thin but quite uniformity. Results were not bad. ✓
3.2	23,24	Stable diameter but still problems with fragility (less than the higher recycled %), just OK. Opaque white colour. ✓	Layers quite uniform. Some parts of the printing are quite dense, others more thin and weak. No holes. ✗

Regarding the washing operations, it was a matter of discussion to establish if the reported variables (water temperature, agitation, water flows) influence on the final result. As we do not have a tool to assess the quality after washing, it was proposed the idea to test if washing scenarios were in connection with the quality of filament or printing. It was concluded some statements: washing operation did not eliminate the glue, highly damaging, as well as inferring the no relation between the washing scenarios and the posterior quality of the products. For instance, if you want to study the impact of the water temperature on the results and prove to extrude the same flakes washed at room or elevated temperature, extrusion does not suffer any difference. This conclusion can be verified by the scenario that brought the best filament, whose washing procedure was the most simple: room temperature, agitation by a glass bar, no-prewashing and reusing the rinse water. Therefore, as the different scenarios do not present differences, it will be performed by the these conditions which have the lowest costs and the major saving of water. With regard to safety issues in washing process, children are able to perform the whole process cause there is no danger either complexity.

5.4 Process characterization for children

Bases on the aforementioned results, this section intends to describe how the system should work to be a successful solution for children. It highlights the best environment to perform the full cycle as well as providing a series of advices and considerations to take account to follow a suitable procedure.

The process will be explained by order of operation. First of all, there is a previous step to the operations that is the collection of PET bottles and remove of its labels. It does have any special requirement cause does not imply any danger. Children could perform this step easily without any regard for safety issues.

Subsequently, it is performed grinding operation that encompasses two main steps: pre-grinding and grinding. Pre-grinding could be done by children cause the employed tool, scissors, is simple to use and it is not dangerous. One recommendation should be to wear glasses to prevent contact between material and eyes. Regarding cutting conditions, pieces must be smaller than 60x80mm. It is irrelevant if pieces have irregular form or different size but must be within this constraint. On the other hand, manage the grinding equipment is a task done by an expert. Therefore, children must be in a safety area keeping distance with the cutting mill. Related to bottom sieve, extruders work perfectly with a mesh of 6mm thus it has been used a 4mm bottom sieve to ensure the success. The output flow is on an average net mass flow of 13,83 grams per minute.

Regarding the washing operations, it was a matter of discussion to establish if the reported variables (water temperature, agitation, water flows) influence on the final result. This operation will be performed under Scenario 1.1.1 related to agitation mode and, under Scenario 2.2.2 related to water flow. In this kind of agitation, the main tool is a glass bar used to increase the contact of the material with the fluid. On the other hand, it has been established the water flow scenario with greater water saving which only has two steps, washing and rinsing, due to the elimination of pre-washing. At the beginning, kids will weigh an enough amount of flakes (around 200-250g) to achieve the extrusion and printing operations of one scholar demonstration. Later, they will dump these flakes into a tank with 2l of room water followed by agitation step. At this point, material will be differed by densities and children will remove the floating flakes using a net. Once the previous step is done, they will put detergent inside the same water and effectuate the washing operation. Subsequently, material is decanted from the dirt water and will be put into another tank with 2l of clean water, at room temperature as well, to do the rinsing step. Finally, material will be decanted again, drain as possible and stored in bags. Half of the rinse water is reused to wash the next batch. With regard to safety issues, children are capable to perform the entire operation because there is no danger either complexity. Anyway, it is advisable to use a lab coat to avoid dirt and get wet.

Washing operation is followed by drying because product remained completely wet and moisture must be removed. It has been established the suitable value for the two main parameters: 150° of temperature and 5h of operating time. In that case, children will have the mission to prepare the aluminium paper used as a box inside the oven and, control the potentiometer that determines the temperature. To put the material inside the oven is preferably performed by an adult due to the risk of burns.

Regarding the extrusion operation the equipment presents the greatest complexity of all. There are a lot of parameters that must be taken into consideration to make a suitable filament. These parameters could be classified into three groups: 1) Temperature of the heaters that influence the mechanical properties of the material and its fluid state; 2) Speeds, whose main function is to calibrate the diameter size. In contrast to extruder for schools which calibrate the thickness manually, in that case you will have to control both conveyor belt speed and screw speed while is measuring with the measuring instrument; 3) Cooling system, it is essential to determine this type of system cause it is highly related to the quality of the filament. It influences to the crystallization of the material as well as its fragile behaviour. The value of all these parameters are shown in Figure 64 below. Anyway, each experimental test could suffer little variations and children could measure the thickness and help to calibrate this parameter by varying the settings.

About safety issues, this operation should be performed by an expert due to the difficulty to manage the brabender single screw extruder. In addition, children must keep the security distance to the machine which is working to a very high temperature. They will be able to attend the entire operation and see how the filament is being produced. In addition, they will be explained how the machine works, the importance to determine each setting and what is considered to have a quality product. When operation is over, they can handle the product and see the transformation from a plastic bottle to filament ready to be used for the last operation, printing. In that point Its awareness about achieving an affordable circular economy's solution will be arisen cause they can see the transformation to a new product, not only bottles cut into pieces as flakes.

