Process Design of Plastic Waste Valorization Using 3D Printing Technology

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Abstract

Mankind's addiction to plastic has led to the current plastic age where the growth of plastic production has surpassed the ability of proper waste management, causing significant environmental damages. To cope with the excessive volumes of plastic, Company A developed a waste valorization solution that involves extrusion and 3D printing of plastic waste into marketable products, however, the complexity of the process integration of this solution at an industrial scale represents an obstacle to its implementation. Therefore, this research aims at filling the literature gap by developing an integrated process design of waste valorization with extrusion and 3D printing operations, at an industrial scale, by adopting a methodology centered on Slack *et al.* (2007) approach, which comprises the five pillars of process design: process technology, product design, layout and flow, job design, and supply network design. A literature review on the plastic market, 3D printing, extrusion, and process design was carried out which provided a theoretical basis to conduct interviews with key players, and experimental testing with extrusion and 3D printing. The results of the analysis, with primary focus to the process technology pillar, enabled the characterization of the extrusion and 3D printing critical operational parameters, the main quality problems and their troubleshooting process, and the proposal of equipment which are available in the market. To assess the viability of the proposed solution, a project appraisal was conducted to twelve scenarios, considering different production capacities and different marketable products.

Keywords: 3D Printing, Extrusion, Plastic Recycling, Process Design

Resumo

A utilização desmedida de plástico originou a atual era do plástico, caracterizada pelo crescimento da produção com plástico que ultrapassou a capacidade de uma gestão de resíduos apropriada, causando perigos ambientais significativos. Neste contexto, a Empresa A desenvolveu uma solução de valorização de resíduos que envolve a extrusão e impressão 3D de produtos comercializáveis utilizando resíduos plásticos, contudo, a complexidade da integração dos processos desta solução numa escala industrial apresenta uma barreira à sua implementação. Assim sendo, esta investigação tem como objetivo preencher a lacuna da literatura através do desenvolvimento do design do processo integrado de valorização de resíduos, com extrusão e impressão 3D numa escala industrial. Foi adotada uma metodologia baseada na abordagem de Slack *et al.* (2007) que define cinco pilares de design de processo: tecnologia de processo, design de produto, configuração e fluxo, design de trabalho e design da rede de fornecedores. É apresentada uma revisão da literatura do mercado de plásticos, impressão 3D, extrusão e design de processos, que serviu de base teórica para a realização de entrevistas e testes experimentais de extrusão e impressão 3D. Os resultados, com ênfase na tecnologia de processos, permitiram a caracterização dos parâmetros operacionais críticos da extrusão e impressão 3D, os principais problemas de qualidade e respetivas soluções, e a apresentação de equipamentos disponíveis no mercado. A viabilidade da solução proposta é examinada após a realização de uma avaliação de projeto para doze cenários em que cada um tinha em conta diferentes capacidades de produção e diferentes produtos comercializáveis.

Palavras-chave: Impressão 3D, Extrusão, Reciclagem de Plástico, Design de Processos

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“Be of good cheer. Do not think of today's failures, but of the success that may come tomorrow. You have set yourself a difficult task, but you will succeed if you persevere; and you will find a joy in overcoming obstacles.”

– Helen Keller

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List of Abbreviations

3D	Three Dimensional
3DP	Three Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
A_G	Air Gap
AM	Additive Manufacturing
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
B_O	Build Orientation
BPA	Bisphenol A
CAD	Computer-Aided Design
COTS	Commercial Off-the-Shelf
DA	Dimensional Accuracy
DE	Differential Evolution
DOE	Design of Experiments
DSC	Differential Scanning Calorimetry
EU	European Union
ExA	Filament Extrusion Line A
ExB	Filament Extrusion Line B
ExC	Filament Extrusion Line C
FDM	Fused Deposition Modeling
GMDH	Group Method for Data Handling
GRA	Grey Relational Analysis
HC	High Capacity
HDPE	High-Density Polyethylene
HEPA	High Efficiency Particulate Arrestance
HIPS	High Impact Polystyrene
ISO	International Organization for Standardization
LC	Low Capacity
LDPE	Low-Density Polyethylene
L_T	Layer Thickness
MBQC	Multiple Building Quality Characteristics
MC	Medium Capacity
MFI	Melt Flow Index
MSW	Municipal Solid Waste
P1	Product 1
P2	Product 2
P3	Product 3

PC	Polycarbonate
PET	Polyethylene Terephthalate
PETG	Polyethylene Terephthalate with Glycol
PID	Proportional Integral Derivative
PLA	Polylactide
PLC	Programmable Logic Controller
PP	Polypropylene
PrA	3D Printer A
PrB	3D Printer B
PrC	3D Printer C
PS	Polystyrene
PT	Processing Time
PU	Polyurethane
PVC	Polyvinyl Chloride
R_A	Raster Angle
rFil	Recycled Filament
rHDPE	Recycled High-Density Polyethylene
RIC	Resin Identification Code
rPET	Recycled PET
RPM	Rotations per Minute
rPP	Recycled Polypropylene
rPS	Recycled Polystyrene
R_W	Raster Width
SEBS	Styrene Ethylene Butylene Styrene
SEBS-MA	Styrene Ethylene Butylene Styrene with Maleic Anhydride
SPI	Society of the Plastic Industry
SR	Surface Roughness
STL	Stereolithography
TGA	Thermal Gravimetric Analysis
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TS	Tensile Strength

1 | Introduction

1.1 | Problem Motivation

The world is currently producing more than 300 million tonnes of plastic each year, and is expected to double again over the next twenty years and almost quadruple by 2050 (MacArthur, 2016). Although versatile, cheap and useful, this miracle material which has made modern life possible, has faced a noticeable shift in production throughout the years from durable and reusable plastics towards single-use and disposable products. In 2015, the dominant application was packaging, a single-use plastic application, with a total of 42% of the global primary production, followed by durable and reusable plastics destined for the building and construction sector, comprising only 19% of production. Additionally, from the 407 million tonnes of plastic produced in 2015, roughly 75% was disposed in the same year (Geyer *et al.*, 2017). The short life-time of these single-use plastics has led to a current "throwaway" culture that is potentially one of the greatest challenges that the environment is facing (Geyer *et al.*, 2017; Ritchie and Roser, 2018; UNEP, 2018). Mankind's inability to cope with end-of-life plastics, which results in greenhouse gas emissions, mismanaged waste, unexploited recycling processes, and health and environmental impacts, has to be acknowledged and addressed (Ritchie and Roser, 2018). From this perspective, 3D printing technology has increased its popularity as a low-cost and sustainable alternative to conventional manufacturing (Huang *et al.*, 2015). In this sense, achieving sustainability of 3D printing feedstock is of utmost importance to manage the projected growth of the 3DP market and as a strategy to deal with plastic waste (Pakkanen *et al.* 2017).

A waste valorization solution has been developed by Company A as a strategy to cope with the concerning volumes of plastic in the environment. The solution involves the extrusion and 3D printing of plastic waste into marketable products. In spite of its appeal, the complexity of the process integration of this solution at an industrial scale represents a barrier to its current implementation. In this context, there is a gap in the literature regarding the development of an integrated process design with extrusion and 3D printing operations. Accordingly, the aim of this research is to adopt a research methodology centered on Slack *et al*. (2007) approach, involving the five pillars of process design, to develop the integrated process design for waste valorization with extrusion and 3D printing, at an industrial scale.

1.2 | Dissertation Objectives

This dissertation aims at developing an integrated process design solution for plastic waste valorization with extrusion and 3D printing operations at an industrial scale. The research seeks to provide *(1)* characterization of the plastic market, *(2)* the state of the art on 3D printing technology, with emphasis to fused deposition modeling, extrusion process, and process design, *(3)* definition of the methodology adopted during the development of the master's dissertation, *(4)* development of the integrated process design through the analysis and characterization of the five process design pillars: process technology, product design, layout and flow, job design, and supply network design, with primary focus to process technology, and *(5)* validation of the proposed solution by conducting a project appraisal to twelve different scenarios: a low, medium, and high production capacity scenario, which are then divided into four sub-scenarios considering different marketable products.

1.3 | Dissertation Outline

To conclude the first chapter of this research, the structure is now described. Chapter 2 provides a complete problem contextualization. The evolution of the plastic market is described so that the reader understands the resulting threats to the environment and the necessity of improving plastic waste management. Additionally, a waste valorization solution developed by Company A is introduced. Since the problem has been defined, a theoretical analysis is required and is presented in Chapter 3. This chapter provides a state of the art on 3D printing, extrusion, and process design, relating its principles with plastic waste and plastic recycling. A literature review on process design is also presented along with its five pillars. Chapter 4 presents the research methodology that was adopted to achieve the objectives defined in this dissertation, which is centered on the five pillars of process design. The findings obtained through the research methodology are discussed in Chapter 5 and 6, representing respectively, process technology, the main process design pillar of the study, and the secondary pillars. Chapter 7 assess the viability of the proposed waste valorization solution by presenting the project appraisal that was conducted. Additionally, this chapter provides a sensitivity analysis that was performed to the 3D printing filament market to evaluate its influence on the proposed solution. To conclude the research, Chapter 8 serves as a conclusion, reflection on the limitations of the study, and future work.

2 | The Plastic Market

This chapter is divided into four sections. Section 2.1 provides an overview of plastic production, consumption and plastic waste management, since its early stages up to the current “Plastic Age”. Although plastics have revolutionized the industry, they are undeniably a key environmental concern, and therefore, plastic pollution is also discussed. Section 2.2, presents the main types of plastics coupled with their industrial applications. Furthermore, in section 2.3, a company whose goal is to valorize waste, is introduced. Lastly, section 2.4 characterizes the problem, which will be the main focus of this work.

2.1 | The Plastic Age

2.1.1 | Plastic Production and Consumption

The early twentieth century marked the beginning of the global plastic industry as the first synthetic plastic was produced (Ritchie and Roser, 2018). Plastics are commonly referred to describe a wide range of synthetic or semi-synthetic materials which are designed to meet the needs of multiple consumer and industrial applications in the most efficient way possible (Plastics Europe, 2018). Additionally, its’ inexpensiveness, versatility, lightweight and durability are qualities that have led plastic production to increase over the past century (UNEP, 2018). Nowadays, “plastics have become the ubiquitous workhorse material of the modern economy” (MacArthur, 2016), not only given their wide range of properties and diversity of applications, but also in terms of their capacity for innovation and sustainability (Plastics Europe, 2018). In other words, plastic provides significant environmental benefits whether in the form of insulation material, saving energy, or light and innovative materials in the automotive sector, reducing fuel consumption and carbon dioxide emissions, and ultimately by ensuring food safety and reducing food waste with plastic packaging (European Commission, 2018).

Plastic prosperity is reflected by its exponential growth in production throughout the past century (Deloitte, 2017). Since 1950, annual production of plastics has increased 200-fold, reaching a staggering 381 million tonnes in 2015 (Geyer *et al.*, 2017), and is expected to double again over the next twenty years and almost quadruple by 2050 (MacArthur, 2016). Correspondingly, the total amount of plastic manufactured in the world by 2015 surpassed 7.8 billion tonnes, from which 50% was produced in only the prior thirteen years, as represented in **Figure 1** (Geyer *et al.*, 2017).

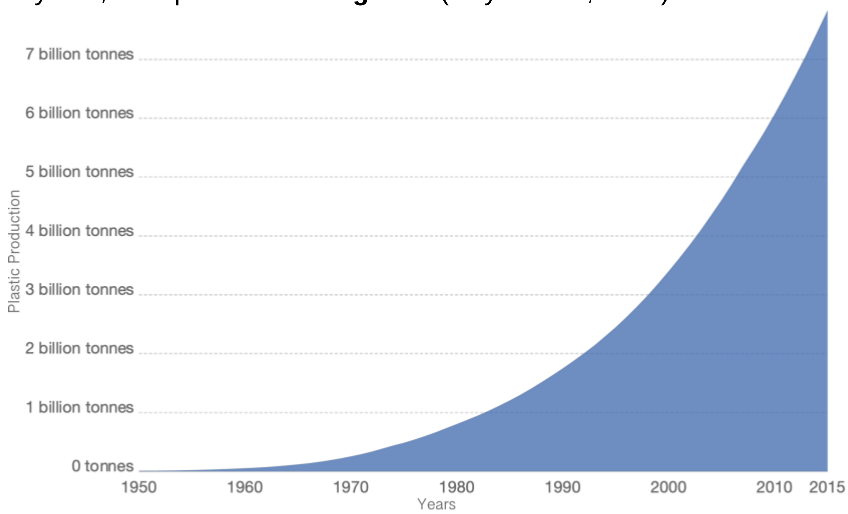

Figure 1: Cumulative global production of plastics (Ritchie and Roser, 2018).

From the early emerging stages of plastic until today, the production of this material has largely outpaced most other man-made materials. Besides this, a substantial shift has occurred in the industrial sector and polymer type used as a result of the different product lifetimes. As represented on the left of **Figure 2**, in 2015, the dominant application was packaging, a single-use plastic application, with a total of 42% of the global primary production, followed by durable and reusable plastics destined for the building and construction sector, comprising 19% of production. While the former is produced and disposed in the same year of production, the latter leaves use only decades after its manufacturing. Accordingly, the increase and excessive production of single-use plastics results in a short lifetime. As shown on the right of **Figure 2**, statistics indicate that in 2015, 54% of plastic packaging were disposed of, whereas only 5% of building and construction materials were plastic waste. Overall, from 407 million tonnes of plastic produced in 2015, roughly 75% was disposed in the same year (Geyer *et al.*, 2017).

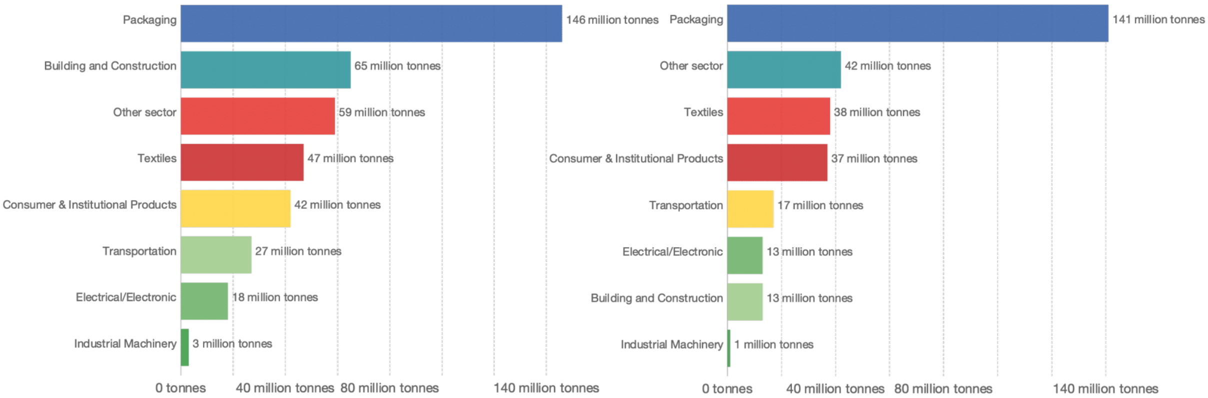

Figure 2: Primary global plastic production and global plastic waste generation by industrial sector in 2015 (from left to right) (Ritchie and Roser, 2018).

So far, an analysis of the exponential growth in plastic production and its noticeable shift towards disposable applications, which has ultimately led to an increase in plastic waste, has been presented above. At this point, it is important to understand how plastic waste is dealt with.

2.1.2 | Plastic Waste Management

There are three main types of plastic disposal. First of all, plastic waste can be recycled or reprocessed into a secondary material. Other than those option plastic goes to final disposable for instance in landfills. Recycling plastic only reduces overall waste if it displaces primary plastic production, but due to its counterfactual nature, this displacement is difficult to obtain (Geyer *et al.*, 2017). Moreover, recycling encounters several technical and economic problems which fall into the following categories*: (1) identification, sorting, and gathering into central stations* and *(2) the economics of recovering value* (Britannica, 2018). Although the first is more straightforward, the latter has inherent limitations as contamination and the mixing of polymers types generates less robust materials that have a lower economic value (Geyer *et al.*, 2017). The second waste treatment method consists of thermal destruction of the material. The most frequently used method is incineration, which consists of burning waste at extreme temperatures, with or without energy recovery. The main environmental impacts involved with this disposal method are the production of carbon dioxide, from burning the waste, which is a primary driver of climate change, and also the release of toxins into the air and surroundings. For these reasons, incineration should be performed under tight control and regulated conditions (Geyer *et al.*, 2017; Ritchie and Roser, 2018). Lastly, plastics can be discarded. This includes waste that is sent to landfills, which are open or closed sites for the disposal of waste material through burial or waste that is left uncontained in open dumps or in a natural environment. Under these circumstances, a concerning issue is the possibility of waste leaching into its surroundings, and therefore, polluting water and soils (Ritchie and Roser, 2018). Estimates indicate that 1.5 to 4% of global plastic production ends up in the oceans every year and that plastic waste accounts for 80% of marine litter. This is a direct result from the non-biodegradable status of most plastics, which instead slowly break down into smaller fragments called microplastics. Plastic debris is transported by wind and marine currents, which then accumulates in the environment, frequently in the sea where marine life is likely to ingest them. This topic is discussed further in subsection 2.1.3. Moreover, microplastics have already been found in the air, drinking water, salt and honey, which may potentially be hazardous for human health and wildlife (European Commission 2018; UNEP, 2018).

The various flows of plastic throughout its life-cycle are illustrated in **Figure 3**. It is estimated that the cumulative production of polymers, synthetic fibers, and additives from 1950 to 2015 was 8.3 billion tonnes, from which 30% is still in use, 55% was sent to landfills or discarded, 8% incinerated and 6% recycled, of which 1,2% is still in use, 1,2% was later incinerated and 3,6% was later discarded or sent to landfill. Only 9% of plastics have been recycled from the 5.8 billion tonnes of primary plastic which are no longer in use (Geyer *et al.*, 2017).

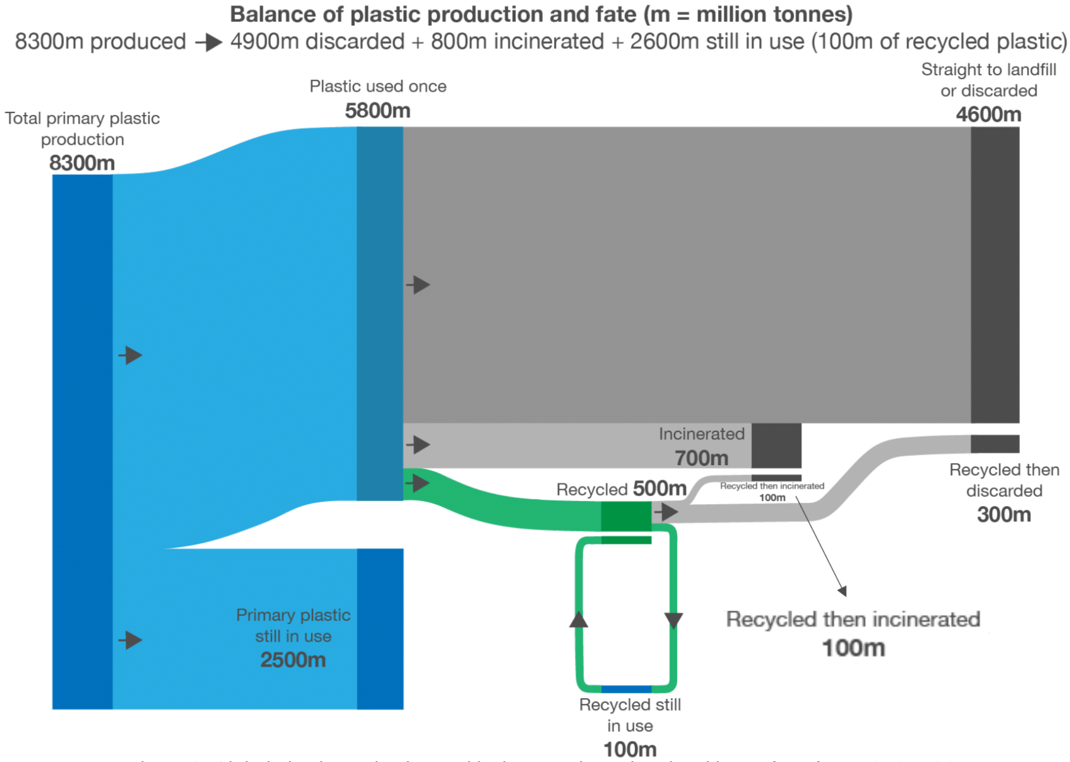

Figure 3: Global plastic production and its journey through to its ultimate fate, from 1950 to 2015 (Adapted from Ritchie and Roser, 2018).

Having approached the three main waste management treatments and the drawbacks related to each, it is necessary to analyze the main areas of concern regarding plastic pollution.

2.1.3 | Plastic Pollution

Today, a world without plastics seems unimaginable (Geyer *et al.*, 2017). While plastics have revolutionized the industry with its unparalleled functionalities at low cost, they are undeniably a key environmental concern (Ritchie and Roser, 2018) and the externalities related to the use of this material must be addressed. There are four main areas of concern*: (1) greenhouse gas emissions as a by-*

product of plastic production and incineration, (2) mismanaged waste leading to degradation of natural systems, (3) excessive consumption of single-use plastics and *(4) health and environmental impacts from substances of concern.*

More than 90% of plastics are produced from chemicals derived from oil, natural gas, and coal, which are unrenewable, dirty resources. Consequently, the extraction of raw material and the production of plastics give rise to greenhouse gas emissions with natural capital costs of USD 23 billion. In 2014, the plastic industry represented 6% of global oil consumption, which is equivalent to the oil consumption of the entire aviation sector. At this consumption rate, the plastic industry will account for 20% of total oil consumption and 15% of the global annual carbon budget by 2050. The production stage contributes the largest to the carbon impact of as it requires around half of the fossil feedstocks allocated to the plastic industry. The remaining carbon, which is trapped in the plastic itself, is released directly if incinerated or is isolated if placed in a landfill. However, if there is a leakage in the landfill, carbon might be released gradually into the atmosphere over many years (MacArthur, 2016).

Furthermore, another critical concern regarding plastics is the underperforming end-of-life treatment. In other words, mismanaged waste is either littered or inadequately disposed of. The first represents plastics that are "dumped or disposed without consent in an inappropriate location", and the second is waste that initially "has the intention of being properly managed through waste collection or storage sites, but is ultimately not formally or sufficiently managed" (Ritchie and Roser, 2018). It is noticeable that high-income countries, including most of Europe, North America, Australia, New Zealand, Japan, and South Korea have extremely effective waste management systems, whereas, low-to-middle income countries have inadequate or inexistent waste management systems. Many countries in South Asia and Subs-Saharan Africa dispose inadequately 80 to 90% of plastic, which can lead to ocean and river pollution. Although high-income countries have effective waste management systems, which lead to negligible inadequate disposed waste, they can effectively contribute to plastic pollution by littering (Ritchie and Roser, 2018).

Correspondingly, mismanaged waste affects ocean health and lifestyle as there are high risks involved with plastic ending up in the ocean via wind, tides or inland waterways. The chart in **Figure 4**, represents the massive 60% of global mismanaged waste from East Asia and the Pacific region. It's clear that waste management systems have a crucial role in preventing oceans' pollution. China alone contributes to slightly more than one-fourth of the global mismanaged waste (Geyer *et al.*, 2017). This is a direct

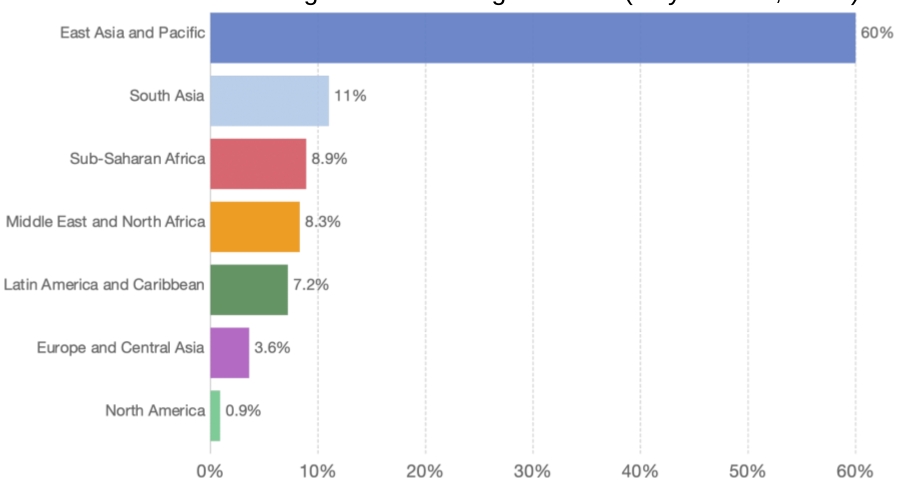

Figure 4: Global mismanaged waste by region, in 2010 (Ritchie and Roser, 2018).

consequence of the large importing rates of plastic waste from China and Hong Kong, which have collectively received 72.4% of global traded plastic waste (Brooks *et al.*, 2018). However, in late 2017, China introduced a complete ban on the imports of non-industrial plastic waste (MEPC, 2017), which will highly impact the exporting countries as they will have to improve domestic recycling infrastructure and generate internal markets (Brooks *et al.*, 2018).

The ocean pollution occurrence is exacerbated by the addiction and increasing consumption of single-use plastics. About half of the total plastic industry is allocated to these types of products which are destined to be thrown away after one utilization and are rarely recycled (European Commission, 2018). Large volumes of single-use plastics are littered in dumpsites or in the environment which aggravates ocean pollution. “Around the world, 1 million plastic drinking bottles are purchased every minute, while up to 5 trillion plastic bags are used worldwide every year” (UNEP, 2018). According to UNEP, scientists have suggested that plastic waste could serve as a geological indicator of the Anthropocene era, given its ubiquitous presence in the natural environment.

Finally, the last aspect to address is related to substances of concern, which are present in plastics. Plastics often contain a complex blend of chemical substances, which might contain impurities or contaminants that may raise some concerns about potential adverse human health effects. Substances such as bisphenol A (BPA), which is used as a plasticizer in polyvinyl chloride (PVC) have already motivated some regulators and businesses to act since it is an endocrine disruptor which presents a risk to human health and the environment. Although there are uncertainties on the consequences of long-term exposure to other substances founded in today’s plastics and the impacts of leakage into the biosphere, there are enough indications that guarantee further research and implementation of adequate measures (Eartheasy, 2019; MacArthur, 2016).

At this point of the research, it is fundamental to get familiarized with plastic as a material instead of a product, hence the following section briefly introduces the plastic families and further details each of the most common recyclable plastics.

