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

David Durán Redondo
Industrial Engineering and Management
Instituto Superior Técnico

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 which reports environmental problems.

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, filament quality, while some of the main results obtained are: the removal of glue, to take into account the appropriate working parameters of the extruder or the incorporation of a cooling system in the extrusion operation.

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

1 - Introduction

Plastic possesses a 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.

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.

The target of this project 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 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.

2 - Plastic market

This paper starts with a short presentation of the current situation of plastic production, followed by the plastic recycling context. At the end of this section is described the project for schools of this study.

2.1) Plastic market context

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. 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. Moreover, 8 million tonnes of plastic are leaked into the ocean every year is quadrupling that amount by 2050 there being disastrously more tonnes of plastic than fish into the ocean. By 2015 as well, just the plastic sector will account for 20% of global annual carbon budget (MacArthur, 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 world production of plastics in 2017, including thermoplastics, polyurethanes, thermosets, elastomers, adhesives and PP-fibers, 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%. According to Europe, the six larger European countries cover almost 70% of the European demand in 2017 (PlasticsEurope, 2018).

2.2) Plastic recycling context

Not all plastic have the same recycling facility, for instance, those composed of thermosetting polymers present more difficulties to recycle, remould or reform due that their strong cross-linked structure shows resistance to higher temperature, which provides greater thermal stability than thermoplastics. On the other hand, plastic recycling technologies are divided generally into four types: 1) Primary, processing of a scrap into a product with similar characteristics than the original product 2)Secondary, processing of a scrap into a product with different characteristics from the original one 3)Tertiary, processing plastic waste into basic chemical and fuel from plastics 4)Quaternary, it uses the incineration to retrieve the energy content of waste/scrap plastics (G. Kulkami,2018).

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 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 5% of discarded share, but this is just following the same tendency (Geyer et al., 2017).

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 (Geyer et al., 2017).

Plastic packaging is an object of study 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. There is other 14% from the total packaging plastic waste which is incinerated and/or converted into energy recovery process. However, 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).

On the other hand, if it is compared the three main 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. The problem is that plastic usually can be recycled for once or twice and finally it will end up in the others options.

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 it is not direct and, to achieve that, a series of operations will be developed as well as its implemented technology. There are several processes with the purpose to adapt the material to the requirements. Figure 1 represents the closed cycle that is created in the project.

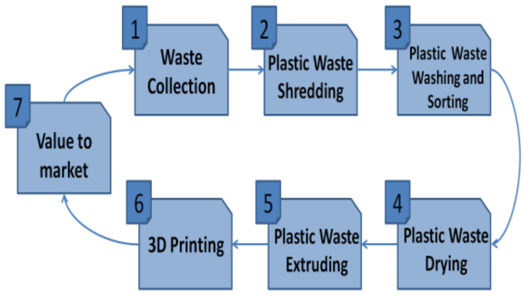

Figure 1. Flow of the general process of the project's solution

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 raise awareness in 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 printed specimens made of this plastic waste. It would allow that the waste generation be back into value products. It is necessary to be appealing for schools to participate in this kind of demonstrations so solution must be affordable with no many financial resources having frugal concept as reference.

3 - Literature Review

This section describes concepts such as circular economy or frugal innovation by analysing its meanings and methodologies to apply them. On the other hand, it encompasses the several involved operations of the object of study: project for schools.

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. 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).

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).

3.2) Frugal Innovation

Frugal innovation (FI) was created as an idea of developing high-value solutions without many financial resources. This concept has been suffering an evolution in its meaning over the years and definitions can be classified into three big groups: i) First generation is oriented to the product, focus on its characteristics. The goal is to reduce the use of material by compact design, raw materials limited, low price, ease of use (Rao, 2013); ii) Second generation is oriented to market and process. FI is developed to satisfy people at the bottom of the pyramid (Zeschky et al.,2014) and to consider in the whole design process the needs of developing world (Basu et al.,2013); iii) Third generation represents a cut-out point. Agarwal et al.(2017), identified three fundamental dimensions of constraint-based innovation: cost-effectiveness, ease-of-use, and prescriptive variables.

3.3) Operations related to circular economy's solution

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. 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).