With regard to the last operation, printing is performed to make a product that represents the completion of the cycle extracting the value of the plastic waste. Children could be engaged in the activity by doing tasks such as cleaning the print bed with the LAC spray, manage the filament and to fit it inside the tub conducted on the nozzle or take the product stuck in the print bed with a trowel. According to constraints for children, it must be taken into consideration that to handle the print bed inside the 3D printer is a risk because of its high temperature. That step should be done by an adult or by children correctly informed on how to proceed and using the suitable clothes (thermal insulting globes). This operation was performed under the conditions shown in Fig. 64 which are pre-sets values when we are working with this type of material. We can verify they are valid settings due to its good printing which presents a high quality product as it was Scenario 1.1 with AEV 331. Furthermore, an expert will be in charge of the control monitor. In order to be an interesting activity and related to the courses taught in schools, children will have the opportunity to create objects in connection with their subjects. Some of the examples will be shown below. Figure 58 illustrates a 3D printing example related to mathematics. Requires 5 bottles of 1,5l to produce 0,1kg of filament and, it takes 5 hours printing time.

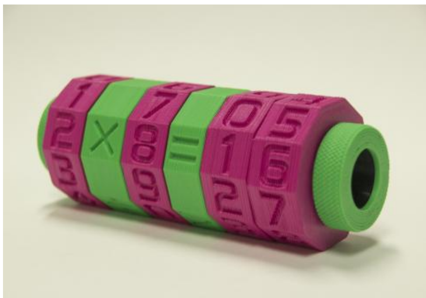

Figure 58. 3D printing example related to mathematics

Figure 59 shows a 3D printing example related to chemistry course. This printing requires the collection of 2,5 bottles of 1,5l to extrude 0,05kg of filament and, it takes 3 hours printing time.

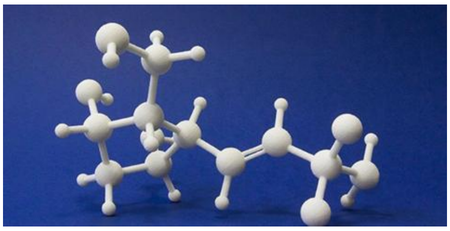

Figure 59. 3D printing example related to chemistry

Figure 60 shows a 3D printing example related to geography course. This printing requires the collection of 0,5 bottles of 1,5l to extrude 0,01kg of filament and, it takes 1 hour printing time.

Figure 60. 3D printing example related to geography

Figure 61 shows a 3D printing example related to science course. This printing requires the collection of 2,1 bottles of 1,5l to extrude 0,043kg of filament and, it takes 4 hours printing time.

Figure 61. 3D printing example related to science (1)

Figure 62 shows another 3D printing example related to science course. This printing requires the collection of 5 bottles of 1,5l to extrude 0,1kg of filament and, it takes 5 hours printing time.

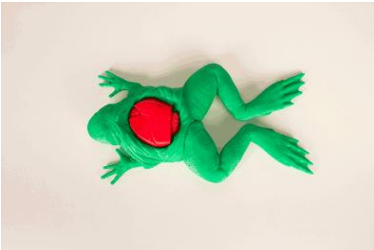

Figure 62. 3D printing example related to science (2)

Figure 62 shows a 3D printing example related to history course. This printing requires the collection of 1,85 bottles of 1,5l to extrude 0,038kg of filament and, it takes 4 hours printing time.

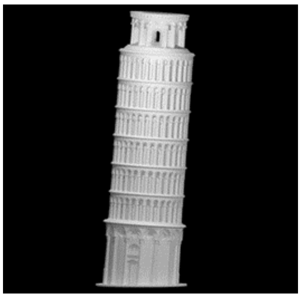

Figure 63. 3D printing example related to history

In this way, apart from developing a solution derived from the circular economy with the objective of reducing plastic waste and changing the management of current resources, schools will have the opportunity to teach children this issue while providing useful tools for teaching of the courses.

Finally, the following scheme summarises the key parameters of each operation besides of highlighting the values that have been set for achieving the best results. The aforementioned sections have already reported how varies the quality of the product when each parameter is being changed. At this way, these guidelines supported by the experimental work should be followed in order to accomplish the goal of the project which makes suitable filament for 3D printing (a specimen at the end) through recycled plastic. Thus, Figure 64 shows the overview of the main parameters of the different processes.

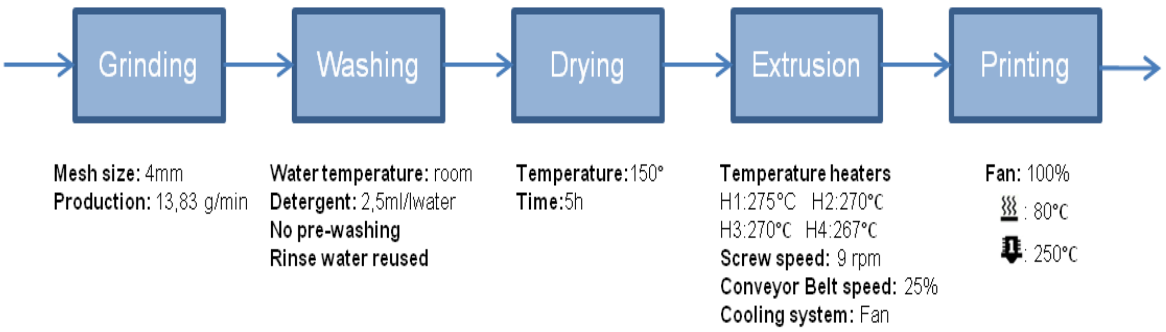

Figure 64. Scheme of the key parameters of the different operations

5.5 Costs

The budget is a fundamental element when assessing the viability of your execution. The economic resources are divided into direct and indirect costs. The first ones refer to costs directly attributable to investment on the project, and in general they can be grouped into personnel, amortizable material and non-amortizable material. The costs derived from the execution of the project, such as operating and administrative expenses, constitute indirect costs.