2.2 | Plastics Classification

Plastics are composed of large molecules called polymers, which consist of monomers joined together in a chain. There are two main categories for plastics, thermosets, and thermoplastics. The first represents 15% of the overall demand in the EU and consist of plastics that are strengthened when heated but cannot be remolded or reheated after their initial forming. Thermoset plastics include polyurethane (PU), which is used in coatings, gears and car seats, and epoxy resins, found in adhesives and electrical and automotive equipment. The second represents 85% of all plastic demand and are plastics that do not undergo chemical changes in their composition when heated, therefore, can be molded repeatedly (Deloitte, 2018). The most common and regulated thermoplastic resins are discussed below.

Classifications of plastics emerge to provide a standard system for identification, sorting and recycling to consumers and manufacturers. Developed initially by the Society of the Plastic Industry, Inc. (SPI), the Resin Identification Code (RIC) comprises the six most commonly found thermoplastic resins in plastics including also a seventh category for the remaining types. The original coding system consists of chasing arrows forming a triangle which is surrounding a number from one to seven defining the resin type. Administrated now by the American Society for Testing and Materials (ASTM), the coding system with chasing arrows has been replaced with a solid equilateral triangle (see **Figure 5**) in order to eliminate common misconception that in the presence of a RIC the plastic is immediately adequate for recycling (ASTM, 2019).

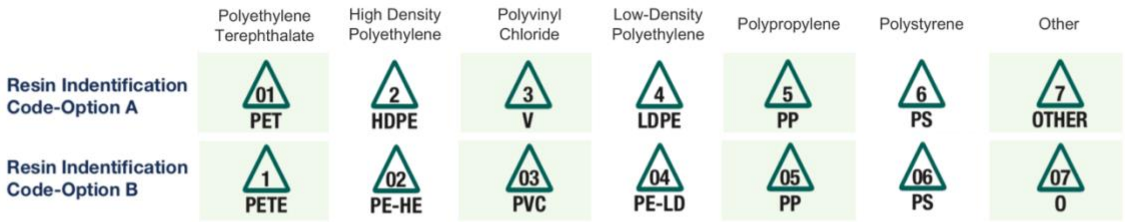

Figure 5: The RIC (Adapted from ASTM, 2019).

Polyethylene Terephthalate | PET

PET is a clear, hard and tough resin. This lightweight plastic presents good gas and moisture barrier properties which lead to its common uses in “beverage bottles and many injection-molded consumer product containers” (ACC, 2019). Plastics of this category can be “heated to their melting point, cooled, and reheated again without significant degradation” (CM, 2019) which results from its thermoplastic properties. Accordingly, hot filling, *i.e.* high-temperature sterilization of the product itself and container, is possible due to PET’s high heat resistance, allowing production of prolonged shelf life products (ACC, 2019; MJS Packaging, 2019). However, when reused repeatedly, these plastics incur the risk of growing bacteria and leaching, for instance, carcinogens (Eartheasy, 2019). Additionally, PET sometimes absorbs odors and flavors from what is stored inside of them (RDC, 2019). Decontamination of this resin is difficult and damaging chemicals are required to perform appropriate cleaning (Eartheasy, 2019). For these reasons, this type of resin is intended for single-use purposes and should be recycled rather than reused (Eartheasy, 2019).

High-Density Polyethylene | HDPE

HDPE is a milky white colored resin which bears higher tensile strengths when compared to other forms of Polyethylene (ACC, 2019). This rigid resin presents a decent stress crack resistance and withstands extreme temperatures and high impact strengths (Alpha Packaging, 2019). In spite of HDPE presenting excellent moisture barrier properties, this plastic is permeable to gas (ACC, 2019). Its excellent chemical resistance (ACC, 2019) makes the product safe against leaching (RDC, 2019) and is one of the main reasons it is widely used for packaging chemicals such as detergents and bleach, besides the usual beverage and shampoo bottles. Although these plastics are reusable and considered one of the safest, due to contamination HDPE bottles should never be reused as a food or drink container if it didn’t initially contain something edible (RDC, 2019). Overall, it is one of the most used thermoplastics as it is easily injection or blow molded into the desired container (APR, 2019). The recycling process of this resin is simple and cost-effective (Eartheasy, 2019).

Polyvinyl Chloride | PVC

PVC plastics are naturally white and their production can be divided into two general forms: rigid and flexible. The latter is less brittle due to the addition of plasticizers, making it softer and bendable (CM, 2019). Flexible PVC is most frequently used for electric cable insulation and pipes due to its stable electrical properties and its lightweight, inexpensiveness, and low maintenance, respectively. On the other hand, unplasticized PVC is commonly found in plumbing, drainage and window frames as it is hard and durable, supports high tensile strengths and is resistant to environmental degradation besides the previously mentioned economic benefits (CM, 2019). Nevertheless, this thermoplastic contains toxins which are hazardous to human health and the environment, which lead to its common designation of "poison plastic" (Eartheasy, 2019). Another drawback is its poor heat stability, which results in the addition of stabilizers to the material when subjected to high temperatures (CM, 2019). The toxicity and additives contained in PVC make it one of the least recycled plastics (SSF, 2019).

Low-Density Polyethylene | LDPE

LDPE is a low-density type of Polyethylene, which is used mostly in film applications as a result of its toughness, flexibility, transparency and waterproof properties (ACC, 2019). Additionally, due to its low melting point, it is appropriate for products that require hot sealing (ACC, 2019; RDC, 2019). This low-cost thermoplastic is considered to be a safe option for food storage as it does not release dangerous chemicals (RDC, 2019) and, therefore, is frequently used for frozen food packages, sandwich and grocery bags and also container lids (ACC, 2019). LDPE also offers excellent resistance to acid, bases and vegetable oils and is electrically stable (ACC, 2019; RDC, 2019). Even though plastics with this code are reusable, they are not always recyclable (Eartheasy, 2019).

Polypropylene | PP

PP is a translucent resin (RDC, 2019) that is characterized by its toughness, fatigue resistance and high melting point (CM, 2019). Accordingly, it is found in flexible and rigid packaging, fibers, automotive molded parts (ACC, 2019) and especially in microwave safe containers (QLP, 2019) and most plastics with hinges (CM, 2019). Moreover, this lightweight resin (Eartheasy, 2019) is a good insulator (CM, 2019) and presents a good barrier against moisture, grease, and chemicals (ACC, 2019). However, the properties of this material depend on whether it is a homopolymer or a copolymer (British Plastic Federation, 2019). The main difference between them is that the first is produced using a single type of monomer whereas the second is a combination of more than one monomer. The latter one is preferred when a more flexible material is desired (CM, 2019). PP plastics are considered safe for reuse (Eartheasy, 2019) regardless of its weaknesses, for instance, its high thermal expansion coefficient, high flammability and its susceptibility to UV degradation and oxidation (CM, 2019). The recycling process of this thermoplastic is complex since achieving consistent quality is hard due to the differences in types and properties (SSF, 2019).

Polystyrene | PS

PS is an inexpensive, versatile and easily-formed thermoplastic (Eartheasy, 2019) that can be rigid or foamed (ACC, 2019). Compact Disk (CD) cases and disposable cutlery are some applications of the solid type of resin (CM, 2019) which has a glassy surface and is hard (ACC, 2019). On the other hand, the foamed form, which is less dense and stiffer is often used as filler for small items being shipped in packages, disposable drinking cups, take-out food containers and egg cartons (CM, 2019). Foam applications are possible due to its excellent moisture barrier for short shelf life products and low thermal conductivity that results in good insulation properties (ACC, 2019). When in contact with chlorinated or other hydrocarbon substances, PS dissolves fairly quickly (CM, 2019). Besides this, styrene may leach to foods when containers are heated in the microwave (Eartheasy, 2019). Moreover, as it is brittle and ultra-lightweight it breaks effortlessly and is dispersed fast, harming the environment (Eartheasy, 2019). Additionally, as these plastics are very inert, the degradation period is very extensive which results in high volumes of litter, a consequence of products being typically thrown away after a short period of use (CM, 2019). This is aggravated by the fact that the recycling process involves high energy consumption and is yet to be efficient (QLP, 2019).

Other

Code 7 comprises miscellaneous types of plastic. Reuse and recycling protocols are not standardized within this category, however, plastics in this category are difficult to recycle due to their high variability and the need of extreme temperatures to break them down (Eartheasy, 2019; QLP, 2019). Recycling has become a critical environmental practice as resources are becoming scarce and plastic waste continues increasing (García *et al.*, 2016). As an attempt to broaden this research, with the goal of acquiring further knowledge on a wider range of resins, an additional resin was included in this section, which is included in code 7. As easily identified in **Figure 6**, the "others" category has a dominant share of the European plastics converter demand, therefore, studying the following resin might be useful for future work.

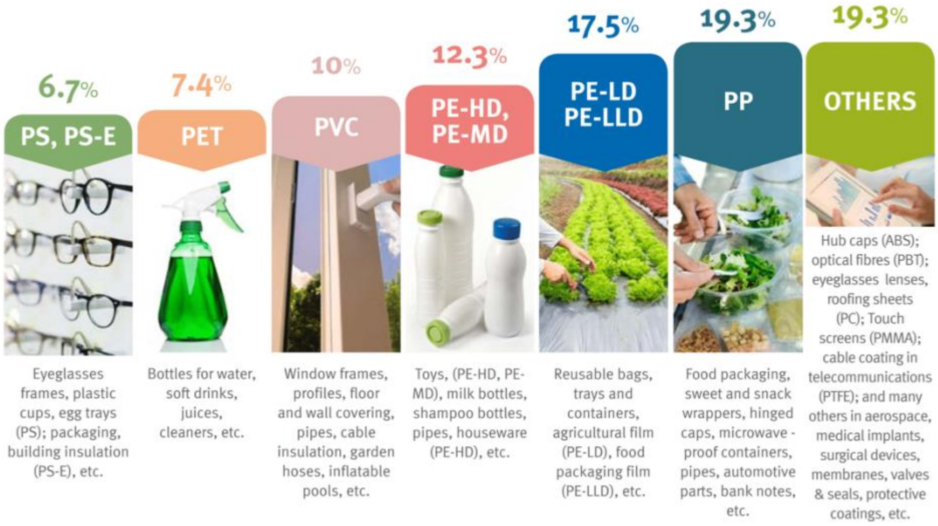

Figure 6: European plastics converter demand by polymer types, in 2016 (Adapted from Plastics Europe, 2018).

Acrylonitrile Butadiene Styrene | ABS

The mixture of three monomers, acrylonitrile, butadiene, and styrene, originates the terpolymer ABS. Acrylonitrile is responsible for providing chemical and thermal stability, butadiene is a rubber which increases toughness and impact strength and, finally, styrene gives ABS its characteristic glossy finish. Accordingly, as each monomer has a different role on the final outcome of the material, varying the proportions of each one results in distinct properties of the plastic (3D Insider, 2019). This opaque thermoplastic and amorphous polymer is used frequently in injection molding manufacturing processes and 3D printing as it is easily machined and has a low melting point. Hence, ABS has a wide range of applications in various industries, for instance, it is found as an automotive interior, computer keyboards, 3D printing filaments, and safety helmets. This inexpensive plastic is also easily recycled (CM, 2019).

An overview of the main properties and applications of these plastics can be found in **Appendix A**. Furthermore, by analyzing **Figure 7**, in 2015, the total plastic waste generated by polymer reached 285

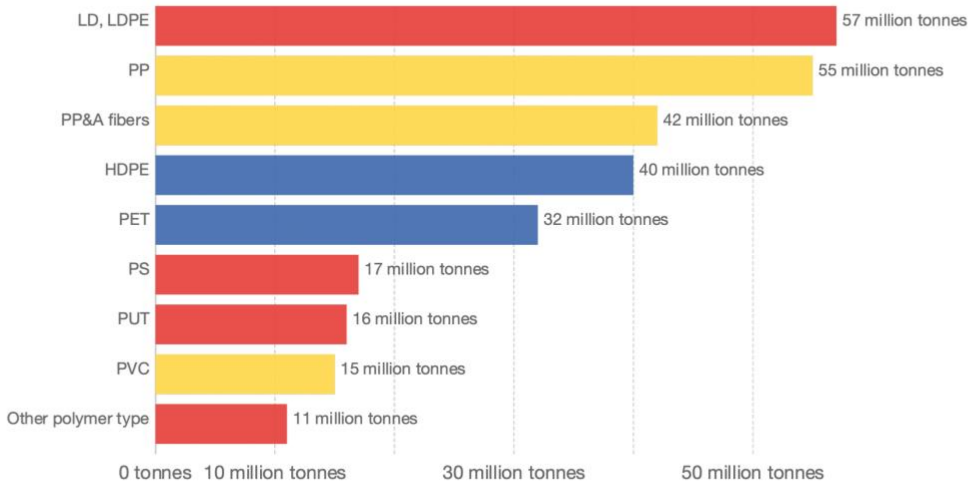

Figure 7: Primary plastic waste generation by polymer. Polymers are colored based on recyclability where blue is widely recycled, yellow is sometimes recycled, and red is usually non-recyclable, in 2015. PP&A fibers (Ployphthalamide fibers) and PUT (Polyurethenes) (Ritchie and Roser, 2018).

million tonnes. Roughly, only 25% of all waste is usually recycled, missing 277 million tonnes of plastic waste which are recycled sometimes, or not at all, resulting regularly in mismanaged waste. It is worrying that the polymer that generates the largest amount of waste is usually not recycled.

As an effort to combat poor recycling rates, there are companies whose core operations are related to recycling, enabling circular economy solutions. An emerging Portuguese company that that offers such sustainable solutions is presented next.

2.3 | Company A

A start-up founded in late 2018 thrives with waste valorization leveraged by new technologies. The company's mission relies on using state-of-the-art technology to bring value to waste by the empowerment of local people and by providing cross-sectional solutions worldwide. Furthermore, their vision is to become the world's leading service in providing connection and management of a world-wide grid of manufacturers, that seek the valorization of waste, in a community effort to eradicate both poverty and waste in the world.

2.3.1 | Business Model

The company's business model is based on four main pillars which are introduced next.

1 | Consulting and training, comprises four main areas:

- *Circular economy solutions,* where waste flows are mapped, critical points are identified and solutions to value the waste are proposed; *Sustainability,* where sustainability practices are implemented, tools for sustainability assessment are provided and sustainability reports are framed; *Technology*, where the know-how on the technological processes that allow competitive advantage is provided; *Market analysis*, in order to identify markets for the new waste valorization channels.

2 | Technology implementation, involves technical installation and implementation of the proposed solution, which has been determined in the consulting phase.

3 | Control and management, related to the post-technology installation, where a specialized team ensures the control of the production line and remotely controls solutions that require 3D printing.

4 | Maintenance and assistance, consists of services such as machine maintenance and 3D printer remote control.

2.3.2 | 3D Printing Solution

This emerging start-up has been primarily focused on a solution that can be implemented by modules, depending on the process stage of the client. The solution, shown in **Figure 8**, brings value to plastic waste by implementing 3D printing technology to the process. Each stage is briefly explained below:

Figure 8: General process behind the 3D printing solution.

1 | Waste collection: waste is gathered and brought into the clients' facility;

2 | Plastic waste cleaning and sorting: waste is sorted by type and cleaned in a designated station. R&D is in progress to ensure minimal use of chemicals and water in this stage;

3 | Plastic waste shredding and drying: waste is dried in a hopper-drier and shredded into same-sized uniform pellets using a shredder and a mill;

4 | Plastic waste extruding: pellets are then heated to melting temperature and passed through an extruder to obtain a filament suitable for fused deposition modeling, a 3D printing technology;

5 | 3D printing: the filament obtained is used as raw material for printing any desired object.

6 | Market value: producing 3D printing feedstock from plastic waste enables circularity in the plastic production industry, *i.e.*, by transforming unwanted and excessive plastic waste into a valuable resource for 3D printing which allows the manufacturing of marketable products.

Although the concept of this solution has been developed, the actual process of transforming waste into filament is rather complex since each type of plastic requires a different treatment at each stage, which involves determining multiple variables. For this reason, the company has been focusing on the downstream process design of this solution. Accordingly, this research will only comprise stage four onwards, *i.e.*, plastic waste extrusion, 3D printing, and market valorization.

2.3.3 | Markets

Company A has two major target clients, recyclers and private waste management companies. The former has the know-how and the processes to valorize waste, although these are frequently outdated and inefficient. The latter work with important clients, which requires them to have optimized processes and up-to-date technology. The general recycling process followed by both clients usually stops at the pelletizing phase as they have limited knowledge of business and markets. For this reason, the company's ambition is to sell their downstream 3D printing solution to these waste collectors that clean, sort and prepare the plastic allowing them to focus on the operation that brings value to the company, market valorization.

All in all, this start-up was created to fill in this gap in the recycling process and to ultimately *(1) optimize the waste management process of these clients* and *(2) introduce technology and new solutions which allow these clients to create value from plastic waste.*

2.4 | Problem Characterization

Cheap, versatile and durable, but plastic has turned out to be one of the biggest threats to the environment. The exponential growth in plastic production has far outstripped the ability to deal with plastic waste resulting in mismanaged waste and unexploited recycling processes. To cope with the excessive and unwanted volumes of plastic, Company A has developed a waste valorization solution that involves extrusion and 3D printing of plastic waste into marketable products. In spite of its attractiveness, the complexity of the process integration of this solution at an industrial scale represents an obstacle for this company to pursue its implementation. The solution not only involves an intricate process but also its core operations, extrusion and 3D printing, vary greatly according to the plastic being processed. Thus, it is necessary to understand how the many variables can be controlled for the different operations. The company has performed experiments on some but not all plastic types and needs to acquire knowledge on how to manage a facility with all types of plastic. As established earlier, the company's target customers are waste collectors that perform the cleaning and sorting of the plastic, which influences the process design of extrusion and 3D printing. For this reason, it is also necessary to understand the modifications required in terms of process design so that the additional operations can be fully integrated as a whole in the already existent process available in the clients. Accordingly, this research focuses on process design, namely how the solution presented by Company A can be adapted and integrated into companies that perform the upstream processes of waste management. Furthermore, it aims at understanding the constraints and variables that can be controlled for each operation and each type of plastic, so that such facilities can be created.

2.5 | Conclusions

The unparalleled amount of plastic in the world is a direct consequence of its great quality-price ratio and the excessive amount of single-use plastics. Annual plastic production is growing exponentially and there has occurred a noticeable shift from durable and reusable plastic towards disposable products. Three waste management methods were introduced, *(1) recycling, (2) incineration* and *(3) discarding*. Additionally, the key environmental concerns related to plastic were addressed, *(1) greenhouse gas emissions as a by-product of plastic production and incineration, (2) mismanaged waste leading to degradation of natural systems, (3) excessive consumption of single-use plastics* and *(4) health and environmental impacts from substances of concern.* Moreover, a thorough analysis of the most common thermoplastics was presented. Furthermore, to cope with this scenery, a company that has developed a downstream waste valorization solution was introduced. However, the complexity of the solution is standing in the way of its implementation. Accordingly, the full characterization of the problem was described.

3 | State of the Art

This chapter provides the theoretical and scientific background that will be used to deal with the problem identified in the previous chapter as well as the chosen approach for the research. Accordingly, in section 3.1, 3D printing is introduced along with its main advantages and applications. Then, subsection 3.1.1 is dedicated to fused deposition modeling as it is the chosen technology for this study. A review of the state of art on the feasibility of recycled plastic as 3D printing feedstock and the influence of process parameters on part quality is presented. Moreover, section 3.2 focuses on the extrusion process, the other main focus of this study. An additional literature review is performed to analyze the suitability of extruding recycled plastic. Finally, the five pillars of process design are described in section 3.3.

3.1 | 3D Printing

The term 3D printing (3DP) is also known as Additive Manufacturing (AM), which was formally introduced by Chuck Hull in the early 1980s (Hull, 1986), although experiments in this field had already taken place prior to this publication (Kodama, 1981; Andre *et al.*, 1984). As AM developed, a plethora of terms and definitions have been used to describe this technology. This ambiguousness has affected the further growth of AM and its application. As an attempt to provide consensus and facilitate communication world-wide on this matter, the International Organization for Standardization (ISO) and the ASTM developed a document with a set of standards on AM terminology and operations. Accordingly, AM is defined by these organizations as "the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing technologies". Additionally, seven operation categories were defined: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization (ISO/ASTM, 2015). These operations not only differ in the range of materials but also the techniques used to deposit layers and bond them together (Huang *et al.*, 2015).

Regardless of the different operations, the basic approach to AM is generally the same (see **Figure 9**). A 3D model that describes the physical part to be built is developed on computer-aided design (CAD) software. Once the 3D model is complete, it is converted into stereolithography (STL) file format (3D Systems, Inc., 1988), which approximates the surfaces of the model using triangles and polygons. Then, a slicing software analyses the STL file, slices the model into cross sections, and generates a set of toolpath instructions, designated as G-code for 3D printers. Finally, the 3D printer reads the instructions defined in the G-code and executes the print to create the physical part (Chua and Leong, 2014; Chua *et al.*, 2017). AM is considered to be a disruptive technology that is emerging and hailing a third industrial revolution (The Economist, 2012; Berman, 2012; Garrett, 2014).

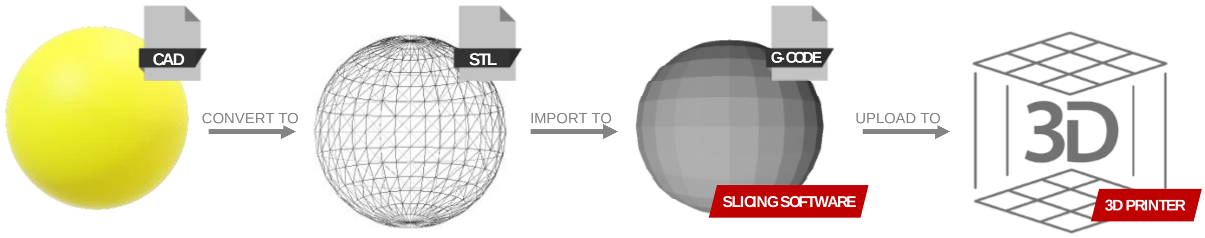

Figure 9: File format flow in AM (Based on Chua and Leong, 2017).

According to Harvard Business School professor Clayton Christensen, products based on such technologies are "typically cheaper, simpler, smaller, and, frequently, more convenient to use"

(Christensen, 2013). In other words, this manufacturing process enables the production of "low-volume, customized products with complicated geometries and advanced material properties and functionality" at a cost and time effective manner (Huang *et al.*, 2015). Accordingly, AM has the potential of transforming manufacturing supply chains, distribution channels and business models (Singh *et al.*, 2018). Furthermore, the growth of the AM industry, which exceeded 7.1 billion USD by 2017 (Wohlers and Caffrey, 2018) has been fueled by the many unprecedented advantages of this innovative technology, some of which are described in **Table 1**. Overall, the multiple benefits are leading to a more sustainable and economic viewpoint of manufacturing processes. The reduction of waste by printing layer by layer is incomparable to traditional manufacturing which can waste up to 90% of raw material. Also, the potential reduction in energy consumption and the ability of just-in-time production are also critical factors that are shaping this new perspective on the manufacturing industry (Huang *et al.*, 2015).

Table 1: AM advantages over traditional manufacturing (Garrett, 2014).

AM ADVANTAGES OVER TRADITIONAL MANUFACTURING	
BOOSTS INNOVATION	RE-INVENTION OF OLD PRODUCTS & CREATION OF NEW DESIGNS
NO COST FOR COMPLEXITY	REGARDLESS OF THE GEOMETRY, THE PROCESS REMAINS UNCHANGED
REDUCES WASTE & EMISSIONS	INCREASES EFFICIENCY IN RESOURCE USAGE & DECREASES CARBON EMISSIONS
INCREASED PRODUCT DESIGN FREEDOM	NO LIMITATIONS FROM EQUIPMENT
INSTANT PRODUCTION ON A GLOBAL SCALE	RAPID DISTRIBUTION OF PRODUCTS THROUGH DIGITAL FILES
ON DEMAND PRODUCTION IN BATCHES OF ONE	PRODUCE LARGE PRODUCT VARIATIES WITH CUSTOMIZATION WITHOUT INVENTORY
SIMPLIFICATION OF MANUFACTURING PROCESS	LOW LEVEL OF OPERATOR EXPERTISE & REDUCTION OF HUMAN INTERACTION
ELIMINATING SUPPLY CHAINS & ASSEMBLY LINES	FINAL PRODUCT MADE IN ONE PROCESS
FROM MASS PRODUCTION TO MASS CUSTOMIZATION	DESIGN & EFFICIENT PRODUCTION OF PERSONALIZED PRODUCTS
DESIGNS, NOT PRODUCTS, MOVE AROUND THE GLOBE	DIGITAL FILES CAN BE PRINTED ANYWHERE

The presence of AM in a wide range of fields, particularly in highly regulated industries such as aerospace, automotive and medical (Chua *et al.*, 2017), is a result of its unparalleled ability to produce economically complex structures and the design freedom engendered by its processes (Hague *et al.*, 2013). A summary of the industries that have adopted and flourished with this innovative process is shown in **Table 2**.

Table 2: AM applications (Adapted from Bogue, 2013).

AM APPLICATIONS	
MEDICAL	RAPIDLY GROWING
	PROVIDES FAST & COST-EFFICIENT PRODUCTION OF MEDICAL IMPLANTS WITH CUSTOMIZED DESIGN
	ELIMINATES THE NEED FOR TIME-CONSUMING ADJUSTMENTS DURING SURGERY
	REDUCES OPERATING COSTS & RISK OF MEDICAL COMPLICATIONS
MASS-PRODUCTION	TOYS & NOVELTY ITEMS
RAPID PROTOTYPING	ABILITY TO PRODUCE RAPIDLY A PART FROM A CAD DESIGN WITHOUT INCURRING COSTLY MANUFACTURING EQUIPMENT
	INCREASES CONVENIENCE WHILE REDUCING TIME & COST
	LOWERS ENTRY BARRIERS TO MANUFACTURING INDUSTRY
AEROSPACE & AUTOMOTIVE	PRODUCTION OF: - SPECIALISED ASSEMBLY DEVICES - TURBINE BLADES FOR AERO ENGINES - CAMBINE COMPONENTS FOR COMMERCIAL AEROPLANES
	ENHANCES PRODUCTIVITY, WORKER COMFORT, EASE-OF-USE & PROCESS REPEATIBILITY
ARCHITECTURE & CONSTRUCTION	PRINT OF ARCHITECTURAL MODEL DESIGN
	FUTURE PROSPECTS TO PRODUCE BUILDINGS

While AM is revolutionizing the landscape of manufacturing, it is not expected for it to replace conventional manufacturing in the foreseeable future, particularly for the high-volume production parts with low complexity and high accuracy. For AM to be widely adopted by the industry, challenges such as “poor part accuracy (…), insufficient repeatability and consistency in the produced parts, and the lack of qualifications and certification methodologies for AM processes” have yet to be addressed (Huang *et al.*, 2015). This study aims to fill some of these gaps.