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. It exists a standard practice that describes a procedure for washing dirty plastic (ASTM International, 2009) which proposes room temperature wash step to facilitate separation of the labels and then, other washing at elevated temperature to let the separation of other contaminants by basing on densities. Santos et. al (2005), established that for each 3kg flakes washed is needed 80dm^3 of water.

3.3.3) Drying

PET is a material characterised for being hygroscopic, what it means that it tends to absorb water from its surroundings of a natural way. As much moisture as possible must be removed from the resin before it is processed in a moulding machine, It is common the use of dryers and two are the parameters to determine: working time and temperature. Torres et al. (2000) proposed two phases of 2h at 120°C more 4h at 140°C for recycled PET whereas CWC (1998) provides a temperature limits between 137,8 and 160°C and for the drying time, at least five to six hours for recycled flakes.

3.3.4) Extruders

Extruders are the machines that provides the plastic recycling filament. They are usually compounded by a barrel segmented into three zones called solids conveying, melting and melt conveying and each generally assembled by a couple of heaters. The polymer is entered in the barrel through a hopper. Afterwards, material passes through the temperature zones and melts. Finally, the process ends pushing the material to the die zone whose final solid form is generally in a cylindrical shape(Ravi et al., 2011; Singh et al., 2017).

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. 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).A 3D printer is a machine capable of manufacturing a physical object from a 3D model, previously prepared in a computer program (Bertier Luyt & Mathilde Berchon, 2016). Regarding the materials of the 3D printing, ABS and PLA are commonly used as printing filaments, but they are expensive and not environment friendly (Berman B.,2012). Zander et al. (2018) concluded that recycled PET filament is able to replace commercial filament in printing a diverse range of plastics parts.

4 - Methodology

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 of children about the environmental problem resulting from such amount of plastic waste worldwide by proposing an application for valorisation of PET bottles. 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

This operation encompasses two steps: pre-grinding and grinding. Labels are removed before pre-grinding, then, bottles are cut into pieces of small size (<60x80mm) and it is mandatory operation because of the feed size of the cutting mill. It was managed two scenarios in order to assess its influence on extrusion results: remove or leave the part of the bottle containing glue. Pre-grinding is performed using scissor as a tool.On the other hand, grinding operation is done by a SM 2000 cutting mill. At the experimental work, it was used a standard hopper and a vessel capacity of 5l. Regarding the configuration of the machine settings, they were selected a 4mm bottom sieve, rotor speed of 750 r/min and a rotor of the type 6-disc. These parameters were set according to work properly with PET material and the needs it requires.

4.2) Washing

This Master's Dissertation proposed various scenarios where the conditions of the processes performed were changed with the purpose to determine the option that reports a better removal of dirt and impurities. Characteristics such as temperature, the agitation type and water flows were tested its impact on the results. The proposed scenarios are shown in Fig.2.

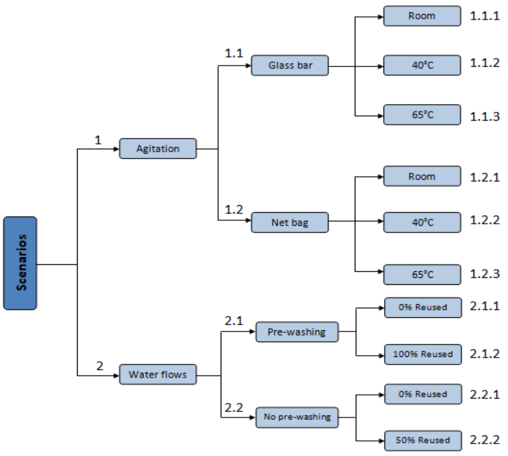

Figure 2. Schematic representation of the washing scenarios

The complete washing operation (Scenario 2.1) has three steps: pre-washing, washing and rinsing. It was proposed other options

such as skipping pre-washing step (Scen. 2.2) or reusing the rinse water (Scen. 2.X.2). The influence of the wash water temperature was also tested. With regard to Scenario 1, two different options were considered: agitation with glass bar and agitation with a net bag. Regarding the material, it was used cheap and manageable tools like plastic tanks, net bags, colander, net, detergent and a sensor to measure the temperature, all in connection to frugal concept. Children are able to perform this operation in its totality. Each operation washes 200g of recycled flakes using 2,5ml of detergent and 2l of water in each of the three steps, two in case of skipping pre-washing. The agitation is done manually to an approximate speed of 200r/min and pre-washing operation takes 1min30s whereas washing and rinsing are performed in 2min time.
On the other hand, due to the difficulty to evaluate the different scenarios and not having a tool to measure this cleaning quality, their validity will be assessed after performing extrusion by testing how influence on the filament quality.