This point will include the investment made to accomplish the project in addition to the expense in carrying out each operation of the entire process. For this, two main aspects must be taken into account: cost of the material used as well as the investment in machinery and the salary of the project producer.

This project should be an affordable solution for schools. Thus, it was reported that the solution is based on frugal concept. We will intend to minimise the budget by finding cheap tools able to perform the operations. It is described in each operation the cost of the necessary tools and equipment to perform. Regarding the time spent to conduct one scholar demonstration, it will be calculated according to the necessary amount of material for its performance, which 250 grams of flakes are expected to be enough.

Regarding the process of the proposed solution, there are some equipment essential to perform the operations. Despite having developed the process with some expensive machinery that has an universal use, we will try to find other cheaper models that serve our specific solution (deal with PET material). Firstly, grinding operation includes the tools to do the pre-grinding steps (scissors) and the cutting mill (NASER Brand model NPCP-100J). Washing process will be the cheapest operation because it is just necessary some simple tools such as plastic nets, tanks, glass bar, net bag, detergent and do not require of machinery. Related to drying operation the budget will be mainly destined to the acquisition of the oven, which is valued at 600€ (model DZF-6020). Its operative costs will be related to the use of aluminium paper. Last operation of the process, 3D printing, has an operative costs of 6€ (3D LAC spray) and, an investment of 1.000€ in the 3D printer (Original Prusa i3 MK3S 3D printer) that works with PET material.

Related to extrusion operation, due to the high price of acquiring an semi-industrial extruder two options were considered: buying or renting.

- Buying Scenario

Two are the main equipment to perform this operation, the brabender single screw extruder and the conveyor belt, with a price of 78.820€ and 6.970€ respectively. The overall cost of both equipment is 85.790€ and according to being machinery within movable property, its useful life will be estimated in 10 years. Thus, it has a lineal depreciation of 8.579€ per year.

The following Table 9 illustrates the investment and the operative costs, which is mainly based on operating time, classified by the five operations that encompasses the full process. These are the costs referred to acquisition scenario.

Table 9. Budget to perform the process divided by the five operations (Buying Scenario)

		Operative Costs	
Operation	Investment (€)	Money (€)	Time (h)
Grinding	3.015	-	2
Washing	10	6	1
Drying	600	4	6,5
Extrusion	85.890	-	2
3D Printing	1.000	6	1
Total	90.515	16	12,5

- Renting Scenario

Extrusion equipment will be used under renting conditions. Therefore, it has to be paid each time the equipment is used. It was considered a deal of 300€/demonstration with the university, lend us the equipment to perform this operation. It has to take account what mode is more rentable. The cost results will be shown in Table 10 as well divided by the five operations related to investment and operative costs. Operative costs encompass the expenses through all the process such detergent and bags in washing, aluminium paper in drying or 3D LAC spray in 3D printing, whereas time is referred to personnel to take into consideration salary. Between the two modes to perform the extrusion, it can be noted the budget is only differed in this operation because the others will operate in the same way.

Table 10. Budget to perform the process divided by the five operations (Renting Scenario)

Operation	Investment (€)	Operative Costs Expenses (€)	Time (h)
Grinding	3.015	-	2
Washing	10	6	1
Drying	600	4	6,5
Extrusion	100	300	2
3D Printing	1.000	6	1
Total	4.725	316	12,5

Thus, both scenarios will be compared:

$$\text{Scenario buying amortization: } \frac{78.820\ (€) + 6.579(€)}{10\ (\text{years})} = 8.579€/\text{year}$$

If renting scenario has a deal of 300€/demonstrations, it will be calculated the number of demonstrations up to be recommendable each of the two options:

$$\frac{8.579\ (\frac{€}{\text{year}})}{300\ (\frac{€}{\text{demonstration}})} = 28{,}6\ \text{demonstration/year}$$

If the number of performed experiments per year is > 28, it is recommendable the option Acquisition Scenario.

If the number of performed experiments per year is ≤ 28 , it is recommendable the option Renting Scenario.

Figure 65 illustrates the project assessment related to costs of the proposed circular economy solution for schools. It summarizes all the expenses as well as operating time of one demonstration.