In the literature, AM and 3DP are used interchangeably although the latter and broader term is generally applied in an industrial and more technical context whereas the former is used in *popularis* language, namely by the media and the consumer-maker communities. For the purpose of this study, the term 3DP will be used instead of AM since the main goal is to succeed in applying 3DP technologies at an industrial scale.

3.1.1 | Fused Deposition Modeling

This research will focus exclusively on material extrusion, which is the most commonly used 3DP technology. This process is universally known as Fused Deposition Modeling (FDM), a rapid prototyping technology originally developed by Stratasys in the late 1980s (Chua *et al.*, 2003). FDM builds 3D models via computer controlled robotic extrusion of molten thermoplastic in an additive layer-by-layer material deposition process (Too *et al.*, 2002). As shown in **Figure 10**, a spool of plastic filament is fed into an extrusion head and is heated to a semi-liquid state. The molten plastic is then extruded from the head, through the nozzle, and deposited onto a build platform in ultra-thin layers, one layer at a time. Moving along the X-Y plane, the head follows the established toolpath creating a layer. Once the layer is complete, the build platform moves along the Z-axis and the head travels to generate the new layer. Accordingly, the 3D model is built from the bottom up (Agarwala *et al.*, 1996; Chua *et al.*, 2003; Singh *et al.*, 2018).

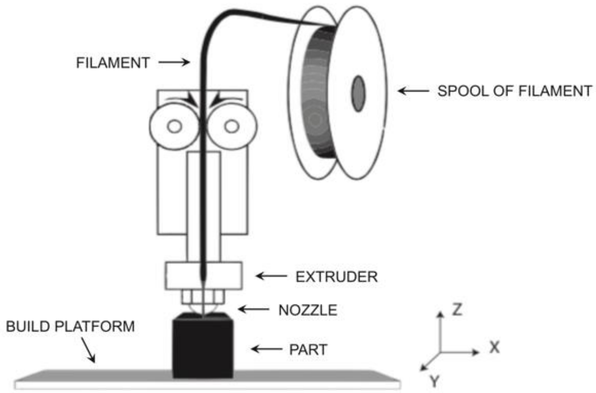

Figure 10: Schematic of FDM process (Adapted from Carneiro *et al.*, 2015).

The use of FDM across manufacturing industries such as automotive, biomedical implants, aerospace and telecommunications is increasing due to its ability to produce high quality products or prototypes with a wide range of materials (Deswal *et al.*, 2019). In addition, FDM enables a safe and neat production of geometrically complex parts, which makes the process suitable to have in an office environment (Mohamed *et al.*, 2015). Furthermore, the most used materials for this process, are ABS, polylactide (PLA) and polycarbonate (PC) (Gardan, 2015).

Achieving sustainability of 3DP materials is of utmost importance to deal with the projected growth of the 3DP industry and to solve the excess and unwanted plastic waste (Pakkanen *et al.* 2017). For this study, it is important to investigate the feasibility of recycled plastics as 3DP filament and determine the adequate FDM process parameters for the various types of plastics so that these can be applied in future stages of the research development.

Zander *et al.* (2018) performed a research study on recycled PET (rPET) as new FDM feedstock material. The filament was successfully produced from 100% recycled and unmodified PET. The filament was dried overnight, at room temperature under vacuum, before being printed into standard ASTM D638 Type V tensile bars. The FDM printer used was a Taz 6 with PET tape on the build platform. The following printing parameters were established: 30ºC build platform temperature, 270ºC nozzle temperature, build orientation in the Y direction, 0.2mm layer thickness, 100% infill, 2 shell layers traversing the sample perimeter (1mm total shell thickness) and infill layers were printed with an alternating 45/−45° tool path. For proof-of-concept, a radio bracket, a long lead time part, was also printed under the same conditions. After experimental testing, the results indicate that first, the tensile strength (TS) of the rPET tensile bars were comparable to those made from commercial off-the-shelf (COTS) PET pellets and commercial PC-ABS filament, although they achieved only about half the TS of their injection molded counterparts. According to the authors, the decrease in TS is expected due to weak interfacial welding between printed roads. The fast cooling of the printed roads does not allow the diffusion of polymer chains between layers. It is stated that post-processing such as annealing could improve this issue, while it may also lead to additional crystallinity and increase brittleness which would largely impact the overall performance of the part. Secondly, the importance of thoroughly drying the filament prior to 3DP is highlighted, as the moisture may create bubbles when it is released, causing voids in printed roads and possibly reducing mechanical properties. It is also pointed out that the printer used had a rare wide range of filament diameters and therefore was able to print the rPET filament regardless of the fairly high diameter variations. Regarding rPET radio bracket, it performed just as well as common ABS filament. All in all, rPET was considered a suitable candidate for 3DP feedstock.

Regarding PP, Domingues *et al.* (2017) developed a 3DP equipment prototype and successfully produced six specimens from a filament made from a blend of 60% granulated tire waste and 40% recycled PP (rPP). The chosen parameters for the printer were a 10mm layer thickness, 10mm/s deposition velocity, 120ºC build platform temperature, and a 198ºC nozzle temperature. The thermal and mechanical properties of the specimens were studied through Differential Scanning Calorimetry and Thermal Gravimetric Analysis (DSC/TGA) and tensile testing, respectively. The results prove the possibility of printing large parts from this plastic blend. Further research has been carried out by Iunolainen (2017) who produced a filament from rPP but was unsuitable for 3DP. The rPP filament had sharp diameter variations and an irregular shape. Printing with this filament could not only result in a poor quality part but also cause printer failure. The author claims that the difficulty of using PP in 3DP resides on its serious warping and poor layer adhesion during printing.

Regarding HDPE, Baechler *et al.* (2013) were able to print increasingly successful parts with an open source 3D printer, RepRap, using recycled HDPE filament (rHDPE). Successive part production revealed increased accuracy, higher density and reduced delamination as extrusion rate, layer thickness and fill percentage were optimized. In addition, by optimizing temperature settings and adjusting the shell layer, thermal warping decreased, and surface finish was improved, respectively. Nevertheless, parts created from rHDPE are still far from having the quality of those from ABS. The authors draw attention to a number of factors that may be causing this discrepancy, *(1) HDPE is harder to work with than ABS*, as it is more sensitive to the effects of thermal warping during printing, *(2) ABS has been* *widely used on RepRaps*, therefore printing settings for this polymer have been optimized, and *(3) the fluctuation in diameter and average mass per meter of filament*, which make it difficult to print at a consistent rate. All things considered, the viability of rHDPE as 3DP filament was proven and it is suggested the addition of a heated build platform to limit the effects of thermal warping in future testing.

On another note, Chong *et al.* (2017) provide techniques to deal with printing HDPE. They underline the rarity of this polymer in 3DP due to several factors. Firstly, as the part is printed layer by layer, the bottom layers that cool down first are likely to shrink causing curling or warping. Secondly, HDPE only adheres to build platform surfaces made from hot HDPE. Lastly, the tensions produced on the part during printing can sometimes tear the object due to HDPE's limited mechanical stability. Nonetheless, a successful case of a team who developed the first 3D printed functional boat using rHDPE milk jugs was presented Their triumph resulted from using an HDPE surface build platform, attaching a heater to the extruder, to soften the previous layers, and printing a sacrificial flange to further prevent warping. Moreover, it is stated that using highly insulating materials with low heat capacity as a surface for the build platform has improved HDPE's adhesion issues. All in all, Chong *et al.* (2017) argue the need for further investigation on mechanical properties and a standard characterization methodology and database before rHDPE can be considered a competitive 3DP filament.

In contrast, Angatkina (2018) considers the aforementioned challenges with HDPE exaggerated. However, special preparations are in fact needed for this material. Accordingly, PP sheet was used as a main print platform surface material due to poor adhesion issues. In her analysis, virgin HDPE and rHDPE test specimens were printed using a miniFactory printer. Initially, an ISO 527-2 1BA dumbbell was chosen as the first specimen to be tensile tested. Five samples of each material were printed with the same printing parameters, 220ºC extruder temperature, 60ºC build platform temperature, 0.2mm layer height, rectilinear infill pattern, 60mm/s perimeter print speed and 80mm/s infill print speed. No significant difference was found between the virgin and rHDPE. In fact, in some cases, rHDPE had a better performance. Additional specimens were printed, namely a hollow cube, a hollow cylinder, and a solid cube, to further investigate the shrinking and warping issues. For these specimens, the extruder temperature was 220ºC, build platform temperature was 60ºC and the printing speed was 50mm/s. For the hollow samples, the shell thickness was 0.4mm and for the solid cube, the infill density was 20%. The printed samples revealed that the solid cubes shrank as they cooled down to room temperature leading to curled corners on the first layers. Regarding the hollow samples, warping is noticeable on the thin walls of the cubes while the cylinders did not warp due to their geometry, *i.e.*, lack of sharp features. Additionally, it was observed that rHDPE layers bonded well to each other comparatively to virgin HDPE. Accordingly, Angatkina (2018) concludes the research by referring that aside from the expected warping and first layer adhesion issues of rHDPE, no irregularity in printing behavior was detected. Also, besides the inconsistent and oval shape of the rHDPE filament, it did not clog the nozzle nor jam the drive gears during printing. Overall, it is established that rHDPE has the potential to be a 3DP filament. Final suggestions indicate that a heated enclosure system for the 3D printer can improve and control the shrinkage and warpage issues.

Zander *et al.* (2019) looked into developing 3DP feedstock from a blend of recycled polymers as an appealing way to reuse mixed waste sources at a lower cost. It is also argued that polymer blending enables easy tailoring of mechanical polymer properties or even improves certain properties while maintaining others. The experiment involved developing filament blends of rPP with rPET (rPP/rPET) and rPP with recycled PS (rPS) (rPP/rPS) with and without compatibilizers, namely styrene ethylene butylene styrene (SEBS) and SEBS grafted with maleic anhydride (SEBS-MA) The choice of these polymer combinations arose from the lack of sufficient strength from PP compared to ABS, although they have similar toughness. Accordingly, reinforcing PP with rigid polymers such as PS or PET is thought to improve its mechanical properties. The filament blends were dried overnight, under vacuum, before being printed to eliminate excess moisture. Using a Lulzbot Taz 6 FDM printer, standard ASTM D638 Type V tensile bars along with DMA (dynamic mechanical analysis) bars (35mm x 12.5mm x 2mm) were manufactured. The rPP/PET and rPP/PS filaments were printed onto a PET tape surface and a polyetherimide surface, respectively. The printing parameters used for all samples were a 100ºC build platform temperature, a 260ºC nozzle temperature, a build orientation in the Y direction or flat, a 0.2mm layer thickness, 2 shell layers, and a 100% infill. For the tensile bars, an alternating 45/−45° infill orientation was used whereas 0º was established for the DMA bars. Additionally, the printer speeds were 50mm/s and 20mm/s for the tensile and DMA bars, respectively. Thermal behavior was studied via DSC and the results showed that the crystallinity of recycled polymers increased due to the reduction in molecular weight and chain entanglements from the repeated thermal processing cycles. Through mechanical testing, it was observed that all printed blend samples had a lower TS compared to those made from only rPET, which was expected due to the weaker mechanical properties of rPP and immiscibility of the blends. The rPP/rPET 50-50 blend had the lowest TS (17.2 ± 3.6 MPa) of all the blend formulations, while the rPP/PET SEBS-MA blend had the highest TS (24.2 ± 1.3 MPa). It is pointed out that SEBS-MA is able to interact with PET chains and therefore increase TS. Likewise, scanning electron microscopy images of printed samples also revealed the rPP/PET 50-50 blend as the one with the weakest interfacial adhesion. As far as the rPP/rPS blends are concerned, their TS did not vary significantly. The results confirm the viability of recycled plastic blends as 3DP feedstock.

An overview of the literature discussed is presented in **Table 3**. The applicability of recycled polymers as FDM feedstock has been validated, although further research is much needed to achieve optimized processes. At this point, it is noticeable the increasing amount of research on this subject. This growth has been fueled by not only by the lower cost of recycled plastic filaments but most importantly as a strategy to tackle the concerning amount of plastic waste by recycling and creating added-value (Pakkanen *et al.*, 2017).

As FDM continues to progress, improvements in part quality, productivity rate, safety, manufacturing costs and lead time are expected. Accordingly, the key to succeed depends on the proper selection of process parameters (Mohamed *et al.*, 2015). However, the complex nature of the manufacturing process together with conflicting parameters of FDM create a struggle to determine the ideal printing variables (Deswal *et al.*, 2019). According to literature, the most critical parameters that should be studied further are *(1) air gap (A_G,), (2) layer thickness (L_T,), (3) raster angle (R_A,), (4) raster width (R_W),* and *(5) build orientation (B_O).* The first variable indicates the gap between adjacent raster toolpaths on the same layer. The second refers to the thickness of the layer deposited by the head. The third variable denotes the angle of the raster pattern in the X-axis on the bottom part of the layer. Defining the raster angle is

Table 3: Literature overview on the feasibility of recycled plastics as 3DP filament.

PLASTIC	REFERENCE	APPROACH	RESULTS	REMARKS
rPET	Zander *et al.* (2018)	Analysed the feasibility of rPET as 3DP filament by testing ASTM D638 Type V tensile bars and a radio bracket.	• TS of rPET tensile bars comparable to those made from COTS PET and PC-ABS filament, although they achieved only about half the TS of their injection molded counterparts; • rPET radio bracket performed the same as ABS. • rPET considered feasible for 3DP.	• Importance of drying the filament before printing.
rPP with tire waste	Domingues *et al.* (2017)	Evaluated the feasibility of a blend of 60% tire waste and 40% rPP as 3DP filament.	• Successful printing of six specimens; • rPP blend considered feasible for 3DP.	-
rPP	Iunolainen (2017)	Assessed the feasibility of rPP as 3DP filament.	• rPP filament with sharp diameter variations and irregular shape; • rPP considered unsuitable for 3DP	• Printing with this filament could lead to poor quality part or printer failure; • Difficulty of rPP as 3DP filament results from warping and layer adhesion issues.
rHDPE	Baechler *et al.* (2013)	Examined the feasibility of rHDPE filament on a open source printer, RepRap.	• Successive part production revealed increased accuracy, higher density and reduced delamination as extrusion rate, layer thickness and fill percentage were optimized; • Optimizing temperature settings and adjusting the shell layer, thermal warping decreased, and surface finish was improved, respectively; • rHDPE considered feasible for 3DP.	• Factors that cause discrepancy in part quality between rHDPE and ABS: - HDPE is harder to work with; - ABS has already been widely used on RepRaps; - rHDPE fluctuation in diameter and average mass per meter of filament. • Addition of a heated build platform can limit the effects of thermal warping.
	Chong *et al.* (2017)	Provided techniques to deal with printing HDPE.	• Use a HDPE surface build platform; • Attach a heater to extruder, to soften the previous layers; • Print a sacrificial flange to further prevent warping; • Also, the use of highly insulating materials with low heat capacity as a surface for the build platform have improved HDPE's adhesion issues.	• Rarity of HDPE in 3DP caused by: - Issues with shrinking and warping; - It only adheres to build platform surfaces made from hot HDPE; - Limited mechanical stability of the polymer can lead to tears in the part during printing.
	Angatkina (2018)	Assessed the feasibility of rHDPE as 3DP filament by testing a ISO 527-2 1BA dumbbell, a hollow cube, a hollow cylinder, and a solid cube.	• No significant difference was found between the virgin and rHDPE dumbbell samples. In fact, in some cases rHDPE performed better; • The solid cubes shrank as they cooled down to room temperature leading to curled corners on the first layers; • The hollow cubes suffered from warping on their thin walls; • The hollow cylinders did not warp due to their geometry; • rHDPE considered feasible for 3DP.	• rHDPE layers bonded well to each other comparatively to virgin HDPE; • Although the inconsistencies and oval shape of the rHDPE filament, it did not clog the nozzle nor jam the drive gears during printing.
rPP/rPET rPP/rPS	Zander *et al.* (2019)	Evaluated the feasibility of rPP/rPET and rPP/PS blends as 3DP filament, with or without compatibilizers, by testing ASTM D638 Type V tensile bars and DMA bars.	• Crystallinity of recycled polymers increased; • All printed blend samples had a lower TS compared to those made from only rPET; • rPP/rPET 50-50 blend had the lowest TS; • rPP/PET SEBS-MA blend had the highest TS; • Scanning electron microscopy images of the samples also revealed that the rPP/PET 50-50 blend had the weakest interfacial adhesion; • TS of rPP/PS blends did not vary significantly; • rPP blends considered feasible for 3DP.	• The choice of these polymer combinations arose from the lack of sufficient strength from PP compared to ABS. Reinforcing PP with rigid polymers such as PS or PET is thought to improve its mechanical properties; • SEBS-MA can interact with PET chains and therefore increase TS.

especially relevant when printing parts with small curves. The R_W, refers to the width of the extruded material used for rasters. The higher this parameter, the stronger the interior of the part, whereas, the lower this value, less material and time will be required for production. Finally, the B_O represents the way in which the part is oriented inside the build platform in the X, Y and Z axes (Mohamed *et al.*, 2015).

Delivering a product that not only meets but exceeds customer expectations is vital to increase market valorization. Accordingly, to ensure customer satisfaction, it is important to not only understand the influence of the critical parameters on the different quality performance characteristics but also the degree of influence.

Several studies have been performed on the quality of printed ABS parts considering the various FDM process parameters. Lee *et al.* (2005) conducted a research study on the optimization of the elastic performance of a compliant ABS prototype. By applying the Taguchi method and the analysis of variance

(ANOVA) the optimal process parameters were determined and it was found that the elastic performance is mostly affected by A_G, L_T and R_A parameters. To verify the effectiveness of this approach, experiments were carried out which demonstrated the close resemblance between the estimated and experimental values. Wang *et al.* (2007) worked on optimizing rapid prototyping processes. The Taguchi method was used initially to establish six control parameters and their various levels. The quality characteristics examined were TS, dimension accuracy (DA) and surface roughness (SR). Through ANOVA and contribution approximation, it was found that B_O in the Z direction had the most influence in TS and DA, whereas L_T had the most impact on SR. Additionally, the optimal parameter combination of each best quality performance was obtained. Further steps of the analysis involved obtaining the estimated multiple building quality characteristics (MBQC) by integrating the Grey relational analysis (GRA). It was shown that the most influential parameters to MBQC were L_T and B_O in the Z direction, which was also notable in the single quality characteristics analysis. Moreover, the optimal parameter combination of the MBQC was determined. This research proved that optimal combinations of MBQC can be obtained by integrating the GRA and the Taguchi method. In addition, the technique for order preference by similarity to ideal solution (TOPSIS) evaluation method was applied to verify optimal building quality objective reliability and it was concluded that the integration design for multiple objective experimental parameters was remarkably feasible.

Later on, Sood *et al.* (2010) studied the effect of the aforementioned critical process parameters along with the interaction of B_O with the remaining parameters on the DA of FDM building. Taguchi's method was used to find the optimum parameter levels and also to determine important parameters and interactions. The experiment results revealed that the measured dimension is always more than wanted along the thickness direction whereas the length, width, and diameter of the test part are less than the desired value. Four performance characteristics were minimized as an attempt to improve DA, however, it was observed that optimal parameter settings for each performance characteristic were different. Therefore, the Grey-Taguchi method was adopted to determine the ideal parameter level settings which would satisfy and optimize all the considered performance characteristics simultaneously. The experimental results indicate that B_O is the most influential parameter followed by L_T, whereas the remaining parameters are insignificant, although their interactions with B_O are important. Bearing this in mind, the optimal parameter settings were established. Finally, overall DA was predicted using an artificial neural network (ANN). A comparison between the experimental and the ANN predicted results show a small error that varied from 0 to 0.12% which allowed the authors to conclude the suitability of the proposed model. In the following year, Nancharaiah (2011) optimized the FDM processing time (PT) by adjusting three process parameters, A_G, L_T, and R_A. By applying, the DOE and ANOVA approach the PT was successfully optimized and the ideal parameter conditions were determined. The results draw attention to L_T and A_G as having the largest influence on PT, while the impact of R_A was found to be negligible.

A more recent investigation on DA of FDM processes has been led by Sahu *et al.* (2013). Similarly, the evaluated parameters were the aforesaid critical parameters, each with three levels. To obtain minimum change in length, width and thickness, the optimization of the parameters were performed individually. However, the results were conflicting independently or in interaction with others. Therefore, the fuzzy logic reasoning was applied to Taguchi's method, which allowed the three performance characteristics to be simultaneously considered and improved. After several experimental investigations, the optimum levels of the process parameters, with regards to DA, were determined. Additional findings state that B_O is the main controlling parameter for achieving better DA. The importance of this methodology is highlighted as it opens the scope of optimization of FDM characteristics by considering more process parameters and their influences on complex parts to ultimately achieve better quality with faster rates.

The latest research on this matter was carried out by Rayegani and Onwubolu (2014) who studied the functional relationship between FDM process parameters and TS. Four process parameters, B_O, R_A, R_W, and A_G were tested and the experimental results were submitted to the group method for data handling (GMDH), which returned predicted outputs. The predicted outputs were found to be closely correlated to the measured values. Due to the complexity of achieving a reasonable relationship between responses and FDM parameters, the differential evolution (DE) was used to optimize TS and hence, determine the ideal process parameters. All in all, relevant findings of this work suggest that a negative A_G and a smaller R_W significantly improve TS, while increasing R_A improves TS only slightly. Additionally, B_O plays a fundamental role in TS, *i.e.*, for a zero B_O (with B_O coinciding with the direction of tensile loading), maximum TS is achieved. The optimized solutions obtained from DE match very reasonably to the experimental observations, leading to the conclusion that the approach presented is reliable and has practical application for the design and production of parts using AM technologies.

Apart from ABS, Masood *et al.* (2010) performed experimental work on the influence of three FDM process parameters, A_G, R_A and R_W, each with three levels, on the TS of PC. First of all, from observing the characteristics of the printed PC parts it was noticeably the great relevance of the process parameters on the overall TS of the part. Besides determining the combination of process parameter levels that provided the highest TS, A_G was pointed out as the strongest variable influencing TS.

This literature analysis is summarized in **Table 4.** It is clear that the optimization of FDM process parameters is one of the most crucial tasks to achieve high quality parts. Although there is a considerable amount of work related to improving ABS mechanical properties and part quality, there is a lack of research on the effect of process parameters on other commonly used in FDM materials. It is important to point out the dominance of Taguchi's method and ANOVA procedure among all the discussed optimization techniques. In any event, literature review confirms that the most critical process parameters are A_G, L_T, R_A, R_W, and B_O and that these must be further explored (Mohamed *et al.*, 2015).

Table 4: Literature overview on the influence of critical process parameters on different quality performance characteristics.

PLASTIC	REFERENCE	METHODS	INPUTS	OUPUTS	SIGNIFICANT INPUTS
ABS	Lee *et al.* (2005)	Taguchi method, ANOVA	A_G, R_A, R_W, L_T	Elastic performance	A_G, L_T, R_A
	Wang *et al.* (2007)	Taguchi method, ANOVA integrated with GRA	L_T, B_O, deposition style, support style	TS DA SR	B_O B_O L_T
	Sood *et al.* (2010)	Grey-Taguchi method, ANN	A_G, R_A, R_W, L_T, B_O	DA	B_O
	Nancharaiah (2011)	DOE, ANOVA	A_G, R_A, L_T	PT	A_G, L_T
	Sahu *et al.* (2013)	Taguchi method with fuzzy logic	A_G, R_A, R_W, L_T, B_O	DA	B_O
	Rayegani and Onwubolu (2018)	GMDH, DE	A_G, R_A, R_W, B_O	TS	B_O, A_G, R_W
PC	Masood *et al.* (2010)	Laboratory experiment	A_G, R_A, R_W,	TS	A_G

3.2 | Extrusion

Preliminary work in this field was accomplished by Joseph Bramah in 1797 who patented the first metal extrusion process (Dickinson, 1941). However, no significant developments are documented until nearly ninety years later when the first patent of the original single-screw extruder was published. This 18th century apparatus, which was initially intended to process natural rubber, incorporated all the main components of a contemporary extruder. Besides the many innovative improvements over the years, the basic principles of the extruder remain the same. Although it was initially developed for conveying and shaping purposes, it was later discovered that it could be used for mixing and plasticating (to change rubber or thermoplastic into a homogeneous moldable mass) polymeric materials. These novel applications gave way to the present polymer processing industry based on screw extruders (Andersen *et al.*, 2009). As so, in 1935, Paul Troester built the first extruder designed specifically for thermoplastic materials. Shortly after, the pioneer twin-screw extruder for thermoplastics was developed by Roberto Colombo (Rauwendaal, 2014). In the late 1950s, the Maddock solidification experiment proved to be an important breakthrough in the understanding of single-screw extruders. His discovery enabled the development of innovative add-on devices and modifications to screw designs (Andersen *et al.*, 2009), especially the development of what is considered to be today's standard single-screw, the barrier screw (Giles Jr *et al.*, 2004). Altogether, Maddock's findings led to improvements in mixing and extrusion rates (Andersen *et al.*, 2009). In spite of the signs of progress in this field, due to Maddock's qualitative studies, it was not until the mid-sixties that the full extrusion process could be defined quantitatively (Rauwendaal, 2014).

Rauwendaal claims that the extruder is "indisputably the most important piece of machinery in the polymer processing industry" (Rauwendaal, 2014). It is mostly used as a polymer shaping device to mass produce products such as pipes, tubing, continuous filaments and coated electrical wire from thermoplastics and elastomers (Groover, 2007). However, with the intensification of plastic waste, extrusion has become widely associated with secondary recycling methods as it is able mechanically to transform material (Singh *et al.*, 2017). Extrusion is essentially a compression process that forces the material to flow through an orifice that determines the final shape of the product (Groover, 2007).

Extruders in the polymer industry are mainly distinguished by their mode of operation: continuous or discontinuous. The former has a rotating member to transport material, allowing the production of a steady continuous flow of material, whereas the latter uses a reciprocating member to cause transport of material, delivering the product in an intermittent and cyclic fashion which is ideal for batch type processes such as injection molding. The earliest and most universally known extruders are the screw type extruders which operate in a continuous fashion. These extruders are divided into single-screw and multi-screw. The first is the most important extruders used in the polymer industry. This type of machinery provides a promising performance-cost ratio as it is relatively inexpensive while conveying reliability, robustness and simple design (Rauwendaal, 2014). For this reason, single-screw extruders will be the focus of this research. A deeper analysis of this type of extruder and the process behind it is provided next.