4.3) Drying

This operation is essential due to washing operation leaves the material completely wet and, moreover, PET is a hygroscopic material. Moisture must be removed because it produces a huge decrease in filament quality. Oven is used to dry the recycled flakes and aluminium paper to insert and hold the material inside the machine. Regarding the drying parameters, it has been established a temperature of 150°C and a working time of 5h. The pre-heated time takes 45min until reaching the temperature set-point.

4.4)Extrusion

This dissertation pursues to develop a suitable methodology to produce a recycled filament as feedstock of 3D printing. First of all, it was proved with 3Devo composer 450. This extruder was performed under different scenarios such as varying the percentage of recycled flakes mixed with virgin material and to extrude flakes with and without glue.

Afterwards, it was proved with the brabender single screw extruder model AEV 331. There are different implemented scenarios as well corresponding to characteristics such as the amount of recycled flakes mixed with virgin, the incorporation of a cooling system and testing with flakes containing glue. Fig. 3 shows the aforementioned performed scenarios with AEV 311 extruder.

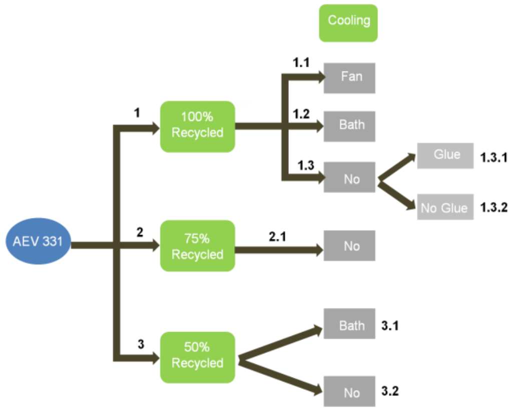

Figure 3. Schematic representation of the extrusion scenarios.

With regard to the equipment, Figure 4 illustrates the brabender single screw extruder without cooling system.

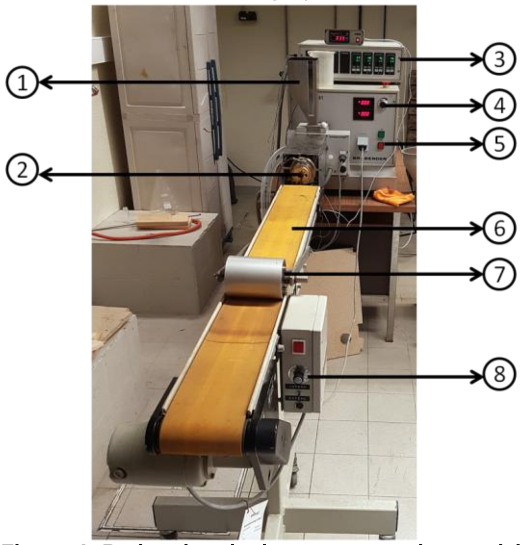

Figure 4. Brabender single screw extruder, model AEV 331

These are the 8 parts: 1)Hopper. Where material feed is produced; 2)Nozzle. Where material is coming out; 3)Monitor. It controls and shows the temperature of the four heaters; 4)Potentiometer. It regulates the screw speed measured in r/min; 5)Two switches to turn on or off the extruder respectively; 6)Conveyor belt. Filament is cooled down and shaped along the belt.

7)Roll. Function to shape the material; 8)Potentiometer. It controls the belt speed.

Regarding the experimental procedure, there are some considerations to take into account. To set the speeds of the belt and the screw is highly related to the diameter size of the filament, whose thickness must between 1,35 and 1,95mm (being 1,75mm the standardised), whereas the temperature of the heaters influences on the thermo-mechanical properties.

4.5) 3D Printing

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. In Fig. 5 is shown the printer used at the experimental work.