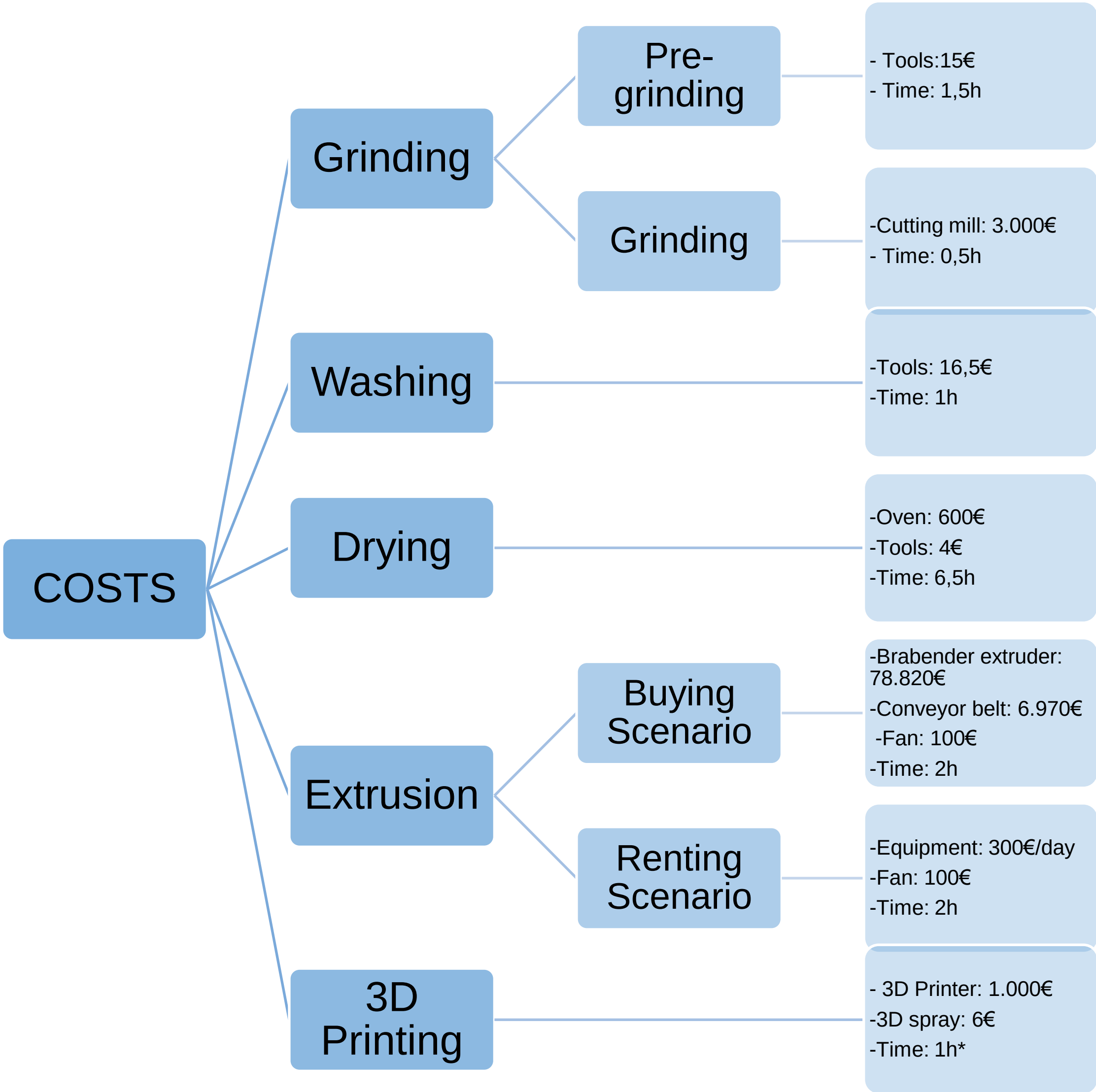

Figure 65. Assessment of the project's cost

**The printing time will be according to the product. Guide values in Section 5.4*

6. Conclusion

This study shows the development of a solution to integrate plastic circularly. The huge growth that plastic usage has experimented recently, brought the topic into discussion due to the ecological problems it causes. Therefore, it is necessary to build alternative business models to make a sustainable world with the main goal to save resources and reduce waste, plastic in our case. Moreover, it was also reported that 3D printing technology emerged as one of the most scalable application to introduce plastic material into circular economy.

In this regard, it is proposed a solution derived from the desire to change plastic management policies intending to give visibility to a current concerning issue showing new ways to extend the life cycle of resources as well as extracting value from the waste. This solution is based on circularity by profiting discarded PET bottles to finish the process by making a product thanks to a 3D printer. This process is a frugal process intended to be used as a demonstration for schools where children can see the full process in addition to participating in product development. We can infer that getting involved scholars to this kind of demonstration its awareness will be raised to create a prosperous future taking care of the environmental problems. As it is not a commercial product that brings us benefits, we have to take into consideration that this process must be performed under frugal conditions in order to be an affordable solution.

Developing the aforementioned idea some conclusions can be drawn. Starting with technical parameters, most difficulties are related to the extrusion operation. Achieving a good quality in the filament having recycled PET material as feedstock is quite complicated being necessary a large number of experiments to determine the suitable performing conditions. We can infer that scholar extruder is not appropriate for this type of material. Thus, a semi-industrial extruder is required as a better choice to work with recycled PET. Regarding this semi-industrial extruder, main issues were dealing with the diameter of the filament which is manually calibrated and, with its quality which presented a great fragility. Temperature and rotor speed have been set to work properly (section 5.4) and achieve a right thickness whereas fragility, a concerning problem that emerges due to the increased crystallinity in recycled PET material, it was highly improved by adding a cooling system, a fan, at the exit of the nozzle.

Moreover, we can conclude some statements related to the rest of operations. During grinding operation, a pre-step where glue is removed is required. Glue brings low quality to the filament. Concerning the importance of the washing performance, it was inferred that the different scenarios do not have much influence on the final result thus the best choice is the option where it is saved more water and money. Regarding drying operation, two are the key parameters to determine: working time and temperature. It was concluded that setting 5h and 150°C, respectively, flakes were correctly dried. On the other hand, we can conclude that for better print quality, we mainly have to get a suitable filament in the extrusion operation.

Regarding to accomplish the scholar demonstration, there are equipments that should be performed by an expert such as cutting mill, extruder or 3D printer due to its higher complexity or safety issues. However, children could participate more actively in other operations like pre-grinding, washing or drying.