A conventional single-screw extruder is illustrated in **Figure 11**. The main components of this machine are the hopper, barrel, screw, heaters, breaker plate, adapter, die, and motor. Located at one of ends of the barrel is the hopper containing feedstock, in pellet or powder form. The feedstock is fed, under the force of gravity, into the barrel and onto the rotating screw which moves the material along the barrel. The extruder screw performs different functionalities throughout the process which correspond to three different geometrical sections of the screw *(1) feed section, (2) compression section* and *(3) metering section*, also shown in **Figure 11**.

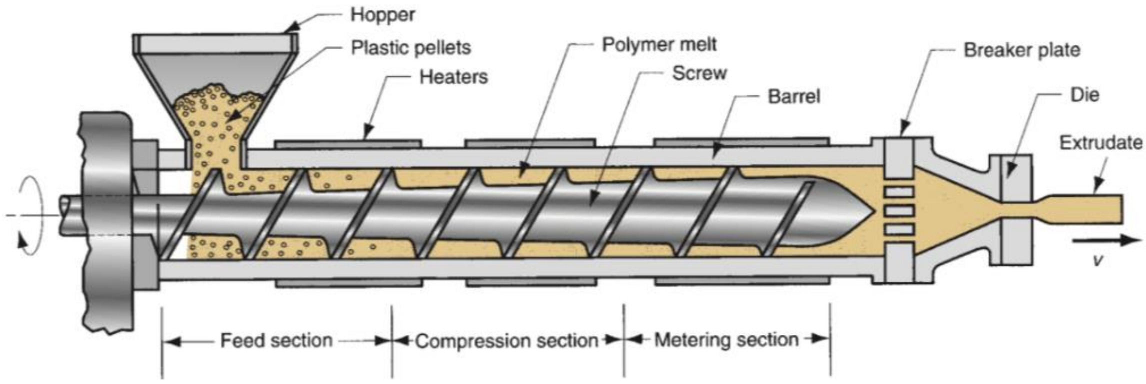

Figure 11: Components and features of a single-screw extruder for thermoplastics and elastomers (Groover, 2007).

The screw is characterized by its spiraled flights with channels between them through which the material is conveyed. The first section usually has deep flights as most material conveyed in this segment is solid (Rauwendaal, 2014). Initially, the solid pellets are melted with electrical heaters, which surround the barrel. However, the rotation of the screw and subsequent mixing of material generates additional heat, which maintains the melt (Groover, 2007; Rauwendaal, 2014; Singh *et al.*, 2017). Around 80 to 90% of the heat necessary to melt the material is generated by screw rotation since barrel heating alone is inefficient due to the poor thermal conductivity of polymers (Giles Jr *et al.*, 2004). The material is then conveyed through the compression section, whose flights are less deep, where the polymer is fully transformed into a liquid consistency and compressed. Finally, the melt is homogenized in the metering section, where the flights are shallow. The reduction in the flight depth from the feed section towards the metering section provides sufficient pressure to pump the polymer through the die opening (Groover, 2007; Rauwendaal, 2014). However, before reaching the die, the molten polymer passes through the breaker plate, a series of wire meshes with small axial holes, and then the adapter, which connects the die to the extruder. The purpose of this plate is to filter contaminants and irregularities in the molten polymer, build pressure in the metering section and finally, straighten the flow of the material and remove the circular motion imposed by the screw. Lastly, the molten material is pumped through the die orifice (Groover, 2007). The shape of the extrudate (extruded product) depends on factors such as pressure, material flow rate, die orifice shape and cross-section, and most importantly, the rheological properties of the material (Singh *et al.*, 2017). Additionally, pulling the extrudate away from the extruder, with a puller farther down the line, controls the draw and tension on the polymer from the extruder exit through the cooling and solidification steps. The final product dimensions are controlled by the extruder throughput rate and the puller speed (Giles Jr *et al.*, 2004).

There is not much that can be changed in the configuration of single-screw extruders besides the screw design. There are various designs and the selection of the most appropriate is crucial in determining the overall extrusion process capability. The selection depends on the polymers being processed, throughput rate, mixing requirements and the die design. The optimum screw design is believed to be the one that processes various polymers at high throughput, providing good melt stability and maximum yield while tolerating any other formulation to be processed under stable conditions with high yields. Although **Figure 11**, leads one to believe that the three sections have equal length, this is not accurate. The optimal section lengths vary according to the polymer. For instance, for crystalline polymers, a short compression section is appropriate as the melting of this polymer is abruptly at a specific temperature. In contrast, amorphous polymers require a compression section of almost the entire length of the screw as they take a long time to melt (Groover, 2007). Nevertheless, companies are interested in general-purpose screws as they are able to function with any polymer and can operate at any time with minimal supervision, equipment setup, or product attention (Giles Jr *et al.*, 2004).

As mentioned previously, the barrier screw is considered the standard extruder screw (Giles Jr *et al.*, 2004). Patented in 1966 (Lacher, 1966), this screw with a single flight provides a good conveying platform for solid pellets in the feed section as it ensures a uniform melt and is able to mix most plastics. Although this may be true, the barrier type screw struggles with polymers that are difficult to melt where the screw controls the production rate *i.e.*, it is unable to achieve higher rates as it cannot melt enough material. Under these circumstances, better mixing is necessary to obtain a more homogeneous product (Giles Jr *et al.*, 2004).

Having discussed that, it is important to highlight the role of the screw speed and the length of the barrel. If the screw has a higher speed, the material will not have time to melt appropriately as it is conveyed through the barrel too fast. On the other hand, if the speed is too low, the material will become over melted as it stays too long in the barrel and the extrudate will not form a proper shape (Singh *et al.*, 2017). In regard to the barrel length, it is important to mention that length-diameter ratios are typically between 10 and 30. Notably, thermoplastic materials require higher ratios while lower ratios are used for elastomers (Groover, 2007).

According to Giles Jr *et al.* (2004), the main goal of the extrusion process is "to produce a quality product that meets customer specifications 100% of the time". Furthermore, the authors establish five distinct objectives to guarantee quality in the extrusion process. These are enumerated next: *(1) correct polymer melt temperature, (2) constant melt temperature (3) correct melt pressure in the die, (4) constant melt pressure in the die* and *(5) homogeneous, well-mixed product.* Notwithstanding, an extruder has very few independent control variables that can be adjusted by an operator to alter the process. Assuming all the components in the extruder are appropriate, installed and functioning correctly and clean, the only variables that can be changed are the temperature setpoints and screw speed.

A recent review of the literature on the extrusion process revealed that the main focus has been on generalizing and extending extrusion theory coupled with the development of numerical techniques and computational methods to solve equations that cannot be solved by analytically. Moreover, the most recent and significant development in this field has been the new mixing devices for single-screw extruders which enable them to achieve the same type of mixing mechanism in high-speed twin-screw extruders. Thus, allowing improvements in the capabilities of the traditional single-screw extruders (Rauwendaal, 2014).

Several analyses on recycled plastic extrusion have been carried out as an attempt to provide an efficient reprocessing technique and a value-added solution to the abundance of plastic waste. Additionally, the extrusion of consumer-grade plastics into 3DP filament is sought as a low-cost and sustainable feedstock solution for 3DP processes (Zander *et al.*, 2019). Experiments on the feasibility of the extrusion of different recycled plastic have been conducted by many authors and are introduced next.

Lehrer and Scanlon (2017) built a custom extruder that successfully extruded a mixture of PET Glycol (PETG) pellets with shredded PET water bottles. They draw attention to the importance of the proper mixture of both plastics prior to extrusion not only as glycol has a fundamental role in improving PET properties, but also because mixing will improve the low intrinsic viscosity associated to PET, which is a constraint in obtaining a cylindrical and consistent filament. On the other hand, Byiringiro *et al.* (2018) were able to produce a filament exclusively with PET water bottles using a twin screw extruder. It was found that rPET has a 2.85g/10min melt flow index (MFI), 35.7MPa TS, 2457 MPa Young's modulus, 250ºC melting temperature and an extrusion temperature between 250 and 260ºC. By comparing the rPET filament with commonly used 3DP filaments, the authors point out the similarity between the mechanical and thermal properties of the obtained filament to those of PLA and ABS. The acceptable ranges of the rPET properties in comparison to commercial filaments have led the authors to confirm the suitability of this material for 3DP filament. Accordingly, the final parameter specifications obtained for the extrusion process were as follows: extrusion temperature of 255ºC, extrusion speed of 15 RPM, room temperature cooling method, pooling device with 8.4 V and a filament size of 1.75 ± 0.02 mm. The authors claim that the key factors that influence filament quality are the puller speed, the distance between the puller and the die and the cooling method during extrusion. Additional conclusions from this research state that although the source of PET waste may influence its quality, the results obtained endure for any type of PET material. Furthermore, Zander *et al.* (2018) conducted an experiment to process PET bottles and packaging into filament without the use of additives or modification to the polymer. Similarly, they reached the same conclusion as the previously mentioned research, however, drawing focus to the fact that rPET has the capability for replacing commercial filament in printing provided the material is properly cleaned and dried. The authors were able to produce 100% recycled and unmodified PET filament and print not only small parts but also long-lead time parts. Nevertheless, they consider that the use of additives may further improve the mechanical properties of rPET and expand its possible applications. Moreover, Zander *et al.* (2018) point out that the tensile strength of the printed parts was equivalent to those made from COTS PET pellets and PC/ABS filament.

Turning now to PP, Domingues *et al.* (2017) research demonstrated the successful printing of large parts using a filament, produced with a twin-screw extruder, made from a blend of 60% granulated tire waste and 40% rPP. In the same year, Iunolainen (2017) studied the suitability of rPP for 3D printing filament. Firstly, an empirical study was conducted that revealed the unfeasibility of producing rPP filament of satisfactory quality, with the equipment available. Although this may be true, the author points out key factors that help achieve the best quality possible for this filament. These factors involve *(1) using a cooling water bath during extrusion*, with water temperature higher than room temperature which helps to achieve the round shape of the filament, *(2) extruding at higher temperatures*, to obtain a smoother surface and eliminate swelled and not fully melted parts, and finally *(3) cleaning the extruder with virgin PP prior to the extrusion of recycled PP*. Regardless, the filament is still considered inadequate for use as it has inconsistent diameters and an elliptical shape rather than round. Moreover, the author performed material property testing. The results show that the rPP filament has a MFI of 16.4 g/10min while ABS and PLA have 6.4 g/10min and 7.8 g/10min, respectively, *i.e.*, it has considerably lower material viscosity and molecular weight. The discrepancy of these parameters, when compared to those from commercially available filament, is another indicator of the unlikelihood of success of this material in 3DP. All in all, the author comes to the conclusion that the rare use of PP as a 3DP material lies primarily in its crystalline structure *i.e.*, its semi-crystalline structure complicates the printing process due to warping and poor adhesion during printing.

Baechler *et al.* (2013) developed a household-scale semi-automated waste plastic extruder, by adapting existing designs, and successfully produced a rHDPE filament. This recycled filament was used to print increasingly successful parts. The filament was extruded at an average rate of 90 mm/min with an average diameter of 2.805 mm. While some product variance occurred, 87% of the samples had a satisfactory diameter and the average mass of extruded filament was 0.564 g/100mm length. Energy use was 0.06 kWh/m which makes filament extrusion roughly forty times more economical in terms of energy than purchasing commercially available filament. However, the printed parts produced with rHDPE did not match the quality of those printed from the commonly used ABS filament. The study discusses three major limitations encountered during the extrusion process, *(1) physical assistance was required to draw the filament from the extruder*, which caused fluctuations in the extrusion diameter due to inconsistent rates of pulling, *(2) inconsistent rate of extrusion* and *(3) heterogeneous waste feedstock,* as the authors realized that thin and light pieces of HDPE, sourced from milk jugs, did not extrude as well as heavier pieces sourced from laundry detergent and shampoo containers. As an attempt to solve this last issue, HDPE was cut into smaller pieces (≤ 5mm x 5mm) which greatly increased the extrusion rate, although the consistency remained poor. While Hamod (2015) also studied rHDPE specifications and extrusion parameters for 3DP filament, these values were obtained by analyzing the relationship between ABS and PLA with rHDPE filament, unlike the previous research. The results show that rHDPE goes along with PLA data with respect to MFI, yield strain, melt temperature and extruding temperature while TS and Young's modulus values are not comparable to either PLA or ABS. Notwithstanding, the data relating to PLA leads the author to conclude that rHDPE is suitable as a 3D filament. Accordingly, it was found that rHDPE has a 2.85g/10min MFI, 25.59 MPa TS, 428.38 MPa Young's modulus, 16.12% yield strain, 190ºC melting temperature and an extrusion temperature between 160 and 190ºC. Furthermore, the optimal parameter specifications obtained for the extrusion process were as follows: extrusion temperature of 175ºC, extrusion speed of 15 RPM, room temperature cooling method, pooling device with 8.4 V and a filament size of 1.75 ± 0.02 mm. Additional findings indicate that the puller speed, extruding temperature, and distance between the die and puller play a fundamental role in optimizing the filament extrusion process. Hamod (2015) concludes the study by suggesting future work in regards to improving rHDPE shrinkage issue. More recently, Chong *et al.* (2017) and Angatkina (2018) have carried out further investigation on this matter. Chong *et al.* (2017) evaluated the feasibility of rHDPE as a 3DP material by comparing it to ABS in terms of physical characterization. The physical characterization testing results, which included diameter consistency, extrusion rate, differential scanning calorimetry, thermogravimetric analysis, Fourier transform infrared spectroscopy, Raman spectroscopy, and water absorption, suggest that producing filaments from rHDPE is a viable option. The outcomes of this study demonstrated that rHDPE pellets had favorable water rejection, with extrusion rate and thermal stability comparable to those of the filament made of ABS pellets. Final observations point out the need for overcoming limitations such as shrinkage and adhesion problems of HDPE, similarly to Hamod (2015). A year later, Angatkina (2018) illustrated the possibility of producing rHDPE filament from municipal solid waste (MSW) and successfully use it as 3DP feedstock. However, appropriate extrusion parameters were not established since the uniformity and roundness of the filament throughout the whole length was not achieved. A heated water bath during the extrusion process was found to be crucial in producing the most round and homogeneous filament. The main concern encountered during the extrusion of rHDPE was material flow stoppage. Although the cause of this problem was not discovered, the author suggests that it could be caused by blockage of the die, melting instability or unsuitability of the extrusion screw since rHDPE consists of various blends of HDPE polymers with different molecular weight, molecular weight distribution, and chain branching. Angatkina (2018) claims that the non-uniformity and inconsistency of the rHDPE filament diameter could also be caused by the same unknown factors that caused the stoppage. The final considerations of her work imply that further research is required to improve the extrusion process and that a heated enclosure system for the 3D printer should be tested to better control the shrinkage and warpage of the printed rHDPE parts, a recurrent issue of this material as previously mentioned by other authors.

As far as recycled PVC (rPVC) is concerned, Janajreh *et al.* (2015) performed an analysis of the mechanical recycling of PVC plastic waste stream from the cable industry. Standard tensile and dynamic stress samples were manufactured and subjected to successive aging, extrusion, and molding. As the results demonstrate that remolding PVC does not affect its thermal stability nor its composition, the research emphasizes its potential for reprocessing. Two successive moldings of PVC waste were performed using a twin-screw extruder and injection molding apparatus. The tensile test showed that the molded samples became tougher compared to untouched ones. This outcome was associated with the aggressive extruder and molding conditions which are unparalleled to those at the cable plant. Nonetheless, Janajreh *et al.* (2015) underline the reasonability of the observed variability between rPVC and pristine PVC bearing in mind the scaled-up extrusion, aging, and post-curing that the sample of the cable material experiences at the plant.

Furthermore, Zander *et al.* (2019) conducted a novel experiment by testing rPP blends as 3DP filaments. Blends of rPP/rPET and rPP/rPS, with and without compatibilizers, were demonstrated to be viable feedstocks for 3DP with tensile strengths comparable to lower-end commercial filaments such as high impact polystyrene (HIPS).

A summary of this literature review is presented in **Appendix B**. This analysis has demonstrated the feasibility of extruding recycled plastics into 3D printing filament. Plastic reprocessing enables a sustainable, cost-effective and socially conscious method of adding value to plastic waste and meeting plastic demands for the 3DP industry (Lehrer *et al.*, 2017). Additionally, it is important to realize that although sometimes it might not be possible to produce a fully recycled filament, as mechanical properties tend to decrease, blends of virgin and recycled material or blends with more than one recycled polymer also provide satisfactory filaments (Pakkanen *et al.*, 2017; Zander *et al.*, 2019).

3.3 | Process Design

Previous literature regarding process design has focused mainly on chemical production processes (Biegler *et al.*, 1997; Smith, 2005; Martinez-Hernandez, 2017; Tsay *et al.*, 2018). Besides from this, and to the best of our knowledge, there is no scientific literature regarding the general activity of process design, what it entails, and how it can be improved. For this reason, the necessary theoretical background on process design, which is presented next, is based on the *Operations Management* book by Slack *et al.* (2007).

Operations management is the field concerned with managing processes, *i.e.*, the resources used for production which will deliver the products and services. This area of management can be categorized into four activity areas *(1) design, (2) operations strategy, (3) improvement* and *(4) planning and control.* The purpose of this study is to explore product process design, so from this point onwards, the focus will be on this activity area (Slack *et al.,* 2007).

According to Slack *et al.* (2007), design is the activity by which functional requirements are satisfied by the shaping or configuration of the resources and activities that comprise a product, or a service, or the transformation process which produces them. This activity is a conceptual exercise in the sense that it is completed prior to its implementation. For this reason, it is essential to understand the design objectives in the initial stages of process design as it will determine the shape and nature of the process. The five main operations performance goals are *(1) quality, (2) speed, (3) dependability, (4) flexibility* and *(5) cost*, and each one of these translate directly to specific process design objectives. Additionally, the design activity must also be environmentally aware by examining the sources and suitability of materials, the sources and quantities of energy consumed, the amount and type of waste material produced, and finally the product life-time and its end-of-life. Furthermore, it is necessary to determine the type of the process. The nature of any process is strongly influenced by the volume and variety of what it has to process, *i.e.*, low volume operation processes frequently have a high variety of products, whereas high volume operation processes often have a low variety of products. Accordingly, the five process types are, in order of increasing volume and decreasing variety, *(1) project, (2) jobbing, (3) batch, (4) mass* and *(5) continuous* (Slack *et al.*, 2007).

Once the overall design of a process has been determined, it is necessary to begin a more detailed analysis. This involves breaking down the process into all the individual activities that are required to fulfill the purpose of the process and deciding the sequence in which these activities will be performed and who is going to execute them. There are, however, constraints that must be respected, for instance, activities that must be executed before others and activities that can only be completed by certain individuals or equipment. For this reason, process design is often carried out using simple visual methods, such as process mapping. This approach enables a visual and simple way of describing the process in terms of how the activities, within the process, relate to each other. An additional benefit from using this tool is that alternative process designs can be compared and improved in terms of their operations performance goals. Finally, process performance can be evaluated in term of throughput time, work-in-progress and cycle time which are related by Little's Law, *i.e.*, throughput time equals work-in-progress multiplied by cycle time (Slack *et al.*, 2007).

At this point, the general notion of process design has been presented. Thus, it is now necessary to deepen the knowledge on the five pillars of process design, *(1) product design, (2) supply network design, (3) layout and flow, (4) process technology* and *(5) job design* (Slack *et al.*, 2007).

Product Design

A good design not only satisfies customer requirements but also communicates the purpose of the product to its market and enhances profitability. Product designers' goal is to conceive aesthetic designs which meet or exceed customers' expectations while attempting to obtain a reliable product that is easily and quickly manufactured. Accordingly, to achieve the final design of a product, it is necessary to pass through five key stages*, (1) concept generation, (2) concept screening, (3) preliminary design, (4) evaluation and improvement,* and *(5) prototyping and final design.* The first stage transforms an idea into a concept, capturing the nature and overall design specifications of the product. The concepts are then screened to evaluate whether they will be a sensible addition to the company's product portfolio. The concept that is accepted is turned into a preliminary design, which involves identifying all the component parts of the product and how they fit together. The preliminary design is then subjected to an evaluation and improvement stage to check if it can be improved. After the re-examination, the final concept is ready for prototyping and final design. The outcome of this stage is a detailed description of the package of components and the processes which will produce and deliver them to customer. This enables the formalization of three important aspects in product design *(1) the concept, (2) the package of components*, and *(3) the process*. All in all, it is suggested that product and process design should be integrated as it can improve the quality of both processes and help achieve a design break even on its investment sooner than otherwise (Slack *et al.*, 2007).

Supply Network Design

An operation is part of a broader and interconnected network of other operations which include suppliers and customers. Materials, parts, information, and sometimes people flow through the network of customer-supplier relationships formed by all of the operations. The benefits of considering the whole supply network in process design are that it *(1) helps an operation to understand how it can compete effectively within the network, (2) helps identifying significant links in the network,* and consequently *(3) helps identifying long-term strategic changes that will affect the operation.* Additionally, analyzing the entire supply network prompts three vital design decisions *(1) the supply network configuration, (2) the location of an operation* and *(3) the physical capacity of an operation.* The configuration decision involves two aspects. First, modifying the shape of the network by reducing the number of suppliers of the operation to develop closer relationships or bypassing customers or suppliers to make contact directly with customers' customers or suppliers' suppliers. Second, "do or buy" decision, *i.e.*, vertical integration *versus* outsourcing which concerns the ownership of the operations within the network. Moreover, the location decision is established by the relative strength of supply-side and demand-side factors. The supply-side factors include labor, land and utility costs which change as location changes. Whereas, the demand-side factors comprise labor skills, suitability of the site, image of the location and convenience for customers. Furthermore, the capacity decision depends on the company's view of the current and future demand. Capacity becomes a critical issue when the future demand is different from the current demand. To cope with demand variability, it is crucial to decide the optimum capacity for each site, balance the various capacity levels of the operation throughout network and time the changes in capacity of each part of the network. Additionally, economies and diseconomies of scale, supply flexibility when demand is different from that forecast, and the profitability and cash-flow implications of capacity timing changes are important aspects that influence the decisions on capacity (Slack *et al.*, 2007).

Layout and Flow

The layout of a process is concerned with the physical location of its transforming resources (facilities, machines, equipment and staff) throughout the process, and with the allocation of tasks to these transforming resources. These two decisions dictate the flow pattern of the transformed resources (materials, information and customers) as they progress through the process. Choosing the right layout is very important, otherwise it can lead to confusing and unpredictable flow patterns, customer queues, long processing times, inflexible operations and high costs. Also, re-designing the process layout can lead to disruption which can cause customer dissatisfaction or lost operating time. Accordingly, the layout decision is considered to be a complex and expensive task that is done infrequently. For this reason, the layout design begins by understanding the objectives that the layout must achieve. The goals of any layout usually depend on the strategic goal of the process. Some transversal goals are material or information flow, safety, accessibility, use of space and long-term flexibility. The layout design is also influenced by the nature of the process type, which in turn depends on the volume-variety characteristics of the process. However, bear in mind that a process type does not necessarily imply only one particular basic layout. The four basic layout types are, in order of increasing volume and decreasing variety, *(1) fixed-position,* locating the product such that it remains mainly stationary while transforming resources are moved to and from it*, (2) functional,* conforms to the needs and convenience of the functions performed by the transforming resources, *(3) cell,* locating transforming resources with a common purpose together in close proximity (a cell) and *(4) product,* locating transforming resources in a sequence defined by the processing needs of a product. Cost and flexibility are the main factors affected by the layout decision (Slack *et al.*, 2007).

Process Technology

Process technology include the machines, equipment and devices that create and or deliver products. Advances in process technology have transformed many operations throughout the years and this technological pace is not expected to slow down. In the present time, all processes use some sort of technology, ranging from a simple internet link to the sophisticated and complex automation system. As a result, operations managers must understand the principles behind the technology, *i.e.*, what it does, how it functions and the value added and constraints it might impose to the process. Different process technologies will be appropriate for different volume–variety process requirements. Accordingly, high variety and low volume processes require general purpose technology to perform a wide range of processing activities, whereas high volume and low variety processes can have more dedicated technologies to perform its narrower processing activities. In order to make technology choices, three perspectives are taken into consideration *(1) market requirements assessment*, which evaluates the impact that the technology will have on the operation's performance objectives, *(2) operations resource assessment*, which reviews the constraints and capabilities imposed by the technology and *(3) financial assessment*, which evaluates the time value of money and the net present value of investing in the technology (Slack *et al.*, 2007).

Job Design

It is worth reminding organizations the importance of "human resources". The proper management of people can have great influence on the effectiveness of the processes within the organization. Accordingly, job design is how an individual's job, environment in which they work and their interface with the technology they use is structured. Job design involves deciding what tasks to allocate to each individual, their duration and the best method of performing them. It is also concerned with the environmental conditions of the workplace, the technology available and how it will be used. Finally, it should ensure a committed and motivated workforce through empowerment, teamwork and flexible working (Slack *et al.*, 2007).

3.4 | Conclusions

3DP has revolutionized the traditional manufacturing industry by enabling low volume, customizable products with complex geometries and advanced material properties and functionality at a cost and time effective manner. Additionally, this technology enables a more sustainable and economic manufacturing process with the potential in energy consumptions and the ability of just-in-time production. However, there are still some issues with part accuracy and insufficient repeatability and consistency in produced parts that need to be addressed. FDM was introduced as it is the most commonly used 3DP technology. Achieving material sustainability of 3DP materials is of utmost importance to deal with the projected growth of the 3DP industry and as a strategy to solve the excess and unwanted plastic waste. A state of the art review confirmed the feasibility of recycled plastic as 3DP filament. Furthermore, the importance of improvements in part quality was highlighted and according to literature, A_G, L_T, R_A, R_W, and B_O are the most critical parameters. A literature review was conducted to understand the influence of critical process parameter on different quality performance characteristics. Moreover, the extrusion process was thoroughly analyzed and a final literature review was carried out that demonstrated the feasibility of extruding recycled plastic into 3DP filament. Plastic reprocessing enables a sustainable, cost-effective and socially conscious method of adding value to plastic waste and meeting plastic demands for the 3DP industry. Finally, the activity of process design was presented along with its five pillars, *(1) product design, (2) supply network design, (3) layout and flow, (4) process technology* and *(5) job design.*

The literature review revealed two main gaps that should be addressed. First, although there are studies with different types of plastics involving extrusion and 3DP, these are all performed isolated in the sense that each plastic is assessed individually and there is no evidence of research on a flexible integrated process. Second, there are no studies that look at these two operations as a whole and how they can work as a process. Since the aim of this research is to develop an integrated process design of waste valorization with extrusion and 3DP at an industrial scale, which involves defining the process and understanding how to assess and develop it as a whole, it is necessary to turn to the process design pillars.