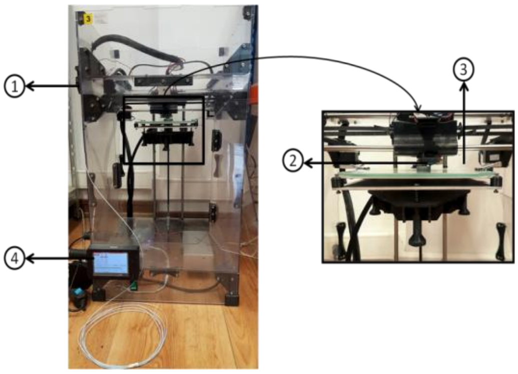

Figure 5. 3D printer, model W300

It has four differentiated parts: 1)3D printer feed. It is the inlet of filament into the equipment; 2)Nozzle. Where the build material is extruded from; 3)Print bed. Where the extruder deposits the filament to form a solid object; 4)Control panel. It determines the printing parameters.

Regarding the experimental procedure, first all, it has to be created a 3D model with one of the software available for 3D printing. Subsequently, it was set a 80°C bed temperature and a 250°C nozzle temperature for all samples. Filament is inserted into the machine and when is fit correctly until the nozzle, drawing is loaded and ready to print in a physical product.

5 - Results

In this chapter the results extracted from the different operations are presented in separate sections.

5.1) Grinding

The cycle starts with the collection of bottles that contain more than one type of plastic, PET bodies and PP caps. Fig. 6 illustrates the plastic waste having removed labels and ready to do the pre-grinding.

Figure 6. Collection of PET bottles

Subsequently, bottles were cut with scissor into small pieces to be able to feed the cutting mil. Fig.7 shows the volume reduction experimented.

Figure 7. Bottles reduced to smaller pieces

Afterwards, grinding operation is performed and results are shown in Fig.8. Flakes have a size of 4mm according to the employed bottom sieve.

Figure 8.Flakes after grinding operation

5.2) Washing

As we do not have any tool to assess the washing quality, these results will be inferred after extrusion regarding the characteristics of the filament. Anyway, the following figures will illustrate results of procedure step. Fig. 9 shows how part of the flakes are floating whereas others are sunken whose phenomenon is explained by the difference of density.

Figure 9. Flakes separated by density

It is followed by the removal of the floating flakes (PP&HDPE) using a small net. PET flakes, material used as feedstock, remains in the glass vessel. Later, it is performed the washing step under the conditions of each employed scenario. PET flakes are at the bottom of the water whereas foam is produced at the top.Fig.10 shows a sample.

Figure 10. Washing step (Scenario 1.1)

Between the three steps, two in case of skipping pre-washing, material is decanted with a colander and stored in bags.

5.3) Extrusion & 3D Printing

These operations are presented together because the product we obtain from each one is highly interconnected. First of all, it has used 3Devo extruder. We could inferred that is not a reliable machine to work with PET material, even more if is recycled. On the one hand, the main issue was the clogging problem which blocks the nozzle. This matter was slightly improved with the mixture of recycled material and virgin, but not solved. Moreover, there were instabilities in the diameter size. On the other hand, we could concluded that glue is a disaster for filament quality. Therefore, as the equipment is not stable and reliable implying a great loss of material, AEV 331 extruder was turned to be a solution for filament production.

Regarding the brabender single screw, model AEV 331, the major problem in scenarios without cooling system was to extrude a very fragile filament that yielded a brittle printed product that breaks in the print bed and presents a soft structure. We could inferred that recycled material increases the degree of crystallinity of filament impacting on a product with lower quality and worse mechanical properties. Thus, it was proposed the incorporation of two cooling system: water bath and fan. On the one hand, water bath cooling solve the problem of fragility but added a new one, the appearance of bubble inside the filament with the consequent decrease of its quality and the formation of holes in the printed product. On the other hand, fan system (shown in Fig. 11) brings very good results.