Following the presented guidelines throughout the project and the set working conditions, we could conclude that is possible to perform the entire process to make a 3D printed product from PET bottles. Extrusion scenario 1.1 presents the successful solution providing a good filament characterised by being elastic, clean, without bubbles and a right size diameter. The quality of the final product after 3D printing was good as well. Moreover, it should be considered that having a very high-quality product is not an indispensable requirement in this type of demonstration for children.

Related to costs, it could be divided into investments and derived from performing operations. It must be taken into consideration two possible scenarios, buying or renting, concerning the extrusion equipment whose acquisition could result unaffordable due to its high budget. As the proposed solution. As the number of times schools do this activity will not be very high, as it could be a product industrialized by factories, the most logical choice is to deal with a renting concept.

For future projects, if the budget is increased it would be possible to create new business model with the purpose to increase the quality of the products thus achieving to sell them commercially at the end of the process. On the other hand, following the same path to do scholar demonstrations, other type of waste could be explored. It means that deal with new materials would change the suitable parameters of each operation whose specific solution should be adapted for each case. Besides, it includes to prove if 3devo extruder works properly with other recycled materials.

7. References

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8. Appendixes

8.1 Extrusion with AEV 331 extruder

This section will provide more figure about the semi-industrial extruder, brabender single screw, to go in depth how the machine is constituted and how it works. Figure 66 illustrates a front view of the AEV 311 extruder where you can see as well the monitor of control. On this monitor, you can increase or decrease the temperature of each heater respectively. Furthermore, at the bottom of these monitors there is a device which includes a potentiometer able to vary the speed of extrusion. In addition, the two bottoms green and red turn on and off the device.

On the one hand, at the left of the figure there is a grey device that contains the hopper where the feedstock enters to the extruder. On the other hand, it can be observed as the material is coming out from the nozzle directly to the yellow conveyor belt.

Figure 66. Front view of the AEV 331 extruder

Figure 67 shows a more general view of the machine. It can be appreciated how the material is coming out from the exit and is becoming in filament passing through the conveyor belt which helps it shape due to the pressure the roll exerts when the filament goes under. Another important thing to highlight is the potentiometer of the conveyor belt, where the value that presents at a certain point, it is the percentage of the motor power is being used.

Figure 67. General view of AEV 331 extruder

8.1.1 More samples of extrusion

The following figures show more results of extrusion operation. Each one illustrates a filament referred to its sample number and performed scenario.

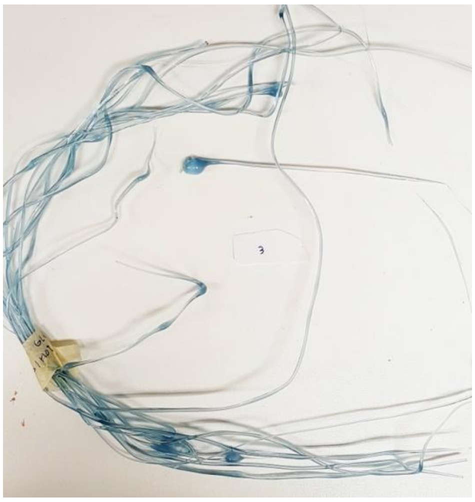

Figure 68. Filament extruded in test 3 (Scenario 1.2 3Devo)

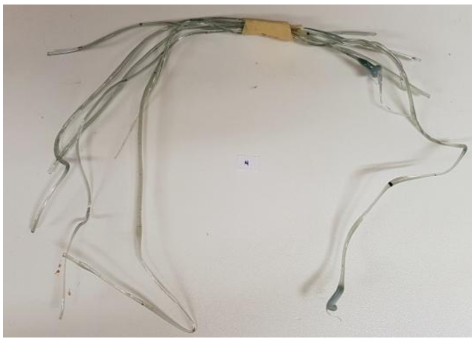

Figure 69. Filament extruded in test 4 (Scenario 1.1 3Devo)

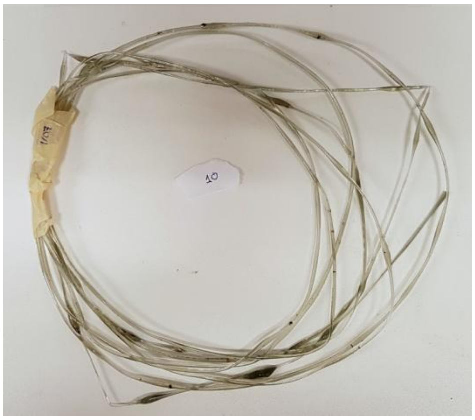

Figure 70. Filament extruded in test 10 (Scenario 1.1 3Devo)

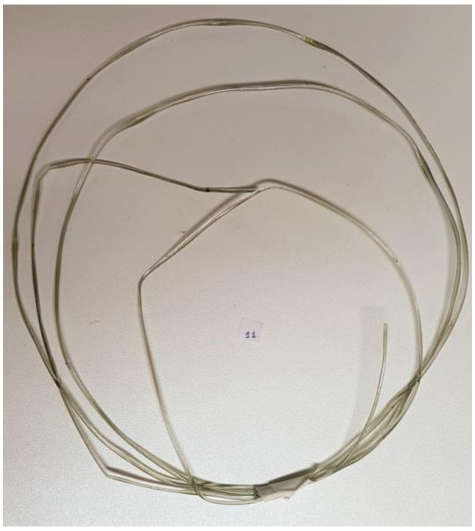

Figure 71. Filament extruded in test 11 (Scenario 1.1 3Devo)