4 | Research Methodology

To pursue the process design activity, Slack *et al.* (2007) proposed the analysis of the five pillars of process design. Accordingly, this chapter describes the research methodology that has been adopted in the present study, which is centered on this approach, and outlined in **Figure 12.**

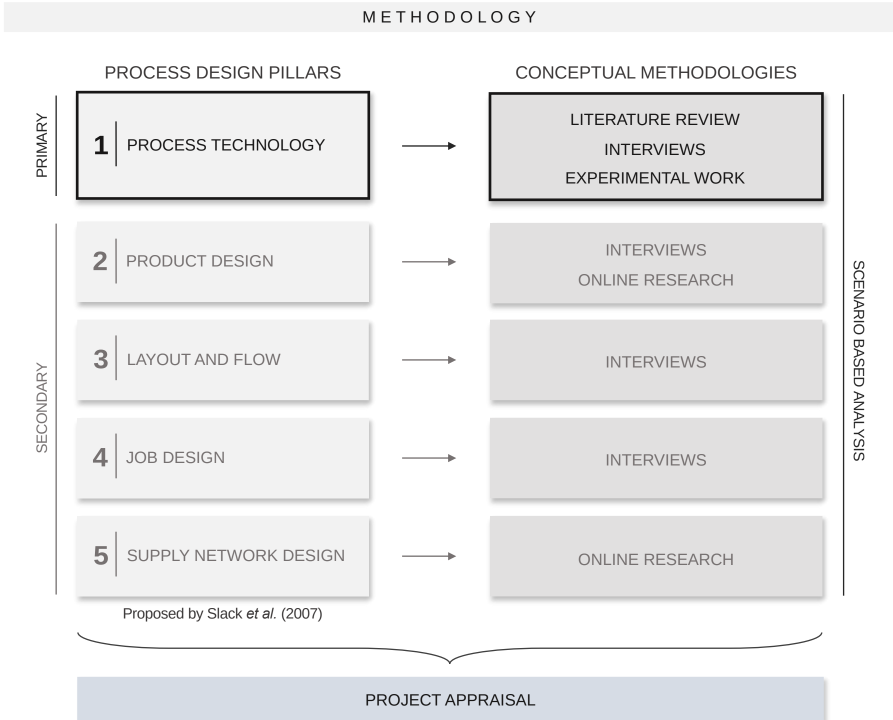

Figure 12: Master dissertation research methodology.

The five pillars of process design were analyzed in a pre-established sequence, and within each one of them, different conceptual methodologies were employed. The primary concern of this dissertation is *(1) process technology*, therefore this is the central process design pillar of this research and hence was analyzed first. Once the primary pillar was dealt with, the secondary ones were assessed in the following order*, (2) product design, (3) layout and flow, (4) job design,* and *(5) supply network design*. Furthermore, to validate the downstream waste valorization solution, a project appraisal was performed for three different scenarios, those of which were constructed throughout the process design pillar analysis. Accordingly, section 4.1 is dedicated to describing the methodology adopted for the primary pillar, while section 4.2 encompasses the remaining pillars, and section 4.3 describes the approach used for the project appraisal.

4.1 | Process Technology

The *process technology* pillar applied to this research aimed at analyzing the filament extrusion and 3DP process technologies through the characterization of the critical operational parameters, the quality problems, and their troubleshooting process, and the selection of the appropriate equipment. To achieve this, three conceptual methodologies were applied and are described below.

Firstly, a literature review was carried out to provide theoretical and empirical contextualization with the available literature on both process technologies, enabling the author to comprehend how these technologies work, their critical process parameters, and also the feasibility of using recycled plastic as a raw material for these processes. Hence, the literature review encapsulates the two process technologies: 3DP and extrusion, as described in chapter 3. The search for relevant research material was performed through online publishers and libraries, e.g. Google Scholar, Science Direct, and Springer, using keywords such as “3D printing”, “additive manufacturing”, “fused deposition modeling”, “3D printing process parameters”, “feasibility recycled plastic 3D printing filament”, “extrusion”, “filament extrusion”, and “feasibility recycled plastic extrusion”.

Secondly, informal interviews were carried out, as a qualitative research method, with key players in both 3DP and extrusion fields. The first interview was conducted on the 19th of February 2019, with the founder and CEO of a Portuguese 3DP company. This interview was followed up by another one, on the 21st February 2019, with the Project Manager of the same company, who has professional experience with 3DP. Moreover, on the 25th of June 2019, an interview was performed with an employee from Company A, whose responsibility is the extrusion part of the process. The questions asked during these interviews all converged to gathering detailed information, clarify ambiguities from the literature, and acquire practical knowledge on the 3DP and extrusion processes, as well as on the types of equipment, which otherwise would not have been of easy access.

Finally, the knowledge acquired in both the literature review and the interviews, provided a sufficient basis and tools to conduct experimental work, which was fundamental for the further analysis of the process. Experimental testing was conducted with both technologies, subsection 4.1.1 and 4.1.2 describe the experimental procedure used for the filament extrusion and 3DP process, respectively.

4.1.1 | Filament Extrusion Experimental Procedure

The extrusion experimental testing was performed using a *Brabender GmbH & Co. KG* system, consisting of an industrial single-screw extruder and a conveyor-belt type pulling system, property of *Instituto Superior Técnico.* The experimental testing was carried out with virgin ABS and HDPE since these were the pellets available for testing. The procedure began by determining the varying operational parameters: the extrusion temperature profile, the extruder speed, and the puller speed. In each experiment, one parameter was altered while the others remained constant, to better understand the impact of each factor. The base temperature profile was established by calculating the average temperature of the recommended interval setpoints of each zone for each resin. The experimental parameters that were adopted are presented in **Tables 5** and **6**. Note that the puller speed does not present a measurement unit since the equipment did not specify the units of these values.

Table 5: Experimental parameters for ABS.

EXPERIMENTAL PARAMETERS FOR ABS			
Extrusion Profile Temperatures			
Heater 1 (ºC)	Heater 2 (ºC)	Heater 3 (ºC)	Heater 4 (ºC)
228	239	248	245
218	229	238	235
208	219	228	225
198	209	218	215
188	199	208	205
Extrusion Speed (RPM)			
5			
10			
Puller Speed			
30			
40			
50			

Table 6: Experimental parameters for HDPE.

EXPERIMENTAL PARAMETERS FOR HDPE			
Extrusion Profile Temperatures			
Heater 1 (ºC)	Heater 2 (ºC)	Heater 3 (ºC)	Heater 4 (ºC)
191	208	228	228
181	198	218	218
171	188	208	208
161	178	198	198
151	168	188	188
Extrusion Speed (RPM)			
5			
10			
Puller Speed			
30			
40			
50			

4.1.2 | 3DP Experimental Procedure

The 3DP experimental testing was performed at the Portuguese 3DP company, where the aforementioned interviews took place. This company purchases 3D printers and tailors them to improve their performance, therefore their equipment is custom-made. For the experiments, three of their 3D printers were used, two from which had Bowden extruders, while the other had a direct drive extruder. The former extruder pushes the filament directly into the nozzle, whereas the latter is usually mounted on the frame of the printer, and uses a tube to enclose the filament while it is fed a longer distance to the nozzle (Hullette, 2018). The experimental testing was carried out with virgin PETG, PET, and white-colored PET. The decision to utilize these materials, and not the same as those used for the extrusion experiments, was informed and well-considered. The reason why ABS was not chosen resulted from the fact that it is one of the most commonly used materials for 3DP, and therefore, its processing parameters are already optimized, and there is a wide range of studies regarding this polymer. On the other hand, HDPE was not chosen since, at the time, there was no 3DP filament available from this material with the minimum quality standards necessary to perform the printing.

The experimental work consisted of printing 3D model samples of a cylinder with the chosen polymers. The procedure began by establishing the varying operational parameters, which are presented in **Table 7**. Contrarily to the extrusion procedure, where the operational parameter values were defined before the testing was conducted, the starting point of the 3DP experiments involved using the last operational parameter values that the company had tested for such materials (see **Table 7**). From this point, the following combination of operational parameters was obtained by observing the issues from the previous print and by fine-tuning the parameters, in order to obtain improved results. The adjustment of the operational parameters, which allowed the understanding of their influence on the printed parts, was performed until a perfect part was obtained, when possible, *i.e.*, a robust cylinder with no visible errors.

Table 7: Initial experimental parameters for 3DP.

INITIAL EXPERIMENTAL PARAMETERS FOR 3DP			
Operational Parameter	**PETG**	**PET**	**PET White**
Extrusion Multiplier	1	1	1
Extrusion Width (mm)	0.48	0.48	0.48
Retraction Distance (mm)	0.8	1.5	1.5
Retraction Speed (mm/s)	20	20	20
Coast at End	Yes	Yes	Yes
Coasting Distance (mm)	1	1	1
Extruder Temperature (ºC)	235	250	250
Bed Temperature (ºC)	60	Layer 1 - 80 Layer 2 - 85	Layer 1 - 80 Layer 2 - 85
Printing Speed (mm/s)	50	40	40
Outline Underspeed (%)	70	70	70
Top Layers	6	2	4
Bottom Layers	3	2	3
Outline Shells	3	2	2
Infill (%)	20	10	10

4.2 | Secondary Pillars

The secondary pillars of process design were analyzed in the following sequence, *(2) product design, (3) layout and flow, (4) job design*, and *(5) supply network design*. As presented in **Figure 12**, under conceptual methodologies, informal interviews played an important role in obtaining the required information to pursue the analysis on the first three secondary pillars. Along the same lines of what was discussed in section 4.1, these interviews were carried out in the same conditions and to the same interviewees, with exception to the 3DP company Project Manager, on the 17th and 18th of July 2019. Further details on these interviews and the remaining conceptual methodologies adopted for the secondary pillars are described below.

The *product design* pillar applied to this study had an important role in the process of plastic waste valorization as it involved determining the possible marketable options that could result from the waste valorization solution. To accomplish this, an interview was carried out with the 3DP company CEO, where questions such as the following were asked: *"what is the portfolio of products that your company most frequently produces and retails*?", *"what are the processing times of such products?"*, *"how much plastic filament such products consume?"* and *"what are the retail prices of such products?"*. To complement this interview, online research, *i.e.*, via the internet, was conducted to collect data on the worldwide 3DP plastic market, namely on the industries in which this technology is being utilized and the products that are being manufactured.

The *layout and flow* pillar aimed at conceptualizing the physical location of the downstream waste valorization solutions, *i.e.*, the layout of the filament extrusion line and the 3D printers, which in turn dictates the flow of plastic throughout the process. To gain insight on the most appropriate layout for the solution, informal interviews were conducted with the experienced employees in both the extrusion and 3DP industries. Questions in the same line as the following were inquired to the 3DP company CEO: *"how does your company display their operating 3D printers?"*, *"is this a common practice amongst 3DP entities?"*, *"do you suggest a better layout for the printers?"*, *"what is the necessary safety distance regarding the display of the 3D printers?"*, *"suppose there is an extruder producing plastic filament that will be used to feed 3D printers, which layout would you suggest for this process?"*, and *"how many 3D printers would you consider to have in a low, medium, and high production capacity?";* and to the employee from Company A: *"how are extrusion filament lines usually displayed?", "what is the necessary safety distance regarding the display of the filament extrusion line?"*, and *"suppose there is an extruder producing plastic filament that will be used to feed 3D printers, which layout would you suggest for this process?"*. With the information gathered in the interviews, three different scenarios were considered for the development of the layout proposals: a low, medium and high production capacity, considering the following assumptions, respectively, 1 Filament Extrusion Line and 12 Printers, 1 Filament Extrusion Line and 72 Printers, and 1 Filament Extrusion Line and 144 Printers.

The *job design* pillar targeted at this research involved people management, *i.e.*, outlining the tasks and responsibilities of the different parts of the process and the respective qualifications required to perform them, to assure the proper operation of the downstream waste valorization solution. The most effective approach to understanding the workforce requirements for this type of operation was to perform informal interviews with the experienced employees since they are familiarized with the processes in question and their necessities. Accordingly, the following questions were asked to both interviewees, respectively to the process they are knowledgeable about: *"how many employees are required to handle one filament extrusion line, what are their necessary qualifications, and what are their responsibilities throughout the* *process?"* and *"what is the 3D printer-employee ratio necessary to handle such equipment, what are their necessary qualifications, and what are their responsibilities throughout the process?".*

The *supply network design* pillar aimed at identifying the potential suppliers and customers of the output products of the proposed waste valorization solution, in order to establish a network of customer-supplier relationships. To evaluate the potential suppliers and customers, online research was conducted to establish the broader and interconnected network of other operations related to the solution.

4.3 | Project Appraisal

To conclude the research methodology, a project appraisal was performed to assess the viability of the proposed downstream waste valorization solution. This was accomplished by establishing three different scenarios, a low, medium, and high production capacity scenario, identical to those considered in the *layout and flow* pillar. These scenarios were built from the findings obtained with the process design pillar analysis. Within each scenario, four sub-scenarios were established, considering different marketable products, leading to twelve different scenarios, depicted in **Figure 13**. The scenarios are fully described and presented subsequently, in Chapter 7.

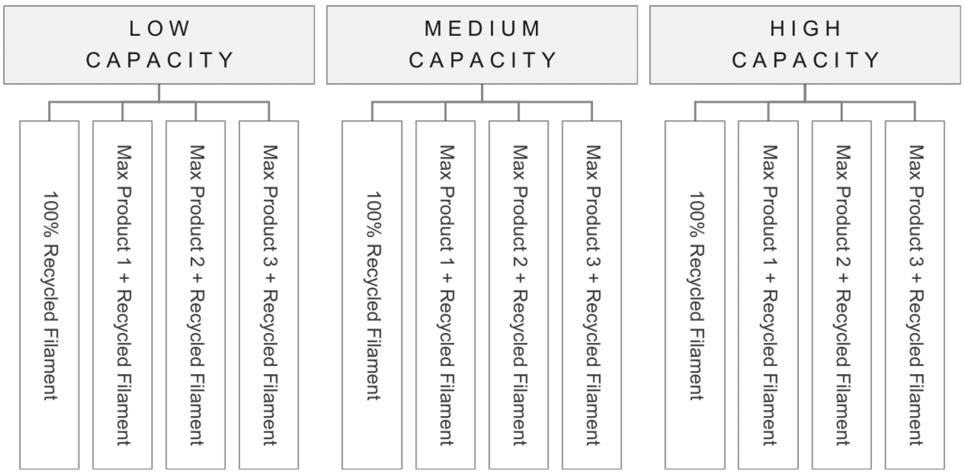

Figure 13: The scenarios established for the project appraisal.

Once all scenarios were defined and the necessary assumptions established, three project appraisal criteria were calculated for each scenario, the Net Present Value (NPV), the Internal Rate of Return (IRR), and the payback period. Based on these criteria, it was possible to determine whether the different scenarios of the proposed downstream waste valorization solution were viable or not. Finally, a sensitivity analysis of the 3DP plastic filament market was conducted to evaluate the impact on the NPV of the different scenarios.

4.4 | Conclusions

The research methodology centered on the process design pillar approach proposed by Slack *et al.* (2007) has been described in this chapter. The primary focus of this research is on the *process technology* process design pillar, and therefore it will be analyzed first. The conceptual methodologies adopted for this pillar consist of a literature review, interviews, and experimental testing. Once this pillar has been dealt with, the secondary process design pillars will be assessed, by adopting the following conceptual methodologies: interviews and online research.

5 | Process Technology

The process of bringing value to plastic waste is initiated at the waste management companies, as illustrated in **Figure 14**. Plastic waste is gathered and brought into the companies' facility so that it is treated adequately. Once in the facility, plastic waste is sorted by resin and cleaned in the designated station. Moreover, the plastic is dried in a hopper-drier and shredded into pellets using a shredder and a mill. The same sized uniform pellets are then inserted into an extruder where they are heated to melting temperature and are forced out the die to form a filament. This filament is then used as feedstock for 3D printing. Producing a marketable product with this filament enables circularity in plastic waste, and therefore, transforms plastic waste into a valuable resource for 3DP.

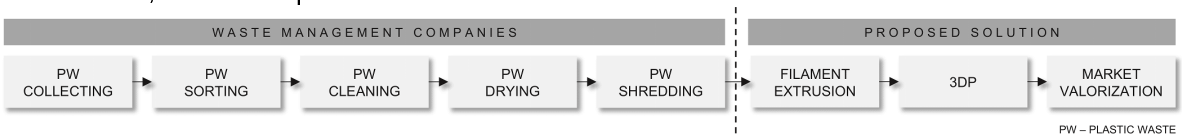

Figure 14: Waste valorization process flowchart.

This chapter focuses on process technology, the central process design pillar for this research. Accordingly, this chapter is divided into two sections, 5.1 and 5.2, referring to the different technologies within the proposed solution, filament extrusion, and 3DP, respectively. This chapter aims at establishing the link between the fieldwork findings and the data collected in the literature review to provide detailed information and guidelines on the operation of these technologies. Correspondingly, both sections are structured into three subsections, the first involves the characterization of the critical operational parameters, the second refers to quality problems and their troubleshooting process, and the last entails the selection of the equipment. The 3DP section entails an additional subsection regarding the development of a visual print quality troubleshooting guide.

5.1 | Filament Extrusion

The available literature on extrusion processes has tended to focus more on sheet, cast, and pipe extrusion rather than filament. Although the basic extrusion technology is generally the same for the different range of products, the behavior of the extrudate after leaving the die is different according to the desired end product, as well as the parameter adjustments and quality problems. For this reason, interviews were carried out informally with experienced employees to gather more information regarding the filament extrusion process. The knowledge acquired in both the extrusion theoretical review (section 3.2) and the interviews provided a sufficient basis and tools to conduct experimental work, which was fundamental for the further analysis of the process. The experimental testing set-up included an industrial extruder and a conveyor-belt type pulling system (see **Figure 15**). Furthermore, the data collected in the literature, together with the fieldwork findings allowed the development of the diagram shown in **Figure 16**, which provides an overview of the topics that will be discussed in this section.

5.1.1 | Operational Parameters

To assess the influence of the different operating parameters on the extruded filament, experimental testing was performed with two different polymer pellets. This was carried out by varying a single parameter whilst the others remained constant, to effectively understand the impact of the varying parameter on the filament. Accordingly, the operating parameters are presented below along with their

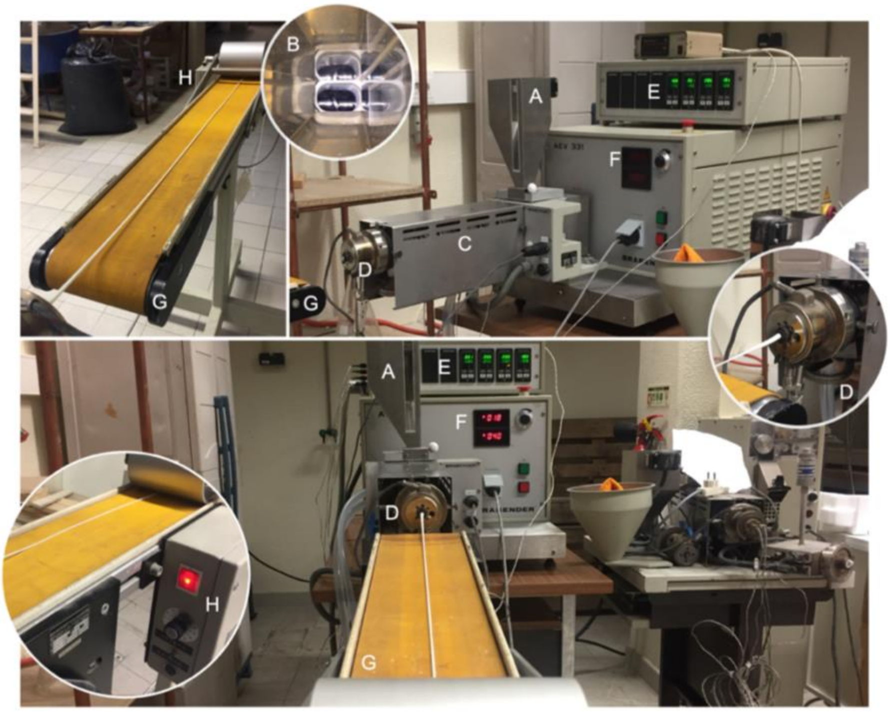

Figure 15: Extrusion experimental testing set-up. The top right image shows the industrial extruder, the top left image shows the puller device, and the bottom image shows the whole set-up. A - hopper; B - hopper interior where the screw is visible; C - barrel divided into 4 zones; D - die; E - zone temperatures settings; F- screw speed setting; G - puller device; H - puller speed setting.

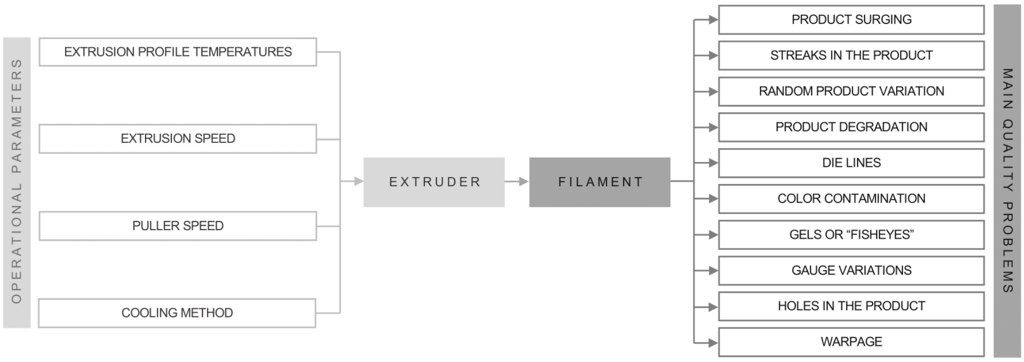

Figure 16: Filament extrusion process characterization.

influence on the filament, which was observed and documented through the experimental testing of virgin HDPE and ABS (see **Appendix C** and **D**).

5.1.1.1 | Extrusion Profile Temperatures

The polymer inside the extruder is conveyed forward, passing through the different zones of the barrel until it reaches the die zone and exits the extruder. As the polymer moves through the extruder, it is melted with electrical heaters which surround the barrel. Regularly, the first temperature zone is the lowest to prevent premature melting and bridging of the resin in the feed throat. The temperatures of the following zones are gradually increased until the die is reached. The temperatures established for the different zones of the extruder are referred to as the extrusion profile temperature (see **Figure 15, E**). Bear in mind that the zones of the extruder do not necessarily refer to the three geometrical sections of the screw, as longer extruders require more heaters. The tests conducted with ABS revealed that when the profile temperature is too high, compared to what the polymer can tolerate, bubbling and smoke are visible as the filament exiting the extruder is at a temperature beyond its melting point. Consequently, this does not allow the filament to cool enough to maintain its round shape as it leaves the die, resulting in an irregular filament with high diameter variation. Additionally, the bubbling causes a rough surface texture and a very brittle filament. It was also established that in case bubbling occurred, there was a great possibility that there were voids in the filament. On the other hand, low temperature profiles may damage or break the screw as there is not enough heat to melt the polymer and convey it through the barrel.

As a guideline for initiating the extrusion process, **Table 8** presents the recommended profile temperature intervals for different polymers and barrel zones. Regardless, having conducted experimental work with HDPE and ABS demonstrated that although these values are a good starting point, it is extremely important to calibrate these throughout the process and according to the zones of the extruder being utilized until the optimal temperatures are achieved.

Table 8: Recommended temperature setpoints for different polymers (Giles Jr *et al*., 2004).

EXTRUSION PROFILE TEMPERATURES GUIDELINE							
Polymer	Zone 1 (ºC)	Zone 2 (ºC)	Zone 3 (ºC)	Zone 4 (ºC)	Zone 5 (ºC)	Zone 6 (ºC)	Zone 7 (ºC)
PET	249-271	271-288	288-300	288-300	288-300	-	-
HDPE	149-171	177-199	199-216	199-216	199-216	-	-
Rigid PVC	143-149	154-166	166-177	166-177	177-185	-	-
Flexible PVC	121-138	132-149	132-160	132-160	160-171	-	-
LDPE	149-171	171-185	182-199	182-199	182-199	-	-
PP[1]	171-193	210-232	227-243	227-260	227-260	-	-
PS	171-182	199-210	221-232	221-232	227-238		-
ABS	177-193	199-216	210-227	216-240	216-240	226-240	210-240

[1] Considering a MFI range from 0.2 to 10.

5.1.1.2 | Extrusion Speed

The extrusion speed denotes the speed at which screw is moving the material along the barrel (see **Figure 15, F**). By varying the extrusion speed, all else constant, the results showed that the higher the extrusion speed, the higher the throughput of material exiting the extruder, which increases filament diameter. Conversely, the lower the extrusion speed, the lower the throughput of filament, which results in smaller filament diameters. Accordingly, by changing the extruder speed, all else constant, it is possible to control the filament diameter. The results from the HDPE tests demonstrated that when the extruder speed was increased, as the throughout increases, the cooling time of the filament decreased, causing swirling at the downstream of the puller. However, this was aggravated as there was no tension mechanism in the set-up pulling the filament properly, and can be attributed to poor puller performance. Accordingly, by increasing or decreasing the extruder speed it is possible to increase or decrease the filament diameter respectively.

5.1.1.3 | Puller Speed

The pulling system (see **Figure 15, G**) controls the draw and tension on the polymer from the extruder exit through the cooling and solidification steps. The speed at which the puller draws the filament away from the extruder is mentioned to as puller speed (see **Figure 15, H**). The laboratory findings demonstrated that the higher the puller speed, the faster the filament is being drawn from the die, resulting in a smaller filament, and *vice-versa*. Similarly to the extrusion speed, it is possible to control the filament diameter by adjusting the puller speed, all else constant.

5.1.1.4 | Cooling Method

The cooling and solidification stages of the extrusion process occur once the filament exits the extruder die. Proper cooling of the filament is critical to guarantee dimensional accuracy, proper shape and performance while avoiding warpage issues. The cooling of the filament can be accomplished with water, air, or contact with a cold surface. Cooling with water is usually associated to cooling water baths, where the water is set at a certain temperature, while air cooling can be simply at room temperature or using a cooling fan.

5.1.2 | Filament Quality Troubleshooting Guide

To asses and improve the quality of the extruded filaments, an operational troubleshooting guide was developed based on Giles Jr *et al.* (2004) handbook on extrusion, together with the experience gained through the laboratory testing. Each quality problem is explained and the possible causes of it are presented. Furthermore, adjustments on the operating parameters are suggested as an attempt to solve the issue.

5.1.2.1 | Product Surging

Surging occurs when the extruder flow rate is unstable or when the output rate is inconsistent. Potential causes for this issue and corrective actions are described below.

Barrel temperature too low

Setting a low temperature at the feed or compression section can cause the polymer to not fully melt in the compression zone, which results into clogging or interference with the screw mixing section as the unmelted pellets entering the metering zone are difficult to melt. In this case, it is advised to increase the extrusion temperature of the zones corresponding to the compression and metering sections.