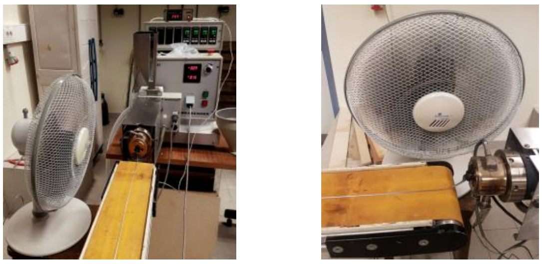

Figure 11.Filament production under Scenario 1.1

With regard to Scenario 1.1, it was performed under the use of 100% recycled flakes and the incorporation of a fan in the machine outlet. It produced a elastic and 1,75mm filament besides of avoiding the bubbles. These results are shown in Fig.12.

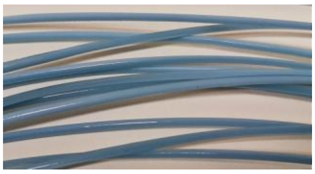

Figure 12. Extruded filament under Scenario 1.1

It was removed the flakes with glue because there were particles even bigger to the limit of allowed diameter size (around 1,95mm). Regarding the printing operation, it was created a product with a solid structure improving the brittleness, no holes and a dense mesh. Figure 13 illustrates the printing of sample 30 corresponding to Scenario 1.1.

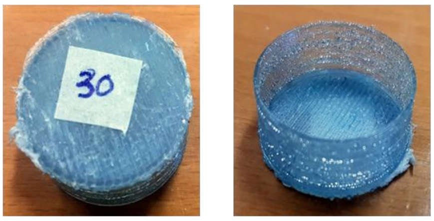

Figure 13. Printing with filament from Scenario 1.1

Table 1 summarizes the conclusions drawn in each scenario.

Table 1.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 related 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. ✗

5.4)Process characterization for children

First of all, it is the collection of PET bottles. Afterwards, children are capable to remove the labels and cut the bottles into smaller pieces (<80x60mm) with a scissor. Glue is removed as well. Grinding operation is a task done by an expert because its higher complexity and danger. Washing operation is performed using frugal equipment under the aforementioned scenarios 1.1.1 and 2.2.2. It is followed by drying because flakes remain completely wet and moisture must be removed to avoid bubble in the extrusion. Children prepare the aluminium paper used as a box to hold the flakes inside the oven, and they set the temperature to 150°C during 5h of working time. Regarding extrusion operation, it should be performed by an expert due to the difficulty to manage the AEV 331 extruder and as a safety issue. Related to the characterisation of parameters, temperature heaters are set to: H1 275°C, H2 270°C, H3 270°C and H4 267°C. Screw speed and conveyor belt speed are established to 9 r/min and 25%, respectively, with the purpose to be close to 1,75mm diameter. Moreover, it is incorporated a fan as a cooling system in order to avoid a brittle filament. Finally, 3D printing operation is performed by setting 80°C in the print bed and 250°C in the nozzle. 3D model created to print are related to the courses of the children such as examples of science, chemistry, history or mathematics (shown in Fig.14).

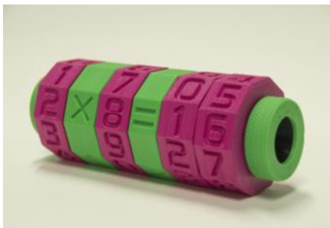

Figure 14. 3D Printing example related to mathematics

6 - Conclusions

This study shows the development of a solution to integrate plastic circularly derived from the desire to change plastic management policies intending to give visibility to a current concerning issue. It shows a new way to extend the life cycle of resources as well as extracting value from the waste based on profiting discarded PET bottles to produce 3D printed product for a scholar demonstration. Regarding the process, children are capable to participate in the activity being guided by an expert.

It could be inferred that 3Devo extruder is not reliable working with PET material. It brings problems such as clogging and lack of stability in the diameter size. AEV 331 turned into a good option to extrude recycled filament. Related to quality, recycled PET leads to a lower performance than virgin material. Using recycled feedstock coming from PET bottles presents an increase in the degree of crystallinity of the filament and a decrease in the impact strength that influences in the 3D printing operation,yielding a brittle product that broke in the print bed. The incorporation of a cooling system (a fan) at the exit of the nozzle was essential to highly improve the results. With regard to pre-grinding operation, it is mandatory to remove the parts of the bottles containing glue. On the other hand, it could be noted no difference between the different washing scenarios concluding that it should be performed the option with a greater water saving and simpler methodology.