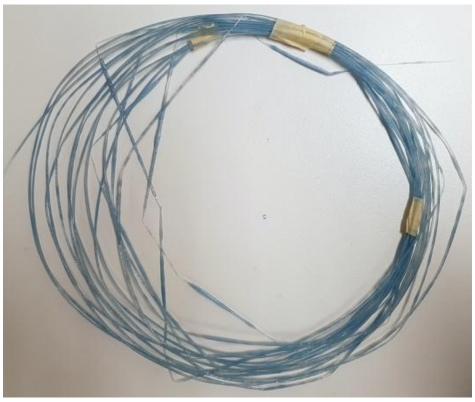

Figure 72. Filament extruded in test 13 (Scenario 1.3.2 AEV 331)

Figure 73. Filament extruded in test 19 (Scenario 1.3.1 AEV 331)

Figure 74. Filament extruded in test 25 (Scenario 2.1 AEV 331)

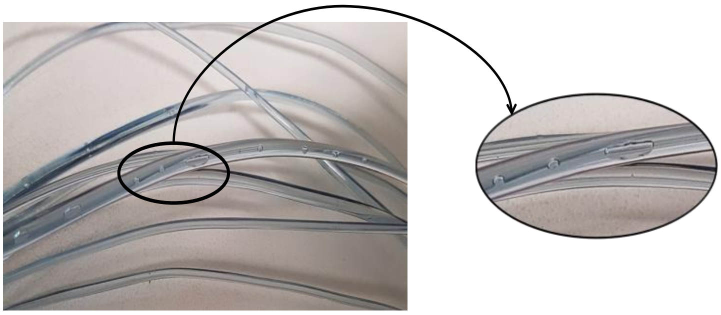

Figure 75. Filament extruded in test 28 (Scenario 3.1 AEV 331)

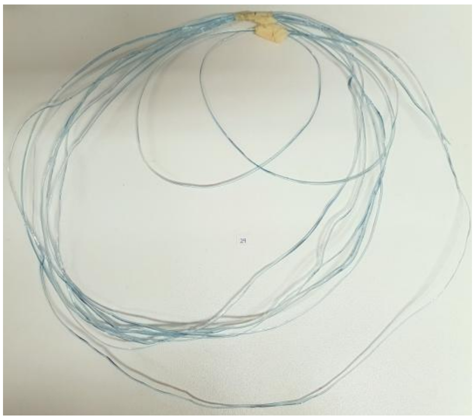

Figure 76. Filament extruded in test 29 (Scenario 1.2 AEV 331)

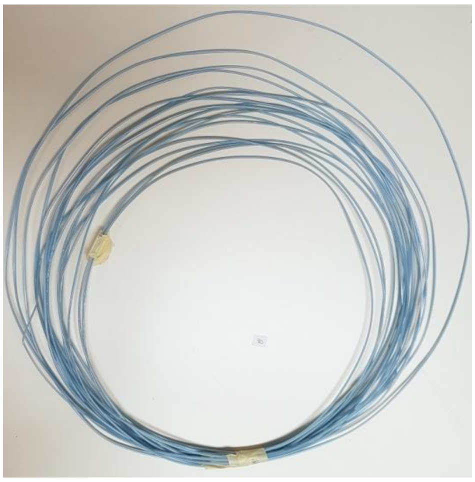

Figure 77. Filament extruded in test 30 (Scenario 1.1 AEV 331)

8.1.2 More samples of the 3D printing operation

The following figures show many of the results obtained in 3D printing with the different types of filaments. The illustrations are classified according to the number of test performed in the extrusion process.

Figure 78. Printing with filament referenced to test number 7 (Scenario 4.1 3Devo)

Figure 79. Printing with filament referenced to test number 8 (Scenario 3.1 3Devo)

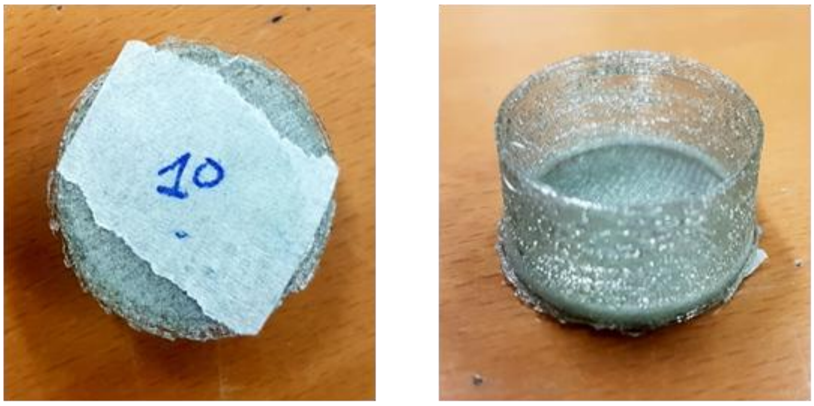

Figure 80. Printing with filament referenced to test number 10 (Scenario 1.1 3Devo)

Figure 81. Printing with filament referenced to test number 14 (Scenario 1.3.2 AEV 331)