Insufficient resin supply

In starve-fed extruders, *i.e.*, extruders with feeders that deposit polymer directly onto the extruder screw and where the throughput rate is determined by the feed rate rather than the extruder screw speed (Giles Jr *et al.*, 2004), the lack of resin supply relative to the screw speed can cause the discharge end to be incompletely filled. Correspondingly, the oscillating metering section fill can result in surging. To cope with this problem, it is recommended to either lower the extrusion speed, increase the feed rate, if possible, or increase the backpressure with finer screens in the breaker plate or a valve.

5.1.2.2 | Streaks in the Product

Streaks in the product which run in the direction of the extruder or the direction of the puller can result from different situations. These causes are described below alongside suggestions to cope with them.

Variation in product consistency

The main cause of product inconsistency is poor mixing. The short-term solutions are to increase the extrusion profile temperatures or increase the die head pressure to generate more mixing. On the other hand, the longer-term solution is to change the single screw to one with an improved mixing section.

Streaks appearing during production

A situation that may occur is the appearance of streaks after production has been consistently manufacturing a good product. This can be a consequence of changing the raw material supply or the colorant package. Other possible causes are the variation of plastic viscosity due to a heater band burning out, cold air blowing on the extruder, a damaged screw, or deposit build-up in the die causing resin degradation. Accordingly, it is recommended to check whether the screw or die needs cleaning or replacing, or if any variation described above has occurred, which resulted in the appearance of the streaks during a run.

Unsuitable die

Another potential cause for streaks is the possibility of the die being unsuitable for the particular process being run. Hence, it is important to determine whether the problem is being caused by the die, and if so, the die may not be assembled properly or may need adjustment.

5.1.2.3 | Random Product Variation

This problem refers to circumstances in which the product varies inconsistently without any observable changes in the process. Even if the changes are attributed to appearance, physical properties, or compositions, the identification of the cause and effect of these types of issues are complex. The potential causes and suggestions to help with this problem are discussed below.

Feed issues

There might be feeding problems caused by sticky material adhering to the feed hopper or feed throat. If this is the case, consider adding talc to lubricate the particle surfaces.

Raw material variations

If a variation in raw material has occurred, for instance, due to regrind, a raw material lot change, or a supplier change, it may lead to product variation during a run. Therefore, when there is an alteration in raw material, it is necessary to check the properties of the new material.

Combination of cyclic issues

Cyclic factors such as melt temperature fluctuation, pressure variation, and screw speed can occur concurrently. For this reason, it can be extremely challenging to identify the issue and correct it. Many processing changes may be required to correct the problem. Thus, the best way to handle this setback is to monitor the process closely and identify and eliminate any cyclic variations.

5.1.2.4 | Product Degradation

Signs of product degradation include discoloration, streaks, black specks, and loss of properties. The many potential causes for degradation are detailed below, together with recommendations on how to solve each situation.

Temperature too high

One of the causes of product degradation is when the temperature inside the barrel is set too high. The solution is to lower the temperature by adjusting the profile temperatures or reducing the extrusion speed to generate less heat or decrease the shear heating, which may involve changing the screw design.

Exposed to high temperature too long

The polymer may degrade over time when the residence time in the extruder, transition pipes, adapters, or the die is too long. Additionally, dead spaces within the die or transition zones allow the polymer to build up and stagnate, leading to degradation as the polymer sits at high temperatures. Under these circumstances, the polymer residency time should be decreased by increasing the extrusion speed, and the die and transition pipes should be streamlined to prevent any dead areas.

Polymer reacts with other polymer or additives

Product degradation may also occur by a reaction of two or more incompatible polymers or additives at the processing temperatures. Therefore, it is necessary to verify if all formulation additives are stable at the processing temperatures, if not, replace with other additives. Moreover, when two or more polymers are being combined, it is also necessary to verify whether they react with each other. If this is the case, avoid combining those polymers or try adjusting the extrusion profile temperatures to a point where the reaction does not occur.

Screw, die, or adapters need cleaning

Black specks can be caused by a dirty screw die, adapters, or transition pipes. Black speck contamination occurs when the degraded polymer accumulated in the extruder breaks off or is scoured off by shear during processing. Accordingly, to solve and avoid this issue, the contaminated areas must be properly cleaned.

5.1.2.5 | Die Lines

Die lines are straight lines in the extrusion direction which remain in the same location on the product during processing. The potential causes for this issue are presented next, as well as how to cope with them.

Surface defect in the die

Surface defects in the die can result from scratches or foreign material in the die, and they cause indentations in the product which remain in the same location over time. If there are scratches on the die lip area (the final part of the die, where the polymer exits), these have to be removed mechanically to eliminate the problem. On the other hand, if there is foreign material located in the die in front of the die lips, or on the die lips, it is necessary to clean the die to eliminate the issue.

Sizing device or take-up unit

Die lines may also occur outside the die by dragging the product across something in the sizing operation or on the take-up unit. It is easy to identify if the die lines occur outside the die by verifying if the lines are not present at the moment the product exits the die but instead is seen partway down the line in the cooling section. In this situation, it is important to determine where or what is scraping or damaging the product after leaving the die to eliminate the cause for the die lines.

5.1.2.6 | Color Contamination

When a previous formulation is inadequately cleaned, it may lead to color contamination. Potential areas for color contamination are identified below.

Extruder and die

Color contamination can occur if the extruder and die are not properly cleaned from a previous run. For this reason, it is usually recommended, if possible, to schedule production runs to go from lighter to darker colors so that color contamination is unnoticeable. In the event a darker color is followed by a lighter color, it is necessary to fully empty and clean the extruder, which takes a long time, to avoid color contamination. Any polymer stagnating or hanging up in the die, transfer pipes, breaker plate area or around the feed throat can lead to color streaks or contamination in following runs until it is completely eliminated.

Feed system

Another potential area for color contamination is the feed system, which must be completely cleaned before any color changes. Therefore, guarantee that all components of the feed system are cleaned and free from contamination.

Inadequate premixing or feeding of colors

Color contamination may also result from improper premixing, feed ratios, or color ingredients added to the extruder. Formulations which are premixed and transferred to the extruder must be mixed in the correct ratio. With starve-fed extruders, the color formulation must be adequately mixed and the feed rate should be such to result in the correct throughput rate to generate the correct color. Color concentrate added at the wrong rate will result in the wrong color.

5.1.2.7 | Gels or "Fisheyes"

Gels, more frequently known as "fisheyes", are high-molecular-weight polymer particles that do not melt during processing. Gels can soften and elongate as they go through the screen pack, which is designed to filter and trap contaminants. Nonetheless, these "fisheyes" never melt, and after they pass through the die, they return to their original shape, forming small hard particles in the melt. Furthermore, gels are also considered by some as any contaminant, *i.e.*, dirt or other polymers, that passes through the die. Accordingly, gels are considered a speck, which may be clear, that form a defect. If gels are being formed in the die, this area needs to be streamlined to prevent stagnation. Additionally, to remove "fisheyes" that are already present in the polymer, it is recommended to increase the extrusion profile temperatures and use a finer screen pack to filter them out.

5.1.2.8 | Gauge Variations

Gauge variations refer to thickness inconsistencies in the final product. Discrepancies in product dimensions are caused by irregular melt temperatures, resulting in polymer viscosity fluctuations that correlate with differences in the flow of the material exiting the die. The most common causes for uneven melt temperatures are discussed next together with corrective measures to eliminate gauge variations.

Poor melt mixing

Irregular melt temperatures can be a consequence of poor melt mixing, caused by a mismatch in screw design for the polymer being extruded, together with low die pressure, which reduces polymer backflow. For this reason, it is necessary to improve mixing to avoid gauge variations.

Unevenly clogged screen pack

When the screen pack is unevenly clogged, the polymer flows more through certain areas of the screen pack in comparison to others. Consequently, the areas that are partially clogged have an increased melt temperature relative to the sections where the material is flowing more freely. To cope with this issue, it is recommended to replace the screen pack.

Burnt out heaters in the screen pack, adapter or die

If the heaters in the screen pack, adapter or die are burnt out, the extrusion profile temperatures established will be inconsistent, as there will be cold spots where the heaters are burned out and hot spots where they are still working. In this case, it is suggested to replace the heaters.

Heaters loose on the adapter or die

Loosely fitting heaters on either the adapter or die can also create hot spots where the heaters are in contact with the die or adapter, and cold spots where they are not. Therefore, consider tightening the heaters to obtain the profile temperatures established and to avoid this issue.

5.1.2.9 | Holes in the Product

The formation of holes in the product can be caused by gases that are generated in the extrusion operation through polymer degradation, steam, or trapped air that is not removed before reaching the die. The potential causes and corrective actions for holes in the product are described below.

Trapped air

If air is trapped in the barrel, it must be removed before the die or holes will be blown in the final product. With flood-fed single screw extruders, the air is forced back through the feed throat by compression and melting in the compression zone. On the other hand, in case of a starve-fed single screw extruder, the screw speed must be slow enough to prevent air from being pumped past the compression zone. However, the last screw flights, regardless of the type of extruder, have to be completely filled with material to prevent air from reaching the die. Any air that is trapped in the metering zone will be forced out the die and blow holes in the final product. When air exits the die on a flood-fed single screw extruder, it may be an indication that the material is not melted in the compression zone, which allows unmelted pellets and air to penetrate into the metering section. To solve this issue, it is suggested to increase the profile temperatures corresponding to the compression section to guarantee the polymer is fully melted in this section. Moreover, by utilizing finer screen packs, the backpressure is increased and therefore helps fill the screw and prevent air from exiting the die. Another approach, if the above recommendations do not help with the problem, is to use two-stage vented single screw extruder to provide an exit path for the trapped air, other than the die.

Degradation of resins or additives

Another cause for holes in product is high melt temperatures that lead to resin or additive degradation, creating gases at the extruder discharge. With a vented extruder, it is possible to remove the gases from the extruder before they reach the die. Regardless, the resin still experiences degradation and may produce a poor quality product. For this reason, approaches such as decreasing the profile temperatures, changing screws to reduce shear heating, or decreasing the extrusion speed to minimize the melt temperature are considered to be the best strategies to cope with this problem.

Contaminated resin

Resin contamination in the extruder can cause chemical reactions that may produce gases. This can be solved by properly cleaning the extruder with a nonreactive resin and avoiding or removing any contamination from the product before feeding it to the extruder.

Moisture

When there is moisture in the extruder, together with resin or additives, it is converted into steam. Holes in the product develop if moisture is not removed, through vacuum or atmospheric venting, before the material reaches the die. When dealing with pre-dried resins that still contain some moisture or moisture that has condensed on the pellet surface, rather than a hole, the moisture can cause surface splay on the product. Splay surfaces indicate that moisture or gases are present, but their concentration is lower than the critical quantity required to blow bubbles in the product. All in all, to improve this issue, it is important to pre-dry the materials adequately, or it may also be helpful to adopt a vented extruder.

Polymer shrinkage through cooling

Vacuum voids are holes that form in thick sections as the polymer cools down and shrinks. In other words, when thick extrudate sections cool rapidly, after leaving the die, a surface skin is formed. As the polymer continues to cool down, the skin continues to thicken. Since the surface skin is solidified, there comes a time when the molten material inside the thick section cannot pull the outer walls toward the center of the filament. This causes the molten material to shrink toward the outer surface, forming a vacuum void in the center. To avoid this problem, it is advised to cool the extrudate more slowly, so that the surface skin can shrink toward the center.

5.1.2.10 | Warpage

Warpage is a direct result of irregular shrinkage in the extrudate cross-sections. This is frequently referred to as internal stresses in the product resulting from the molecular orientation, molecular relaxation outside the die, or molecular orientation induced in the final product by drawing. Stresses endured by the filament are caused by some part sections shrinking differently from other sections. The main factors for warpage are described below together with suggestions on how to deal with this issue.

Molecular packing uniformity

When the packing forces or pressure in the die are not uniform, some molecules can be more tightly packed in some areas compared to others. Areas with higher packing or more molecules packed into a given volume shrink less than areas with fewer molecules in the same volume. To obtain a uniform flow pressure in the die to minimize shrinkage dissimilarities, the die and part design require uniform cross-sectional areas with the correct taper and lead into the polymer flow channels in the die.

Solidification uniformity

To prevent warpage, all surfaces must solidify at the same time and rate. Consider an extrudate where the bottom is cooled by water and the top by air, as the bottom solidifies more rapidly, the top curls and warps towards the hotter side. In other words, as the product exits the extruder before it comes in contact with the water cooling, the part is expected to shrink the same throughout. As the bottom is submerged in the water, a skin is formed, and shrinkage starts to occur. The top half, that is exposed to air, is still molten while the polymer chains move as the bottom part shrinks. After a given time, a skin is formed on top and shrinkage on that part begins. Since both the top and bottom are expected to shrink a specific amount, the bottom shrinks less compared to the top as it was shrinking while the top was still molten, causing the product to warp toward the hot side. Accordingly, the cooling rates should be similar throughout the entire filament to ensure the skin thickens homogenously. Nevertheless, if the melt temperature on one side is hotter coming out of the die than the other side, warpage can result even with uniform cooling, as the hotter side may solidify later in the process compared to the side with the cooler melt temperature. Uniform melt temperature criteria are important to minimize warpage.

5.1.3 | Filament Extrusion Lines

Proper equipment selection is vital for efficient polymer processing. The literature review regarding the extrusion process (section 3.2) and the filament quality troubleshooting guide (subsection 5.1.2) have proven that the selection of the most adequate extruder components, such as the screw, feed-hopper and die designs, are critical in obtaining the best extrusion processing capability and for overall filament quality. To provide some examples of the different filament extrusion lines which are available in the market, several requests were sent to different suppliers to obtain a detailed description of their filament extrusion lines and the retail price of such equipment's. Accordingly, three different filament extrusion lines are presented and characterized below. For confidentiality purposes the identity of the suppliers and their equipment are omitted.

5.1.3.1 | Filament Extrusion Line A

The filament extrusion line A (ExA) is a high speed 3D filament production line with a maximum capacity of 20 kg per hour that retails at 114 990€. With a vacuum calibration for high strand diameter precision, the ExA is made to produce filaments with an exact diameter from 1.75 to 3.00 mm, allowing for various brands of 3D printers. The full characterization of ExA is presented in **Table 9**.

Table 9: The technical specifications of ExA.

FILAMENT EXTRUSION LINE A			
Price	114 990 €		
Max Capacity	20 kg/h		
Max Screw Speed	200 RPM	Max Production Speed	100 m/min
Components	• Single screw extruder: - screw and barrel in high-grade nitride steel with 30mm and a 30 L/D ratio - compression ratio 1:3 - max screw speed: 200 RPM - large oversized drive with 7.5 kW AC motor - 4 heating zones, all with air-cooling - digital programmable set and readout temperature controllers for 5 zones - stainless steel hopper • 3D strand die and calibration items for 1.75 mm and 2.85 mm • Vector motor: - 11kW motor drive - high RPM accuracy and high torque through the entire screw speed range • Stainless steel vacuum cooling and calibration bath: - water heater to eliminate shrinkage voids - length: 4.0 m - max temperature: 85ºC - vacuum pump outside the frame to reduce water vibrations • Second cooling tank: - large vacuum suction system with twin nozzles for efficient removal of all water on the filament		
	• High speed caterpillar haul off unit - variable speed drive of belt - max pulling speed: 100 m/min	• High speed two-station wind up unit - max wind up speed: 100 m/min	

5.1.3.2 | Filament Extrusion Line B

The filament extrusion line B (ExB) is a 3D filament production line that is easy to operate and maintain due to its programmable logic controller (PLC) control system. The ExB retails at 31 670€ and has a maximum capacity of 30 kg of filament per hour. This system includes a precise cooling water temperature control system, a laser measuring system and an efficient loading winding system. The diameter is controlled automatically according to the data retrieved from the laser system, which guarantees a tolerance of less than 0.03 mm. The proposed layout for this extrusion line is illustrated in **Figure 17.** Additionally, the detailed characterization of ExB is presented in **Table 10**.

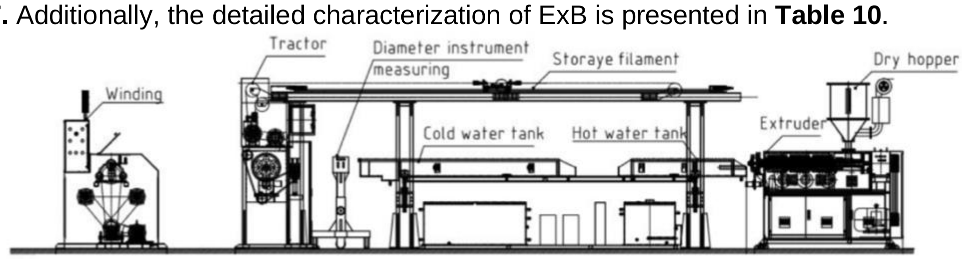

Figure 17: The layout drawing of ExB.

Table 10: The technical specifications of ExB.

FILAMENT EXTRUSION LINE B			
Price	31 670 €		
Max Capacity	30 kg/h		
Max Production Speed	200 m/min	Install Dimensions	11 x 1 x 1.9 m (l x w x h)
Components	• Single screw extruder: - screw and barrel in 38CrMoALA alloy steel with 45 mm and a 25 L/D ratio - 3 heating zones, all with high efficiency noiseless cooling fan - 7.5 kW driving AC motor - PLC control system		
	• Roundness laser: - can carry out high-speed, high-precision, non-contact type measurement of tubular objects to be measured on the production line - measuring range: 0.05 – 50 mm - tolerance: +/- 3 µm - resolution: 0.0001 mm - scanning speed: 1800 times/s - automatically and continuously sends roundness data to the PLC program that will automatically control the cooling water temperature and other systems to control the roundness tolerance		
	• Vacuum loader: - 1.1 kW / 1.5 HP 1Ø - loading distance: 6-8 m - pipe diameter: Ø38 mm - capacity: 350 kg/h - material storage: 7.5 L • Mixer machine; - capacity: 50 kg/batch - motor power: 1.5 kW • Hopper dryer: - volume: 50 L - capacity: 50 kg/h - heating power: 3.9 kW • Storage thread stand: - length: 6 m - automatic tension adjustment	• Hot water tank: - temperature: 30ºC – 80ºC - 6 kW heating power • Cooling water tank: - 0.75 kW direct-coupled centrifugal pump - immersion bath cooling • Tractor machine: - max pulling speed: 100 m/min • Rolling up machine: - max wind up speed: 200 m/min • Vacuum packaging machine: - for different spool sizes	

5 .1.3.3 | Filament Extrusion Line C

The filament extrusion line C (ExC) is a 3D filament production line from the same manufacturer as ExB but with higher output capacity. Accordingly, it has a maximum capacity of 50 kg of filament per hour and retails at 45 220€. The full characterization of ExC is presented in **Table 11**.

Table 11: The technical specifications of ExC.

FILAMENT EXTRUSION LINE C			
Price	45 220 €		
Max Capacity	50 kg/h		
Max Production Speed	200 m/min	Install Dimensions	13.5 x 1.2 x 2 m (l x w x h)
Components	• Single screw extruder: - screw and barrel in 38CrMoALA alloy steel with 90 mm and a 25 L/D ratio - 4 heating zones, all with high efficiency noiseless cooling fan - 18.5 kW driving AC motor - PLC control system		
	• Roundness laser: - can carry out high-speed, high-precision, non-contact type measurement of tubular objects to be measured on the production line - measuring range: 0.05 – 50 mm - tolerance: +/- 3 µm - resolution: 0.0001 mm - scanning speed: 1800 times/s - automatically and continuously sends roundness data to the PLC program that will automatically control the cooling water temperature and other systems to control the roundness tolerance		
	• Vacuum loader: - 1.1 kW / 1.5 HP 1Ø - loading distance: 6-8 m - capacity: 300 kg/h • Mixer machine; - capacity: 200 L - motor power: 1.5 kW • Hopper dryer: - capacity: 60 kg/h - heating power: 4.5 kW • Storage thread stand: - length: 7 m - automatic tension adjustment	• Hot water tank • Cooling water tank: - 0.35 kW direct-coupled centrifugal pump - immersion bath cooling • Tractor machine: - max pulling speed: 90 m/min • Rolling up machine: - max wind up speed: 200 m/min • Vacuum packaging machine: - for different spool sizes	

5.2 | 3D Printing

Contrarily to the lack of information observed with the filament extrusion process, the growth of the 3DP industry has encouraged further investigation and research which have contributed to a considerable amount of data available regarding the process and quality problems. Notwithstanding, there is still a lack of an incorporated 3DP operational guideline that not only provides a detailed description of the operational parameters and their influence on the process, but also establishes the correlation between these parameters and the quality problems that might occur. Interviews with the 3DP company CEO were conducted to get a better perspective on the overall 3DP process from the slicing software, where the operational parameters are set, through the actual printing of the part, until the post-processing stage, when it is necessary to assess the quality of the part. Similarly to the extrusion process, the knowledge acquired in both the 3DP theoretical review (section 3.1) and the interviews provided a sufficient basis and tools to conduct experimental work, which was vital for the further analysis of the process. The experimental testing set-up is shown in **Figure 18**. Furthermore, by establishing the link between the data collected in the literature and the fieldwork findings it was possible to develop the diagram illustrated in **Figure 19,** which provides an outline of the topics that will be discussed in next.

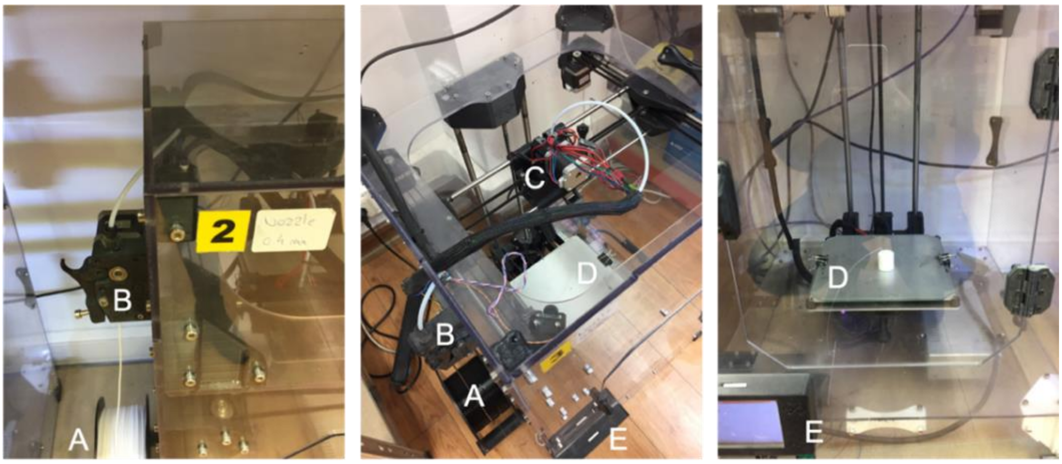

Figure 19: 3D printing experimental testing set-up. All images show different perspectives of the 3D printers that were used. A - filament spool; B - small gear that pushes the filament back and forth; C - extruder head; D - build platform; E - control panel.

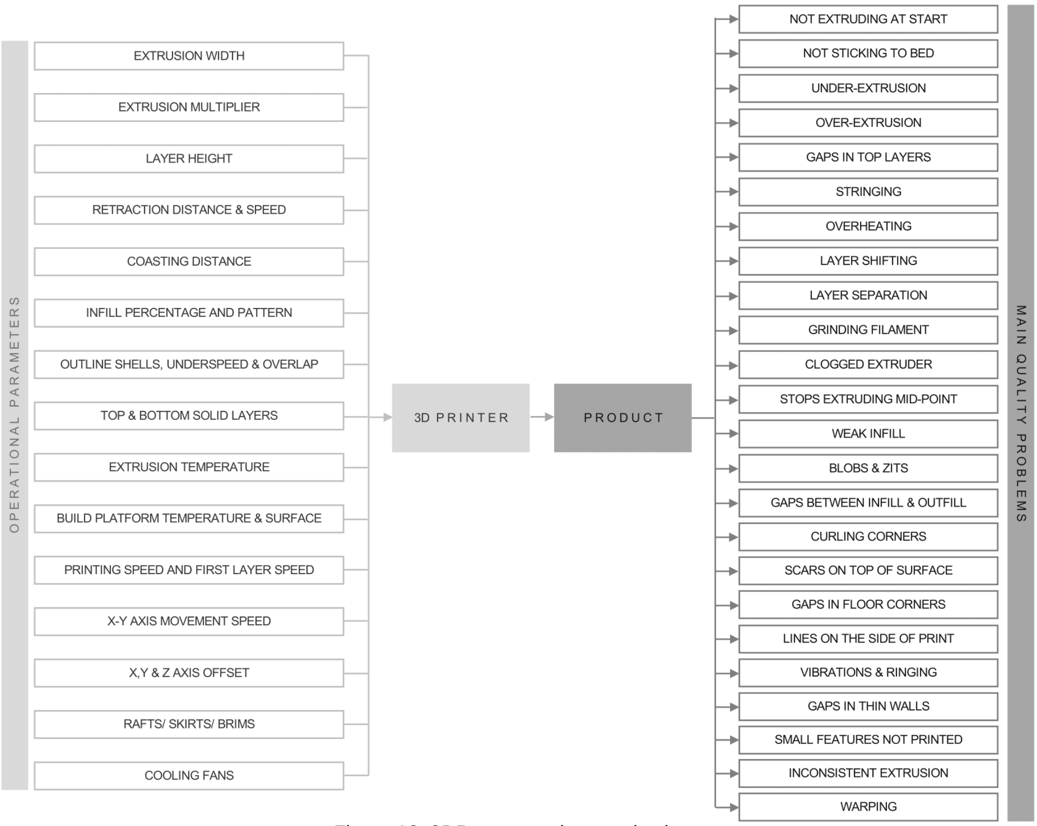

Figure 18: 3DP process characterization.

5.2.1 | Operational Parameters

To assess the influence of the different operating parameters on printed parts, experimental testing was performed with virgin PET, white PET, and PETG (see **Appendix E**). This was carried out by printing a 3D model of a cylinder and adjusting the operational parameters until a perfect part was obtained, *i.e.*, a robust cylinder with no visible errors. Accordingly, the operating parameters are presented below along with their influence on the printing process and suggestions on how to set these values.

5.2.1.1 | Extrusion Width

The extrusion width is the setting that determines the width of the toolpath during printing since the slicing engine does not use the nozzle diameter as the value for the width. Generally, an extrusion width of 1.2 times the nozzle diameter is recommended. However, if the nozzle is extremely thin, it might be better to lower this value. A thinner width will result in the increase of the total toolpath length, print time, and will decrease the amount of plastic extruded per millimeter. The opposite occurs when setting a thicker width.