For future projects, other type of waste could be explored as well as proposing an adapted scholar demonstration for this new type of material. Moreover, it could be proved if 3Devo extruder has a better behaviour with other recycled materials.

References

Agarwal, N., Grottke, M., Mishra, S., & Brem, A. (2017). A Systematic Literature Review of Constraint-Based Innovations: State of the Art and Future Perspectives. *Transactions on EngineeringManagement, 64(1), 3-15*

ASTM International (2009). Standard practice for separation and washing of recycling plastics prior to testing. Designation D6288-09.

Ayo, A. W., Olukunle, O. J., & Adelabu, D. J. (2017). Development of a Waste Plastic Shredding Machine, *7*(2), 2–5.

Basu, R., Banerjee, P., & Sweeny, E. (2013). Frugal Innovation: Core Competencies to Address Global Sustainability. Journal of Management for Global Sustainability, 1(2), 63–82.

Berman B. (2012). 3-D Printing: The new industrial revolution. *Business Horizons.* Volume 55, Issue 2, pp.155-162

Bertier L., Mathilde B. (2016). La impresión 3D Guía definitiva para makers, diseñadores, estudiantes y profesionales.

CWC (1998). Best practices in PET recycling.

Despeisse M., Baumers M., Brown P., Charnley F., Ford S. J., Garmulewicz A.,Rowley J. (2017). Technological Forecasting & Social Change Unlocking value for a circular economy through 3D printing : A research agenda. Technological Forecasting & Social Change, 115, 75–84.

Frosch, D., Gallopoulos, N., (1989). Strategies for manufacturing. Sci. Am. 261 (3), 94–102

Gaurav S. Kulkarni (2018). Introduction to polymers and their recycling techniques. Sabu Thomas et. al (Ed.). *Recycling of Polyurethane Foams* (pp 1-16).

Geissdoerfer, et al. (2017) The circular economy – a new sustainability paradigm. *J. Clean. Prod., 143 (2017), pp. 757-768*

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made.

MacArthur, E. (2016). The New Plastics Economy: Rethinking the future of plastics. *Ellen MacArthur Foundation*, (January), 120.

PlasticsEurope (2018). Plastics - the Facts 2018. An analysis of European plastics production, demand and waste date.

Rao, B. C. (2013). How disruptive is frugal? Technology in Society, 35(1), 65–73.

Ravi, S., Sudha, M., & Balakrishnan, P. A. (2011). Design of intelligent self-tuning GA ANFIS temperature controller for plastic extrusion system. *Modelling and Simulation in Engineering, 2011, 1–8.*

Santos, A.S.F., Teixeira, B.A.N., Agnelli, J.A.M., Manrich, S., 2005. Characterization of effluents through a typical plastic recycling process: an evaluation of cleaning performance and environmental pollution. *Resour. Conserv. Recycl. 45, 159–171.*

Singh, N., Hui, D., Singh, R., Ahuja, I. P. S., Feo, L., & Fraternali, F. (2017). Recycling of plastic solid waste: A state of art review and future applications*. Composites Part B: Engineering, 115, 409–422.*

Tiwari, R., & Herstatt, C. (2012). Frugal Innovations for the “Unserved” Customer: An Assessment of India’s Attractiveness as a Lead Market for Cost-Effective Products.

Torres N., Robin J., Boutevin B. (2000). Study of thermal and mechanical properties of virgin and recycled poly(ethylene terephthalate) before and after injection molding. *European Polymer Journal* 36 2075-2080

UNEP (2018).Single-use plastics, a roadmap for sustainability.

Wu H., Shi Y., Xia Q., Zhu W. (2014) Effectiveness of the policy of circular economy in China: a DEA-based analysis for the period of 11th five-year-plan. *Resources, Conservation and Recycling* , 83 , pp. 163-175

Zander, N. E., Gillan, M., & Lambeth, R. H. (2018). Recycled polyethylene terephthalate as a new FFF feedstock material. *Additive Manufacturing*, 21(January), 174–182.

Zeschky M. B., Winterhalter S. , Gassmann O (2014). From cost to frugal and reverse i nnovation: mapping the field and i mplications for global competitiveness. *Res. Technol. Manag.,57(4),pp.20-27*