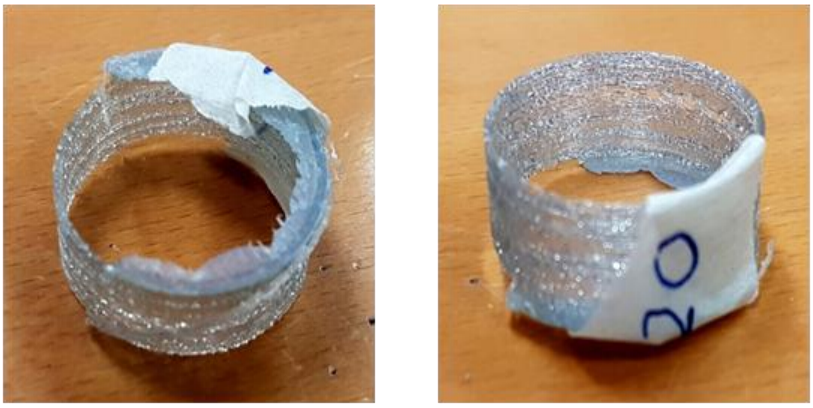

Figure 82. Printing with filament referenced to test number 20 (Scenario 1.3.1 AEV 331)

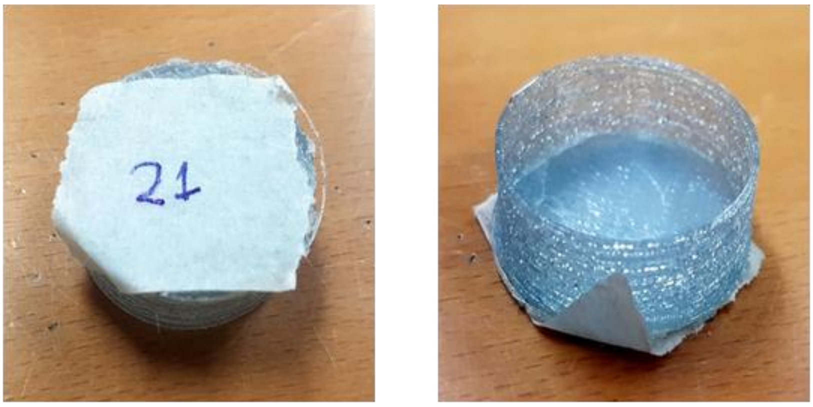

Figure 83. Printing with filament referenced to test number 21 (Scenario 1.3.1 AEV 331)

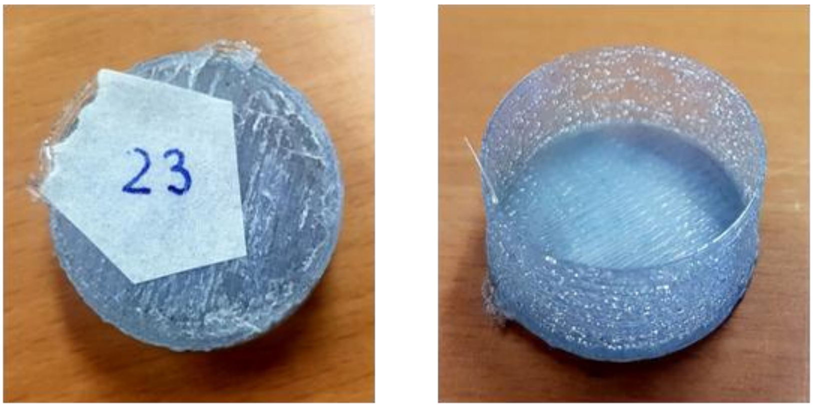

Figure 84. Printing with filament referenced to test number 23 (Scenario 3.2 AEV 331)

Figure 85. Printing with filament referenced to test number 26 (Scenario 2.1 AEV 331)

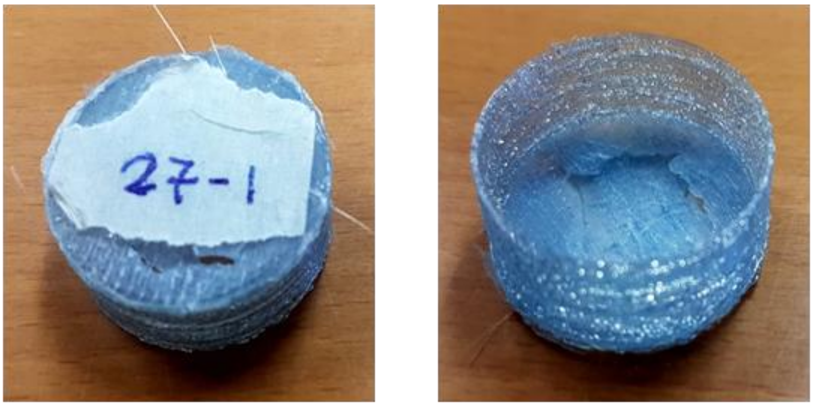

Figure 86. Printing with filament referenced to test number 27 (Scenario 1.3.2 AEV 331) (1)

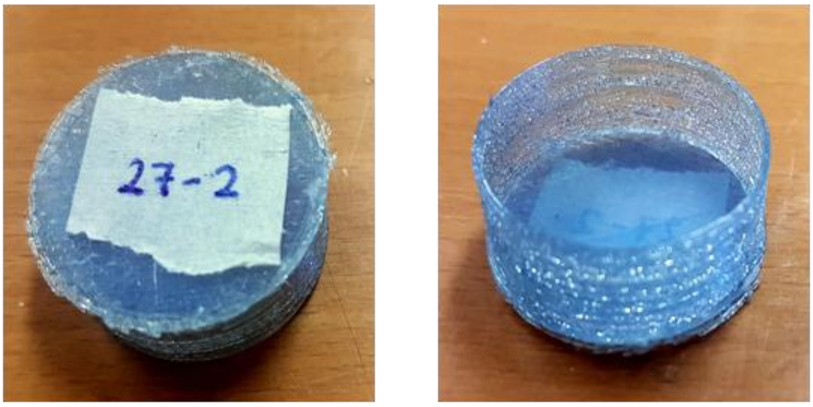

Figure 87. Printing with filament referenced to test number 27 (Scenario 1.3.2 AEV 331) (2)

Figure 88. Printing with filament referenced to test number 28 (Scenario 3.1 AEV 331)

All the pieces were made by the same 3D printers in the printing laboratory. These figures show the conclusions gathered in the master dissertation describing the characteristics they possessed and their main disadvantages. One consideration, it is that product number 27 was printed twice in order to check if leaving the specimen cooled down during more time his fragility improved. In the second attempt despite not cracking it can be seen that the mesh that constitutes it is also very thin and could even break with its manipulation, so it is a matter of the characteristics of the filament which proceeds.