5.2.1.2 | Extrusion Multiplier

This parameter allows the fine-tuning of the extrusion flow rate, *i.e.*, the amount of filament extruded for the entire print. The slicing software calculates, based on the nozzle and filament diameter, layer height and others, the speed at which the extruder must run to push the right amount of filament to achieve a certain thickness. Accordingly, the extrusion multiplier essentially multiplies the amount of material to extrude during each move by a certain percentage. For instance, if this parameter is set to 1, the quantity of filament to extrude is the same as the value calculated by the software, whereas if the value is set to 1.5, the printer will be extruding more 5% of filament. It is important to tune this parameter according to the printer and the filament.

5.2.1.3 | Layer Height

This parameter refers to the thickness of each layer, on the Z-axis, in millimeters and has a great influence on the overall print quality. The thinner each layer is, the higher the resolution of the model, resulting in better print quality, and *vice-versa* for thicker layers. However, decreasing the layer thickness also means more layers need to be printed, which can dramatically increase print time. Accordingly, it is important to establish the desired balance between quality and print time. Usually, it is expected that the layer heights of 0.3 mm, 0.2 mm and 0.1 mm result, respectively, in low resolution and fast printing, normal resolution and medium speed printing, and high resolution and slow printing.

5.2.1.4 | Retraction Distance and Speed

When the extruder head performs non-printing moves between two points, molten plastic can ooze out of the nozzle forming unwanted strings or blobs on the printed model. Retraction, therefore, is a strategy used to reduce this effect, instructing the extruder to pull a specific length of the filament back into the nozzle, denoted by retraction distance, at a specific speed, representing the retraction speed, to reduce the odds of oozing. If the retraction distance is set too low, the molten plastic will still be able to ooze from the nozzle. On the other hand, if the distance is set too high, the filament will be pulled far too back from the nozzle and can take a long time to start extruding again. It may also clog the extruder. For direct drive extruders, a reasonable distance lies between 0.5 to 2.5 mm, whereas for Bowden extruders the most suitable values range from 5 to 8.5 mm, as the distance between the nozzle and the drive gear where the filament feeds in is longer. Regarding the retraction speed, if it is set too slow, the molten plastic has time to ooze from the nozzle. Conversely, if it set too fast, the material can take longer to start extruding again, and it can also lead to filament grinding, detailed in 5.2.2.10. Recommended speeds range from 30 to 100 mm per second, however, the most efficient speed will depend on the type of filament.

5.2.1.5 | Coasting Distance

When retraction begins, there may be some filament residue in the nozzle that can ooze out and create defects at the ends of the perimeters of the model. Accordingly, coasting is a strategy to avoid this issue by instructing the printer to stop extruding material a certain distance before a non-printing move, referred to as coasting distance. This allows any left-over filament to be emptied out of the nozzle before retraction begins. For instance, if the coasting distance is set to 5 mm, the nozzle will not extrude filament for the last 5 mm before the end of a perimeter, and will rather depend on the filament's momentum and gravity to let the left-over filament ooze out and fill the last 5 mm. Generally, a coasting distance between 0.2 to 0.5 mm is enough to have a noticeable impact on these defects.

5.2.1.6 | Infill Percentage and Pattern

The infill is a structure that is printed inside the 3D object in a specific percentage and pattern. In addition to filling the empty space inside the part, the infill influences the print time, material usage, and the strength and weight of the part. The infill percentage refers to the density of the infill, *i.e.*, if this value is set to 0% there is no infill, whereas if it is set to 100% the printed object will be completely solid. Accordingly, the higher the infill percentage, the stronger, heavier, and more solid the part is, but the longer the print takes. In contrast, a lower infill percentage produces a simpler and lighter object, at a faster printing speed. Therefore, it is recommended to set the infill considering the trade-off between robustness and cost. Common infill percentages range between 20 and 25%, however, for a low-cost solution, the infill can be set between 10 and 15%. In case structure and durability are a concern, the best range is between 30 and 50%. Regarding the infill pattern, there are several, each with strengths and weaknesses. Generally the patterns that provide the best structure are those that incorporate grids, lines, honeycombs, as well as, rectilinear or concentric patterns.

5.2.1.7 | Outline Shells, Underspeed and Overlap

The outline shells refers to the number of outlines or perimeters printed on each layer of the object. The higher the number of shells, the denser the outside walls, and therefore, the stronger the object. The default number of shells is usually 2, and it is not recommended to set more than 5. The speed at which the perimeters of the model are printed is referred to as outline underspeed and is expressed as a percentage relative to the printing speed. The final parameter related to the shells of the model is the outline overlap which determines the amount of infill that will overlap with the outline to merge these sections together. For instance, if this value is 0%, it means that the infill would start of the perimeter and not overlap at all, whereas if this value is set to 100% there would be a complete overlapping. The typical value for this parameter is 30%.

5.2.1.8 | Top and Bottom Solid Layers

The top and bottom solid layers enclose the structure of the print and have a great impact on the outcome of the part, in terms of durability and final appearance. Therefore, the top and bottom solid layers are the number of 100% infill layers that are printed at the top and bottom of the model, respectively. If either of these values is too low, the top and bottom solid layers will be too thin and will expose the internal infill pattern, compromising the look of the part. Besides this, having few top and bottom solid layers will result in a weaker structure for the model. Accordingly, it is recommended to experiment with the number of solid layers as they depend on the layer height established, *i.e.*, the lower the layer height, the more number of layers necessary to produce a completely solid and flat surface, and *vice-versa*. Note that additional solid layers will occur within your part dimension and will not add size to the exterior of your part.

5.2.1.9 | Extrusion Temperature

This parameter denotes the temperature at which plastic is extruded. There are some general guidelines for the extrusion temperatures for different polymers, however, these values depend on the printer and filament manufacturer. Therefore, it is recommended to use these values as a starting point and adjust them throughout the process. In general, higher extrusion temperatures improve layer adhesion which leads to a physically stronger part. However, higher temperatures also mean the plastic is more fluid coming out of the nozzle, and therefore is more likely to sag and flow even after being deposited. This leads to a worse performance when printing small details and in some cases, the extreme temperatures can cause the filament to thermally degrade, which can clog the extruder. Correspondingly, setting an extrusion temperature too low results in poor layer adhesion, consequently leading to layer shifting or separation (5.2.2.8) and a part with a striated appearance. Nonetheless, when printing a design with fine details, it is recommended to keep the temperature as low as possible.

5.2.1.10 | Build Platform Temperature and Surface

When the plastic filament is extruded from the hot nozzle onto a cold build platform it can cause issues with adhesion (5.2.2.2) and warping (5.2.2.24). For this reason, using a heated build plate helps preventing these issues as it keeps the lower layers of the print warm as the hotter top layers are extruded, allowing a more even cooling and improving adhesion to the plate. Accordingly, the build platform temperature is the temperature value of the bed where plastic is printed on. Similarly to the extrusion temperature, there are guidelines for the build platform temperature for different polymers, that should be used as a starting point. Moreover, the adherence of the part onto the build plate is also affected by the type of plastic filament used as different plastics adhere better to different materials. Therefore, it is recommended to choose an appropriate build platform surface according to the filament being utilized.

5.2.1.11 | Printing Speed and First Layer Speed

The printing speed is the speed at which the extruder head moves while extruding the filament to produce the 3D model. Increasing the printing speed reduces the production time, however, setting this value too high may lead to print imperfections and failures. On the other hand, setting the speed too low may case print deformation due to the nozzle sitting on the plastic for too long. Correspondingly, it is recommended to set the printing speed as fast as the printer can without sacrificing too much print quality. It is also possible to set a specific speed for the first layer extruded, designated as first layer speed. This is important because printing the first layer at a slower speed will allow more time for the plastic to melt and properly adhere to the build platform.

5.2.1.12 | X-Y Axis Movement Speed

The X-Y axis movement speed denotes the speed at which the extruder head moves while not extruding filament and it can generally be up to two times faster than the printing speed. Usually, the default value for the movement speed is optimized for the printer. Nonetheless, this setting can be useful to reduce stringing, since increasing the movement speed reduces the time the extruder has to ooze when moving between two points. However, setting this speed too high can cause the motors to struggle and lead to motor failure.

5.2.1.13 | X,Y and Z Axis Offset

The X, Y and Z axis offset are three different parameters that are used to correct situations where the prints are misaligned, for instance off-centered or too high off the build plate. For example, if the prints are 2 mm too high off the build plate, setting the Z-axis offset to -2 mm will counterbalance this error and solve it, and so on and so forth for the X and Y axis offset.

5.2.1.14 | Rafts, Skirts and Brims

All these techniques provide a starting point for the printed 3D models. A raft is a horizontal latticework of filament that is placed underneath the part. Accordingly, instead of the part being printed directly on the plate, it is printed on top of the raft. The main functions of rafts are to deal with bed adhesion and warping issues, which are detailed in 5.2.2.2 and 5.2.2.24, respectively. They also help stabilize models with small footprints, and create a strong foundation for the upper layers. A skirt is an outline that surrounds the model but does not touch it. The skirt is extruded on the print bed before the model begins printing. They help prime the extruder and establish a smooth flow filament, which is discussed in 5.2.2.1. A brim is a specific type of skirt that is attached to the edges of the model. The brim is printed with an increased number of outlines to create a large ring around the part. They are used to hold down edges of the model, which can also help with bed adhesion and prevent warping.

5.2.1.15 | Cooling Fans

Cooling fans have a fundamental role in improving the quality of the end product. When printing a part with small details, if the print is coming out deformed and with melted spots, enabling the fan can help preventing overheating and help maintain the shape. However, using the cooling fan for the first few layers of the print can contribute to build platform adhesion issues. For this reason, slicing software allows the adjustment of the cooling fan speed setpoints so that it is turned off for the first few layers and then turns on for the remaining layers.

As a guideline for initiating the 3DP process, **Table 12** presents some of the recommended operating parameters for the most common plastic filaments. Although these values are a good starting point, it is advised to fine tune them throughout the process, until the optimal parameters are achieved. It is clear

Table 12: Recommended 3DP setpoints for different filaments (Simplify3D, 2019).

POLYMER SETPOINTS FOR 3DP				
Filament	Extruder Temperature (ºC)	Build Platform Temperature (ºC)	Recommended Build Surfaces	Other Hardware Requirements
PETG	230-250	75-90	• Glue stick • Painter's tape	• Heated bed • Part cooling fan
PP	220-250	85-100	• Packing tape • PP Sheet	• Heated Bed • Enclosure • Part Cooling Fan
ABS	220-225	95-110	• Kapton tape • ABS slurry	• Heated bed • Enclosure

that the plastic type filament range is limited, and therefore there is a lack of processing information regarding the remaining types of polymers.

5.2.2 | Print Quality Troubleshooting Guide

The increase of the 3DP manufacturing has called attention to the insufficient quality of printed parts due to limitations and inconsistencies of this technology (Gordeev *et al.*, 2018). Therefore, it is critical to properly assess and improve the quality of these products. Accordingly, an operational troubleshooting was developed with the most common 3DP quality problems based on the experimental work, different authors' experience, and through free troubleshooting guides (3D VERKSTAN, 2019; Simplify3D, 2019; RichRap3D, 2019). Each issue has a detailed explanation, along with the possible causes of the problem. Additionally, methods on how to improve print quality and modifications in the operating parameters are suggested as an attempt to solve these problems. If none of these issues below are encountered, the part is considered to have an acceptable quality.

5.2.2.1 | Not Extruding at Start

This issue is common for beginners handling 3D printers. If the extruder is not extruding plastic at the beginning of the printing process, there are four possible causes. These are described below together with a way to solve them.

Extruder was not primed before beginning the print

Whilst extruders are idle at a high temperature, either preheating for a print or at the end as it is slowly cooling, they frequently leak plastic. The hot plastic inside the nozzle oozes out of the tip creating a void inside the nozzle where the plastic has drained out. Consequently, at the beginning of the print, it will take a few seconds before the plastic starts to come out of the nozzle, delaying the extrusion. To solve this issue, it is crucial to prime the extruder right before initializing the printing process so that the nozzle is full of plastic and ready to extrude. A common way to prime the extruder is by including a skirt in the G-code which will draw a circle around the part at the initial printing phase, guaranteeing the nozzle is filled with plastic.

Nozzle starts too close to the bed

If the nozzle is too close to the bed of the printer, there will not be enough space for plastic to extrude as the hole where it is supposed to extrude is blocked. This situation can be quickly identified if the printer does not extrude plastic for the first layer or two, but begins extruding normally for the following layers, as the bed is lowering along the Z-axis, allowing room for plastic to extrude from the nozzle. In order to solve this problem, either adjust the height of the printer bed manually or increase the Z-axis offset setting in the G-code as it will move the nozzle further away from the print bed. Adjust this value until there is enough room between the nozzle and the platform.

The filament has stripped against the drive gear

Most 3D printers use a small gear to push the filament back and forth. The teeth of the gear bite into the filament to have a good grip on it, allowing it to accurately control the position of the filament. However, sometimes when the gear bites into the filament or moves it back and forth too often, a section of the filament is stripped away by the teeth, leading to plastic shavings. Once this happens, the gear will not have any plastic left to grasp onto to move the filament. Instructions on how to solve this problem are detailed in 5.2.2.10.

The extruder is clogged

If none of the above situations are able to solve the issue, it is likely that the extruder is clogged. This can occur if foreign debris is trapped inside the nozzle when hot plastic sits inside the extruder too long, or if thermal cooling is not sufficient and the filament begins to soften outside of the desired melt zone. To fix this issue, disassembling the extruder might be required, and therefore, contact the printer manufacturer before proceeding the dismantling is recommended. Nonetheless, using the “E” string of a guitar has also proven to be successful at unclogging extruders by feeding it into the nozzle tip.

5.2.2.2 | Print not Sticking to Bed

The first layer to be printed is crucial to obtain a robust outcome as it is the foundation of the part. Accordingly, the first layer must be strongly attached to the build platform, otherwise, it will compromise the remaining printing process. There are six main causes that lead to first layer adhesion problems, these are examined and different ways to cope with them are suggested.

Build platform is not leveled

Most printers have an adjustable build platform with screws and knobs that control the bed’s position. If the bed is not properly leveled and flat there is a high chance that the first layer will not adhere correctly as one side of the bed is closer or farther to the nozzle than the other. For this reason, leveling the build platform is fundamental to achieve a proper first layer.

Nozzle starts too far away from the bed

Besides having a leveled build platform, it is necessary to guarantee that the nozzle is at the correct height relative to the bed, neither too close nor too far. To obtain good adhesion the filament should be slightly squished against the build plate. Adjusting the height of the bed can be performed manually or by changing the Z-axis G-code offset, as mentioned previously.

First layer is printing too fast

If the first layer of plastic is being printed too fast there is a possibility that it is not having enough time to stick properly to the plate before starting the next layer. Therefore, decreasing the first layer speed parameter gives the plastic more time to bond to the bed which may help to solve the adherence problem.

Temperature or cooling settings

Plastic usually shrinks when cooled down from a hot temperature, therefore, when plastic is extruded from the hot nozzle onto a cold build platform, it is expected to condense. However, as the bed doesn’t shrink together with the first layer, the plastic tends to separate from the bed as it cools. Accordingly, if the first layer seems to stick initially but later separates from the bed, it is most likely that the temperature and cooling settings must be adjusted. To solve this issue, avoid printing onto a cold platform, and rather set the bed temperature to a given value that will prevent the first layer from shrinking. Additionally, if the printer has a cooling fan, it might be necessary to disable it while the first few layers are being printed to prevent them from cooling too fast.

The build platform surface

The adherence onto the build plate is also affected by the type of plastic filament used as different plastics adhere better to different materials. It is therefore suggested that the build platform material used is appropriate and optimal for the adherence of the plastic filament being utilized. Additionally, it is important to guarantee that the bed is free of dust, grease, or other dirt before starting the print. Cleaning the bed with water or isopropyl rubbing alcohol can make a great impact. Nevertheless, if the printer does not include a special build platform material, there are different solutions that can help with adhesion. There are many types of tape that stick well to various 3D printing materials, so strips of tape can be applied to the bed surface and easily removed and replaced when printing with a different material. Furthermore, users have also been successful in improving adherence by applying temporary glue, hair spray, and other sticky substances on the bed surface.

When all else fails: brims and rafts

When none of the above solve the adherence problem, there is a possibility that the part being printed does not have enough surface area to stick to the plate surface. There are mainly two options to increase the surface area of the part, providing a larger contact surface to the bed. First, a brim can be added to the part, *i.e.*, extra rings around the exterior of the part. Second, a raft can be added under the part, providing a larger adherence surface for the bed.

5.2.2.3 | Under-Extrusion

Slicer software usually includes printer profiles, which provide pre-configured settings for a diverse range of 3D printers. Within these settings is the amount of plastic the printer should extrude, however, since printers do not provide any feedback about the quantity of plastic that actually exits the nozzle, it is possible that there might be less plastic extruding than predicted by the software. Gaps between adjacent extrusions of each layer can occur due to under-extrusion. To identify if the printer is extruding enough plastic print a 20mm cube with at least three outline shells. Once it is printed, check whether the three shells are strongly bonded together at the top of the cube. If there are gaps between the perimeters the printer is under-extruding. The possible causes for this issue are described below.

Incorrect filament diameter

The first aspect to verify is if the filament diameter value specified in the software matches the actual diameter of the filament being used.

Increase the extrusion multiplier

Given that the filament diameter is correct and under-extrusion is still occurring, adjusting the extrusion multiplier is required. By increasing this parameter, the amount of plastic being extruded increases. It is suggested to increase the extrusion multiplier by 5% and reprint the test cube to check if the gaps between the shells still exist. In this case, keep increasing this parameter until the gaps cease to occur.

5.2.2.4 | Over-Extrusion

In the same way, as printers might be extruding less plastic than predicted by the software, there is also a chance that more plastic is being extruded than initially expected. This over-extrusion leads to poor print quality as the excess plastic can damage the outer dimensions of the part being printed. To resolve this issue, check the suggestions presented for under-extrusion (5.2.2.3) and adjust the settings in the opposite way.

5.2.2.5 | Holes and Gaps in Top Layers

As a strategy to reduce plastic consumption, 3D printed parts are usually designed with a solid shell that surrounds a porous, partially hollow interior. Regardless, depending on the settings defined in the G-code, there are occasions where the top layer is not completely solid. These gaps and holes between extrusions that make up the solid layers can be fixed by modifying simple settings, which are described below.

Not enough top solid layers

First of all, adjust the number of top solid layers in the software. While printing a 100% solid layer on top of a partially hollow infill, the plastic that is extruded on top of the hollow air pockets tends to droop or sag down into them. For this reason, several solid top layers are usually desired to ensure a flat and completely solid surface. A reasonable rule of thumb is to guarantee that the solid section at the top is at least 0.5 mm thick. For instance, if the layer height is set to 0.25 mm, it would be recommended to have at least two top solid layers. Therefore, if there are visible gaps and holes in the top layers, increase the number of top layers. Note that additional solid layers do not add size to the exterior of the part and rather occur within the dimension of the part.

Infill percentage is too low

As previously mentioned, the solid layers at the top sit on the partially hollow infill which acts as a sort of foundation. Thus, the lower the infill percentage, the larger the air gaps and the weaker the foundation is to support the top solid layers, ultimately resulting in noticeable gaps and holes. Accordingly, if increasing the number of top layers does not solve this issue, it is advised to increase the infill percentage to have a more robust foundation for the top solid layers to avoid the gaps and holes.

Under-extrusion

If the previous suggestions did not solve this problem, it is likely that the printer is encountering an under-extrusion issue. Therefore, refer to section 5.2.2.3 for further details on this problem.

5.2.2.6 | Stringing

Stringing, otherwise known as oozing or whiskers, happens when small strings of plastic are left behind on a 3D printed part. This is a result of plastic oozing out of the nozzle while the extruder is moving to a new location. The most utilized tool to avoid excessive stringing is to enable the retraction setting. As explained formerly, this functionality will pull the filament backward into the nozzle when the extruder finishes printing a section of the model, acting as a countermeasure against oozing. Once it is time to begin printing again, the filament is pushed back into the nozzle and plastic begins extruding again normally. The settings that should be adjusted to avoid stringing are discussed below.

Retraction distance

The retraction distance is the most important retraction setting as it determines the amount of plastic being pulled out of the nozzle. Generally, the higher the retraction distance, the less likely it is for the nozzle to ooze plastic while moving. Most direct-drive extruders only require a retraction distance of 0.5 to 2 mm, whereas Bowden extruders may require a distance as high as 15 mm as the distance between the extruder drive gear and the heated nozzle is longer. To sum up, it is proposed to increase the retraction distance by 1 mm and re-test to see if the performance improves.

Retraction Speed

The following setting that can affect stringing is retraction speed as it determines how fast the filament is retracted from the nozzle. If the filament is retracted too slowly, the plastic will gradually ooze down the nozzle and may start leaking before the extruder is at its new destination. On the other hand, if the filament retracts too fast, it can either separate from the hot plastic inside the nozzle or the quick movement of the drive gear may grind away pieces of filament. Ideal values for retraction speed fall in between 1200 to 1600 mm/min or 20 to 100 mm/s. Nevertheless, the most adequate value which can vary depending on the material used, therefore, it is suggested to experiment with different speeds to achieve minimum stringing.

Extruder temperature is too high

Once retraction settings have been verified, the next most common cause of excessive stringing is the temperature of the extruder. If it is set too high, the plastic inside the nozzle becomes less viscous and leaks easily out of the nozzle, unlike low temperatures, where plastic becomes somewhat solid and has difficulty leaving the nozzle. Accordingly, if retraction settings are optimal, it is advised to try decreasing the extruder temperature by 5 to 10 degrees.

X-Y axis movement speed

The speed of movement can also impact the amount of stringing. By increasing the movement speed of the printer, the time the extruder has to ooze when moving between two points is reduced. Therefore, if the printer can handle moving at higher speeds, increase the X-Y-axis movement speed setting to decrease stringing.

5.2.2.7 | Overheating

To obtain a precise 3D printed model it is fundamental to achieve a correct balance between temperature and cooling that allows the plastic to be easily extruded from the nozzle and quickly solidified to maintain the exact dimensions of the part. When plastic is hot, it is flexible and easily moldable into different shapes, conversely, as it cools, it quickly becomes solid and rigid. For this reason, if the balance is not successfully managed it may jeopardize the print quality and produce an inaccurate and poorly defined model. The main causes of overheating are presented next, as well as how to prevent them.

Insufficient cooling

The most common reason for overheating is plastic not cooling as fast as it should. When this occurs, the plastic extruded onto the layers remain moldable and instead of cooling down into the desired shape, it slowly melts into a deformed model. For many plastics, it is better to quickly cool the layers to prevent them from changing shape after being printed. In the case of the printer having no cooling fan, it is recommended to install an aftermarket fan or use a small handheld fan to cool down the layers faster.

Printing at too high of a temperature

In the situation where the cooling fan does not solve the overheating issue, it is suggested to try printing at a lower temperature. By decreasing the extrusion temperature, the plastic will be able to solidify faster and maintain its shape. Nonetheless, be aware to not decrease the temperature too much as the plastic might not be hot enough to extrude through the nozzle.

Printing too fast

Another cause for overheating is the printing speed. If each layer is being printed too fast, they do not have enough time to properly cool and set before receiving another hot layer of plastic on top of it. This is especially relevant when printing very small parts, where each layer requires only a few seconds to print. Even with a cooling fan, it may still be required to decrease the printing speed for these small models to guarantee each layer has time to solidify.

When all else fails: print multiple parts at once

If neither of the previous situations has solved the overheating issue, there is one more thing that can help with cooling. Create a copy of the part or import a second part to be printed at the same time. This will provide more cooling time for each individual part as the nozzle will move to a different location to print the second part, for each layer. This simple strategy can fix the overheating problem.

5.2.2.8 | Layer Shifting or Misalignment

Most 3D printers function with an open-loop control system which means the equipment does not have feedback on the output movements. Once the printer has received instructions to begin printing, it simply moves the tool head to a specific location and hopes it gets there. Generally, there are no problems with the non-feedback controller as the stepper motors that drive the printer are quite powerful and there are no significant loads to prevent the tool head from moving. Nonetheless, if the tool head is misplaced or something goes wrong mid-print, the printer has no way of detecting it and will keep printing. If the printed 3D model has layers shifted or misaligned it is usually due to one of the causes below. The most common operational cause for this issue is described below.

Tool head is moving too fast

If the printing speed is set too high, the motors may struggle to keep up with the printer and a clicking sound is triggered as the motor fails to achieve the desired position. In this event, as the printer has no feedback system, it will continue printing at the wrong location, resulting in a defect part. Therefore, as an attempt to avoid this from happening it is suggested to decrease both the printing speed and the X-Y axis movement speed. The first controls the speed of the movements where plastic is being actively extruded, while the second controls only the speed of movements where no plastic is being extruded. If either of these settings is too high, it can result in a shift.

5.2.2.9 | Layer Separation and Splitting

To achieve a strong and reliable 3D model it is important that each layer adequately bonds to the layer below it, or else, the part may split or separate. There are several causes that lead to layer separation. These are explained next, as well as how to solve them.

Layer height is too large

A frequent cause for this issue if having the layer height set too high. The usually small size of nozzle diameters create limitations for what values the layer height can assume. As a general rule of thumb, the layer height should be 20% smaller than the nozzle diameter to guarantee that each layer of plastic properly bonds to the layer beneath. Therefore, it is suggested to decrease the layer height in order to solve layer separation.

Print temperature is too low

If the layer height is not the cause of layer separations, there is a great possibility that the print temperature is too low, and therefore, plastic is not molten enough to bond correctly. Accordingly, it is recommended to increase the extrusion temperature by 10 degrees to verify if adhesion between layers improves.

5.2.2.10 | Grinding Filament

Most 3D printers use a small gear to push the filament back and forth. The teeth of the gear bite into the filament to have a good grip on it, allowing it to accurately control the position of the filament. If the filament does not move while the drive gear keeps spinning, it can grind away plastic from the filament to the point where there is no more material to grasp on to. This is known as the filament being "stripped", as no material exits the extruder since too much plastic has been removed from the filament by the teeth of the gear. Under these circumstances, it is usual to see small plastic shavings from the plastic that has been stripped away, and also, as mentioned before, the extruder motor keeps spinning while the filament is not being pulled into the extruder body. The causes and solutions to help with this problem are discussed below.

Aggressive retraction settings

If the retraction speed is too high, or the printer is retracting too much filament, the extruder might be put in excessive stress and the filament will struggle to keep up. To test if this is causing the filament to be stripped, it is suggested to decrease the retraction speed by 50%. If this impacts the model, it is certain that the retraction settings are part of the issue.

Increase the extruder temperature

If the previous solution did not solve the problem, it is recommended to increase the extrusion temperature by 5 to 10 degrees. This will enable plastic to flow easier and prevent the filament from being stripped.

Printing speed too high

After testing out the previous suggestions, if the filament grinding continues, there is a possibility that the printing speed is too fast. By decreasing this setting, the extruder motor will spin at a slower speed as the filament is extruded over a longer period of time. The slower rotation of the motor can help avoid filament being stripped.