The following Figure 89 shows all the tests performed in the extrusion process. It illustrates all the data related to extrusion operation such as temperature of the heaters and screw speed. In the case of AEV 331 extruder, it is incorporated the information about conveyor belt speed. Moreover, it shows the characteristics employed in the washing and drying operations in each test.

Test No.	Type of Plastic	Dirt	Washing Process	Machine	Drying Time	Drying Temperature (°C)	Temperature of Heater 1 (°C)	Temperature of Heater 2 (°C)	Temperature of Heater 3 (°C)	Temperature of Heater 4 (°C)	Extruder Speed (rpm)	Fan Speed (%)	Conveyor Belt Speed	Comments
1	PET (Recycled)	No	Glass/Cold	3devo-Composer 450	5	150						-		
2	PET (Recycled)	No	Glass/Hot	3devo-Composer 450	5	150	262	267	262	267	3,5	50		
3	PET (Recycled)	No	Glass/Hot	3devo-Composer 450	5	150	260	265	260	265	5	-		
4	PET (Recycled)	Glue	Cold/Bar	3devo-Composer 450	5	150	280	280	280	280	6	50		
5	PET (Recycled)	Glue	Cold/Bar	3devo-Composer 450	5	150	275	275	275	275	5	-		
6	75%Virgin-25%PET (Recycled)	Glue	Cold/Bar	3devo-Composer 450	5	150						-		
7	75%Virgin-25%PET (Recycled)	Glue	Glass/Warm	3devo-Composer 450	5	150	275	275	275	275	6,6	50		
8	50%Virgin-50%PET(Recycled)	No	Glass/Warm	3devo-Composer 450	5	150	275	275	275	275	11	50		
9	25%Virgin-75%PET(Recycled)	No	Glass/Warm	3devo-Composer 450	5	150	265	265	265	265	4	30		
10	PET (Recycled)	Glue	Net/Hot	3devo-Composer 450	5h-2days	150-130	270	270	270	270	3	50		Drying twice
11	PET (Recycled)	Glue	Net/Hot	3devo-Composer 450	5h-2days	150-130	275	270	270	270	4	50		Drying twice
12	PET (Recycled)	Glue	Glass/Hot	3devo-Composer 450	5h-2days	150-130	275	270	270	270	4	50		Drying twice/No-Pre
13	PET (Recycled)	No	Glass/Cold	AEV 331	2	150-130	265	260	260	260	5			No-Prewashing
14	PET (Recycled)	No	Glass/Cold	AEV 331	2	150-130	270	265	265	260	5		20	No-Prewashing
15	PET (Recycled)	Glue	Glass/Cold	AEV 331	5	150	275	270	270	270	9		35	No-Prewashing
16	PET (Recycled)	Glue	Glass/Cold	AEV 331		150	275	270	270	265	7		20	No-Prewashing
17	PET (Recycled)	Glue	Glass/Cold	AEV 331	5h-2days	150-130	272	270	270	266	6		25	Drying twice
18	PET (Recycled)	Glue	Glass/Hot	AEV 331	5	150	272	270	270	266	8		20	
19	PET (Recycled)	Glue	Glas/Warm	AEV 331	5	150	272	270	270	266	8		20	
20	PET (Recycled)	Glue	Net/Cold	AEV 331	5	150	274	270	270	268	8		20	
21	PET (Recycled)	Glue	Net/Warm	AEV 331	5	150	274	270	270	268	9		25	
22	PET (Recycled)	No	Glass/Warm	AEV 331	5	150	280	275	275	270	9		28	
23	50%Virgin-50%PET(Recycled)	No	Glass/Cold	AEV 331	5	150	270	265	265	265	6		25	No-Prewashing
24	50%Virgin-50%PET(Recycled)	No	Glass/Cold	AEV 331	5	150	275	270	270	265	6		25	No-Prewashing
25	25%Virgin-75%PET(Recycled)	No	Glass/Cold	AEV 331	5	150	275	270	270	265	7		25	No-Prewashing
26	25%Virgin-75%PET(Recycled)	No	Glass/Cold	AEV 331	5	150	270	267	264	264	7		25	No-Prewashing
27	PET (Recycled)	No	Glass/Cold	AEV 331	5	150	272	268	268	265	8		25	No-Prewashing
28	50%Virgin-50%PET(Recycled)	No	Glass/Cold	AEV 331	5	150	275	270	270	268	8		30	Bath path/No-pre
29	PET (Recycled)	No	Glass/Cold	AEV 331	5	150	270	270	270	265	10		45	Bath path/No-pre
30	PET (Recycled)	No	Glass/Cold	AEV 331	5	150	275	270	270	267	9		25	Fan/No-pre

Figure 89. All test data