Check for a clogged nozzle

If none of the above have solved the grinding problem, it is likely that the nozzle is partially clogged. For instructions on how to proceed when faced with a clogged extruder check 5.2.2.11.

5.2.2.11 | Clogged Extruder

3D printers must melt and extrude many kilograms of plastic over their lifetime. To complicate this, all plastic must exit through a very small nozzle. Inevitably, something can go wrong with this process, preventing the extruder from pushing plastic through the nozzle. These jams are frequently caused by something blocking the plastic from leaving the nozzle. The several steps to unclog the extruder are described below.

Manually push the filament into the extruder

One of the first things to try, when faced with a jammed extruder, is to manually push the filament into the extruder. Perform this by heating the extruder, according to the type of plastic, and then instruct the printer to extrude a small amount of plastic. As the extruder motor is spinning, lightly push the filament into the extruder. Typically, this added force is enough to push the filament past the problem area.

Reload the filament

The following step, if the extruder is still clogged, is to unload the filament. As mentioned before, make sure the extruder is heated to an adequate temperature and instruct the printer to retract the filament out of the extruder. If the filament is not retracting, lightly pull the filament manually while the motor is spinning. Once the filament is fully removed, use a pair of scissors to cut away the melted or damaged portion of the filament. Finally, reload the filament into the extruder and check if the printer is able to extrude plastic with the new undamaged section of the filament.

Clean out the nozzle

If the printer is not able to extrude plastic with the new section of the filament, then it is most likely that the nozzle must be cleaned before printing again. Many users have been successful by heating their extruder to 100ºC and then manually pulling the filament out, hopefully along with what is blocking the nozzle extruder. Another commonly used technique is to use the E string from a guitar to push the material backward through the nozzle tip. There are several other methods, however, it is suggested to consult the printer manufacturer for the most suitable technique to unclog the extruder.

5.2.2.12 | Stops Extruding Mid-Print

There are only a few causes that may lead the printer to stop extruding in the middle of a print. Each of these causes is explained below, together with suggestions for fixing this issue.

Out of filament

First of all, verify that there is still filament leading into the nozzle. If the spool has run out, it explains why the printer stopped extruding mid-print. To proceed with the printing process, simply load a new spool onto the printer.

The filament has stripped against the drive gear

During a print, the extruder motor is constantly spinning to push the filament into the nozzle so that it is extruded. If the printer is extruding too quickly or it is trying to extrude too much plastic, the motor may end up grinding away the filament until the gear has no plastic to grip onto. Accordingly, if the extruder motor is spinning and the filament is not being extruded, then it is likely that the filament has been stripped away. For suggestions on how to solve this problem check 5.2.2.10.

The extruder is clogged

If none of the above describe the situation that is happening, then there is a possibility that the extruder is clogged. If this happens mid-print, verify if the filament and that there is no dust on the spool. Otherwise, dust might be accumulating at the nozzle causing a block. There are other causes for a clogged extruder, as described in 5.2.2.1 under “the extruder is clogged”. For advise on how to unclog the extruder check 5.2.2.11.

Overheated extruder motor driver

The extruder motor is constantly spinning back and forth to pull and push plastic during the printing process. The motor requires current to perform these movements quickly, and if the printer’s electronics do not cool enough, it can cause an overheating problem with the motor. Generally, these motors have a thermal cutoff that stops the driver from working if the temperature gets too high. In this event, the X and Y axis motors will be spinning and moving the extruder tool head while the extruder motor will not be moving at all. The only solution for this is to turn off the printer and allow the electronics to cool down. If this is a recurrent issue, adding an extra cooling fan is advised.

5.2.2.13 | Weak Infill

The infill inside the 3D model is a key factor in the overall strength of the printed part. The infill connects the outer shells of the model and must support the surfaces that are printed on top of it. If the infill of the model seems weak or stringy, it is an indicator that some settings should be adjusted to improve the robustness of the model. These parameters are described below.

Try alternate infill patterns

Start by analyzing the infill pattern set in the software. Infill patterns such as grid, triangular and solid honeycomb tend to be more solid than rectilinear and fast honeycomb, which sacrifice strength for faster prints. Therefore, changing the infill pattern is recommended to see if there are improvements in the overall strength of the model.

Printing speed too high

The following step is to verify the printing speed. If it is set too high, the extruder will not be able to keep up and under-extrusion can happen inside the part. Consequently, the core of the part will be weak since the nozzle was not able to extrude as much plastic as determined by the software. In this situation, reducing the printing speed is advised to guarantee the infill is stronger and more solid.

5.2.2.14 | Blobs and Zits

During the printing process, the extruder must constantly start and stop as it moves through the different printing points. Extruders usually produce a uniform extrusion while running, but each time they are turned off and on again they can create extra variation. When observing the outer shell of a 3D printed model, it is sometimes noticeable a small mark on the surface which represents the location where the extruder started and finished printing that section of plastic. These marks are usually referred to as blobs or zits. Although these marks are inevitable, the techniques that may help minimize their appearance are described below.

Coasting settings

When noticing small defects on the surface of the 3D model, the best way to diagnose the cause is to closely watch the printing process of the outer shells. If the defect occurs when the perimeter is completed and the extruder is coming to a stop, the setting that should be adjusted is coasting distance. This setting turns off the extruder a short distance before the end of the perimeter to relieve the pressure that is built up inside the nozzle. Accordingly, it is recommended to increase this value until the defect ceases to occur. Generally, a coasting distance between 0.2 to 0.5 mm is enough to have a noticeable impact.

Select the location of your start points

If none of the above solve the issue, there is a technique that might help disguise the surface defects. If the slicing software includes a feature that allows the control of the location of the start points of the print, a solution is to position these points in a less visible part of the 3D model, for instance, at the backside. To perform this, the X-Y coordinates of the desired starting points must be set in the software.

5.2.2.15 | Gaps between Infill and Outline

Each layer of the 3D model is created using a combination of outline shells and infill. The shells outline the part, creating a strong and accurate exterior. On the other hand, the infill is printed inside of these shells to fill the remainder of the layer. As the infill is printed in a different pattern than the outline, it is important to guarantee that these two sections merge and form a solid bond. If there are gaps between the edges of the infill of the part, adjust the following settings to avoid this from happening.

Not enough outline overlap

The first step is to verify the strength of the bond between the perimeter outlines and the infill. This parameter is the outline overlap, which determines the amount of infill that will overlap with the outline to join these sections together. Therefore, when facing this issue, it is suggested to increase this setting to see if the gaps disappear.

Printing too fast

If increasing the outline overlap did not solve the issue, there is a possibility that the infill is being printed too fast. Although the infill is usually printed at a much faster than the outlines, if this speed is too fast, the infill will not have enough time to bond to the outline perimeters. Accordingly, decreasing the print speed is advised. Begin by decreasing it by 50% to check if the gaps disappear. In this case, gradually increase the printing speed until the optimal speed for the printer is achieved.

5.2.2.16 | Curling or Rough Corners

If curling is occurring later on in the print, it is typically due to overheating issues. When plastic is extruded at a very hot temperature and does not cool fast enough, the part may deform over time. To avoid curling, each layer must be cooled down quickly so that it does not have time to change shape before it solidifies. For more detailed information on overheating and strategies to overcome this issue check 5.2.2.7. If curling occurs at the start of the print, read 5.2.2.2 to address first layer adhesion issues.

5.2.2.17 | Scars on Top Surface

Scars on the top layers of the model occur when the nozzle tries to move to a new location but ends up dragging across previously printed plastic. The most common operational cause for this issue is presented below.

Extruding too much plastic

One of the possible causes is that the printer is extruding too much plastic. If this is happening, each layer will tend to be thicker than intended, and therefore, when the nozzle tries to move across each layer it may drag some of the excess plastic. Check 5.2.2.4 for details on over-extrusion.

5.2.2.18 | Holes and Gaps in Floor Corners

The foundation of a 3D printed model is crucial as it must be strong enough to support the layers being printed on top. Besides this, the amount of plastic that is used for the print is also a concern, so it is important to achieve a correct balance between the strength of the foundation and the amount of plastic used. If the foundation is weak, holes and gaps will happen between the layers. This issue is typically more noticeable in the corners, where the size of the model is changing. When transitioning, for instance, to a smaller size, it is necessary to guarantee that the foundation is strong enough to support the section that will be printed above. Described below are the various causes for weak foundations, together with recommendations to prevent this issue from occurring.

Not enough outline shells

As the interior of the model is partially hollow, the thickness of the perimeter walls has an important role in the overall strength of the printed part. Accordingly, one of the first steps that is suggested to improve the strength of the foundation is to increase the number of outline shells.

Not enough top solid layers

The second setting that should be verified when the foundation turns out to be weak is the number of top solid layers. A thin ceiling will not be able to support the different sized structures being printed on top of them. Therefore, to improve the performance of the foundation it is advised to increase the number of top solid layers.

Infill percentage is too low

The last setting that should be adjusted is the infill percentage. As the top solid layers are printed on top of the infill of the model, it is important to make sure that this infill is enough to support the top layers. Accordingly, it is recommended to increase the infill percentage to avoid further issues.

5.2.2.19 | Lines on the Side of Print

The sides of the printed model are composed of several individual layers. If the print runs properly, these layers appear to be a single smooth surface. Contrarily, if there is a flaw, even in a single layer, it is usually very noticeable on the outer sides of the model. These improper layers may appear as lines or ridges on the lateral surfaces of the part. These defects are often cyclical, meaning that the lines appear in a repeating pattern. The main causes and suggestions on how to solve them are presented next.

Inconsistent extrusion

One of the main factors for inconsistent extrusion is poor quality filament. If the filament does not have very tight tolerances, there is a great possibility that the sides of the model will have noticeable variations. To achieve a perfectly smooth side wall, the printer needs to produce a very consistent extrusion which requires a high-quality filament. For other possible causes of inconsistencies in extrusion check 5.2.2.23.

Temperature fluctuation

Another possible cause is temperature fluctuation. Most printers use a proportional integral derivative (PID) controller to regulate the temperature of the extruder. If this system is not properly tuned, the temperature can vary over time. The fluctuation caused by PID controllers is frequently cyclical, meaning that the temperature will vary with a sine wave pattern. The temperature variability results in different performances of the plastic being extruded, which then create visible ridges on the sides of the model. Generally, it is expected that a properly tuned printer can maintain the extruder temperature within more or less 2 degrees. Therefore, it is advised to monitor the temperature of the extruder during the print. If there is a fluctuation of more than 2 degrees, the controller might need to be recalibrated. In this case, it is recommended to contact the printer manufacturer for instructions on how to perform this adjustment.

5.2.2.20 | Vibrations and Ringing

Ringing is a wavy pattern that can appear on the surface of the 3D printed model as a result of the printer vibrating or shaking. This pattern is typically noticeable when the extruder is making a sudden direction change, for instance a sharp corner. The inertia of the extruder can create vibrations when these abrupt direction changes happen, leaving a visible mark on the part. The most common operational cause for ringing is addressed below together with how to improve this issue.

Printing speed too high

One of the main causes of ringing is having the printing speed set too high. Printing at high speeds creates an additional force when changing directions suddenly resulting in the vibrations. It is therefore suggested to decrease the printing speed as well as the X-Y axis movement speed. While the first dictates the speed of the extruder while printing plastic, the second controls the speed of rapid movement where no plastic is being extruded.

5.2.2.21 | Gaps in Thin Walls

Printing thin walls that are only a few times larger than the nozzle diameter is complicated as most printers have a fixed size nozzle. Accordingly, to guarantee that the printer creates a completely solid wall without leaving a gap in the middle, it is recommended to adjust the operational parameter described below.

Adjust the extrusion width to fit better

In some cases, changing the extrusion width has turned out to be very helpful. For instance, printing a 1.0 mm thick wall would be a faster and stronger print if the nozzle was set with a 0.5 mm extrusion width. Therefore, adjust the extrusion width to an adequate value concerning the model being printed. Note that this adjustment works best for parts that have fairly consistent wall thicknesses.

5.2.2.22 | Very Small Features not being Printed

Printing extremely thin features is often an issue in 3D printing as most printers have a fixed sized nozzle ranging from 0.4 to 0.5 mm in diameter. When attempting to print features that are smaller than the size of the nozzle, frequently these structures are simply not printed. Recommendations on how to tackle this issue are presented below.

Redesign the part to have thicker features

A possible solution for this issue is to redesign the part so that it only includes features that are larger than the nozzle diameter. This involves editing the original CAD model to modify the size of the small features. Once the redesign process is concluded, re-import the model into the slicing software to verify if the printer is able to reproduce every detail of the model.

Install a nozzle with a smaller tip

In the situations where it is not possible to modify the original CAD model, either because the client does not want to or the CAD file was downloaded from the internet, it is suggested to acquire a smaller nozzle that is able to print small features. Many printers have a removable nozzle tip, which make these adjustments easy. For further information on how to install a smaller nozzle tip size, it is advised to contact the printer manufacturer.

5.2.2.23 | Inconsistent Extrusion

To obtain accurate 3D models, the printer must be capable of extruding a very consistent amount of plastic. If the extrusion fluctuates during the print, the final print quality is compromised. Inconsistent extrusions are usually detected by observing the printing process. The most common causes of inconsistent extrusions are summarized below, as well as techniques to address each one of them.

Filament is getting stuck or tangled

The first step is to check if the spool of filament that is feeding the printer is able to rotate freely and if the plastic is easily unwound. If the filament is becoming tangled or the spool is offered too much resistance to spin, the extrusion of the filament will turn out to be inconsistent. Furthermore, if the printer includes a Bowden tube, which is a small hollow tube where the filament is routed through, it is also advised to check if the filament is able to move easily through it. If there is too much resistance, cleaning the tube or applying some lubrification inside is recommended.

Clogged extruder

The following step is to check the nozzle itself. There is a possibility that foreign debris is trapped inside the nozzle, preventing proper extrusion. A simple way to verify if the extruder is clogged is to manually extrude some plastic. If plastic is not being extruded consistently the nozzle might need to be cleaned. For instructions on how to deal with this issue check 5.2.2.11.

Very low layer height

If neither of the above is the cause for the issue, it might be useful to check some of the settings in the slicing software. One of the settings that can be causing inconsistent extrusions is the layer height. If this value is very low, the nozzle has little to no room for plastic to extrude. Accordingly, make sure that the layer height is reasonable. If it is too low, increase the value and check if the issue stops.

Incorrect extrusion width

Setting the incorrect extrusion width can also cause this issue. Problems in extrusion can occur if the extrusion width specified is significantly smaller than the nozzle diameter. Under these circumstances, the extruder is not able to push a consistent flow of filament. As a general rule of thumb, the extrusion width should be within 100 to 150% of the nozzle diameter.

Poor quality filament

Regardless of the previous causes discussed, one of the main reasons for inconsistent extrusion is the quality of the filament. Low-quality filaments can contain extra additives that impact the consistency of the plastic or may have inconsistent diameter values which also jeopardizes the extrusion. Additionally, many plastics tend to degrade over time. Therefore, if there is a chance that the filament is causing the issue, it is suggested to change the spool for a new, unopen, high-quality spool to see if the problem is solved.

5.2.2.24 | Warping

A common situation, when printing larger models, is that even though the first few layers of the part successfully adhere to the bed, later on, the part begins to curl and deform. If the curling is severe, then it can cause the model to separate from the bed and even cause the entire print to fail. This situation is particularly common when printing very large or long parts with high temperature materials, such as ABS. The main reason for this is that plastic tends to shrink as it cools. During the print, each successive layer deforms a small amount until the entire part curls and separates from the bed. Although this can be a tough issue to solve, several helpful suggestions have been discussed below.

Use a heated bed

Having a heated build platform helps keep the bottom layers of the part warm throughout the print. This ultimately helps to prevent the plastic from shrinking in these layers. Accordingly, it is advised to set an adequate bed temperature for the plastic filament being used for the print. For instance, it is common to set the bed temperature to 100 to 120ºC for materials such as ABS.

Disable cooling fan

The printer’s cooling system is often a problem when faced with warping issues. Therefore, many users find it useful to disable any external cooling fans when printing with high-temperature materials. This will allow the plastic to stay warm for a longer period of time, decreasing the chance of shrinkage.

Use a heated enclosure

Although the heated build platform prevents the bottom layers from shrinking, the remaining upper part of the model still struggles to keep warm. In this case, it is useful to place the printer inside of an enclosure that can maintain the heat, keeping the whole model warmer for longer periods. Some printers already include an enclosure specifically to preserve the temperature. Simply guarantee that the doors are closed during the entire print to avoid the heat from escaping.

Add brims and rafts

If all of the previous recommendations have failed to solve the issue, consider including printing a brim or a raft with the model. These features will help hold the edges down and may warp less, since they are typically only a few layers tall. For further information on brims and rafts, read section 5.2.1.14.

5.2.3 | Print Quality Troubleshooting Guide Diagram

To support the troubleshooting process, an auxiliary diagram was developed based on the issues presented before and their respective Ishikawa diagram. Also known as a fishbone diagram, this tool is considered a quality control method which enables a visual and simple graphical way of presenting a chain of causes and effects by sorting out and relating these causes (Ishikawa, 1986). **Appendix F** serves as an illustration of this technique for issues 5.2.2.1 and 5.2.2.2. Once this method was concluded, the troubleshooting diagram was created combining the issues, their causes, and the respective recommendations (see **Appendix G**). The main goal of this visual troubleshooting guide is to facilitate and speed up the identification of the causes and solutions to the various problems that may be encountered. As soon as the troubleshooting process is complete, the printed part is considered to have satisfactory quality standards, *i.e.*, decent processing time with accurate dimensions and adequate surface finish that can withstand a reasonable amount of tension. Regardless, considering there are several quality standards for different products, it is advised to consult the client to guarantee the part is suitable for its desired purpose, or else, the printing parameters must be adjusted.

5.2.4 | 3D Printers

To consolidate this section and provide some examples of the different 3D printers available in the market, several requests were sent to different suppliers in order to obtain a detailed description of their 3D printers and the retail price of such equipment's. Hence, three different 3D printers are presented and characterized below. For confidentiality purposes the identity of the suppliers and their equipment are omitted.

5.2.4.1 | 3D Printer A

Printer A (PrA) is a compact desktop 3D printer with an enclosed chamber with air filtration and circulation, wireless file transfer, touch screen interface, built-in camera for remote monitoring, and an autocalibration system. It retails at 3 700€ and has a maximum printing speed of 250 mm per second. The full characterization of this 3D printer is presented in **Table 13**.

Table 13: PrA technical specifications.

PRINTER A			
Price	3 700 €		
Technology	FDM	Frame	Cartesian
Build Volume (d x h)	Ø200 x 200 mm		
Max Print Speed	250 mm/s		
Layer Resolution	50 μm		
Extrusion System	• Single-nozzle • All-metal hot-end and feeder		• Max temperature: 300ºC • Default nozzle: 0.4 mm
Size	• Dimensions (w x d x h): - 340 x 370 x 641 mm - 340 x 390 x 641 mm (with spool holder)		• Weight: 22.5 kg
Build Plate	• Type: glass • Max temperature: 120ºC		• Heat-up time: 5 min
Build Chamber	Enclosed		
Safety	• Air filtering: air and active carbon filters		• Overheating protection
Software	• Supplied software: - Slic3r (slicer) - FabControl® (printing, drying profile management software) - FabControl® Embedded (device control software) • Supported 3D models file format : .stl, .obj, .3mf • Supported print file format: .gcode (up to 150MB)		
Additional Features	Automatic calibration; built-in camera; status notification; touch screen interface; wireless file transfer; Wi-Fi; USB port; Ethernet jacks; automation ready.		

5.2.4.2 | 3D Printer B

Printer B (PrB) is a professional large-format 3D printer with dual extrusion that has a retail price of 3 450€ and a maximum printing speed of 150 mm per second. This printer offers excellent build quality, power outage resume, High Efficiency Particulate Arrestance (HEPA) filter, full enclosure for proper heat management and a strong, magnetic heated bed. A detailed characterization of this 3D printer is presented in **Table 14**.

5.2.4.3 | 3D Printer C

Printer C (PrC) is a professional compact 3D printer which allows the printing of objects up to 40 cm height. It includes a resurrection system, which allow users to save their print job and resume it in the

Table 14: PrB technical specifications.

PRINTER B			
Price	3 450 €		
Technology	FDM	Frame	Cartesian
Build Volume (w x d x h)	Single extrusion: 305 x 305 x 300 mm	Dual extrusion: 280 x 305 x 300 mm	
Max Print Speed	150 mm/s		
Layer Resolution	10 µm		
Extrusion System	• Dual-head with electronic lifting • Max temperature: 300ºC	• Default nozzle: 0.4 mm	
Size	• Dimensions (w x d x h): - 620 x 590 x 760 mm	• Weight: 44 kg	
Build Plate	• Type: aluminium with magnetic holding • Max temperature: 110ºC		
Build Chamber	Enclosed		
Software	• Slicing software: ideaMaker • Supported 3D models file format : .stl, .obj, .3mf • Supported print file format: .gcode		
Additional Features	Touch screen; HEPA filter; power outage resume; live camera; Wi-Fi; USB port; Ethernet jack; auto-bed levelling; removable print bed.		

case of power failure, a suspended Bowden, which makes it possible to download the inertia on the hanging rubber-bands, improving the printing speed and quality, a free zed system, that allows to print a file starting from a precise height of the model, and turbine cooling, that allows a sharp finishing of the pieces and the precise separation of the supports, eliminating the need for a dual extruder. It has a maximum printing speed of 300 mm per second and retails for 3 080€. The full characterization of this 3D printer is described in **Table 15.**

Table 15: PrC technical specifications.

PRINTER C			
Price	3 080 €		
Technology	FDM	Frame	Delta
Build Volume (d x h)	Ø200 x 400 mm		
Max Print Speed	300 mm/s		
Layer Resolution	50 µm		
Extrusion System	• Steel single-nozzle • Max temperature: 260ºC	• Default nozzle: 0.4 mm	
Size	• Dimensions (w x d x h): - 490 x 440 x 870 mm	• Weight: 20 kg	
Build Plate	• Type: stainless steel • Max temperature: 100ºC		
Build Chamber	Enclosed		
Software	• Slicing software: - Cura - SLic3r - Simplify3D® • Supported 3D models file format : .stl, .obj • Supported print file format: .gcode		
Additional Features	Resurrection system; suspended Bowden; free zed system; interchangeable extruder; turbine cooling.		

5.3 | Conclusions

The *process technology* pillar analysis allowed the characterization of 4 and 26 critical operational parameters for the filament extrusion and 3DP processes, respectively. Additionally, the most common quality problems were analyzed for each of the technologies, and a troubleshooting process was provided to solve and improve these issues. Since the 3DP troubleshooting process was extensive, a visual diagram was developed to aid the identification of the causes and solutions to the various problems. Finally, three filament extrusion lines and three 3D printers were presented as an example of the different types of equipment available in the market.

6 | Secondary Pillars

Having discussed the core process design pillar of this research in the previous chapter, *process technology*, the secondary pillars will be presented next. Accordingly, this chapter is divided into four sections, each one dedicated to the results obtained for the different secondary pillars of process design: *product design* (section 6.1), *layout and flow* (section 6.2), *job design* (section 6.3), and *supply network design* (section 6.4).

6.1 | Product Design

Today, most products are designed to be a "one-size-fits-all" as businesses strive for standardization to make products more cost-effective to manufacture. However, with the introduction of 3DP technology, companies have been able to tailor product designs for each customer without additional tooling costs by simply adjusting the digital designs. For this reason, 3DP started gaining popularity in industries where customization was essential, such as medical and dentistry. Besides customization, 3DP enables the production of products with complex geometries and advanced material properties and functionalities at a cost and time-effective manner (Formlabs, 2019). Accordingly, companies across multiple industries, such as automotive, aerospace, electronics, healthcare, and education, are increasingly using this technology to produce a wide array of products. A survey conducted by Sculpteo (2019), a global leader in digital manufacturing, questioned several employees of different industries to understand how companies use 3DP. The main uses of this technology are illustrated in **Figure 20,** and it is possible to see that proof of concept and prototyping are dominating the 3DP applications in 2019.

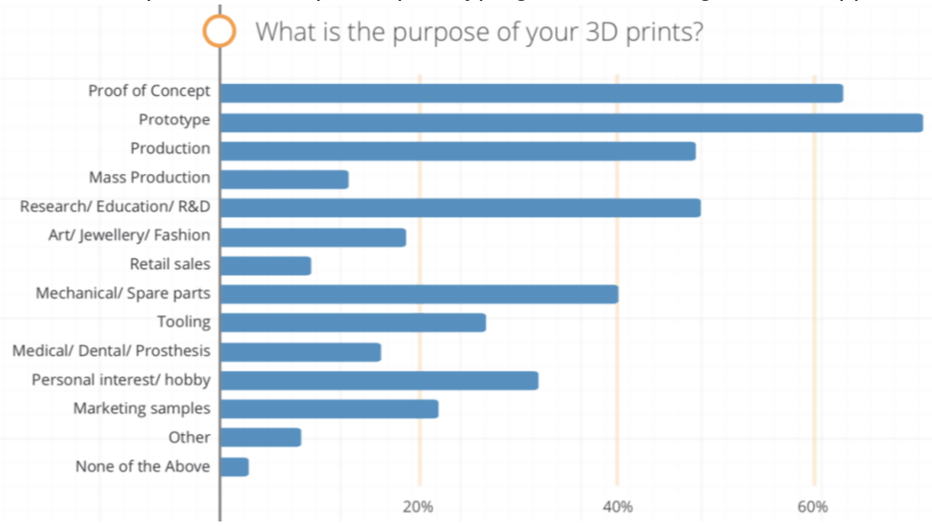

Figure 20: The different 3DP applications in 2019 (Sculpteo, 2019).

Therefore, this section focuses on *product design*, the process design pillar which has an important role in the valorization of plastic waste. The 3DP plastic market size in 2018 is estimated to have been 616 million USD, and this value is expected to reach an astonishing 2,499 million USD by 2027, at a compound annual growth rate of 16.8% between these years (Markets and Markets, 2018). The growth of the 3DP plastic market allied to the use of the large volumes of plastic waste as 3DP feedstock, enables the production of sustainable, cost-effective and marketable products, leading to plastic waste valorization and circularity. Therefore, to understand the possible products that could be marketed, online research was carried out together with interviews with the CEO of a 3DP enterprise. The findings indicate two possible marketable products, the recycled filament itself, which is discussed in subsection 6.1.1, or a vast range of 3D printed consumer products, which is explored in subsection 6.1.2. The former is targeted to 3DP companies that consume plastic filament, while the latter can be integrated into various end-use industries due to the versatility of 3D printed products, as highlighted previously.

6.1.1 | Recycled Filament

The first marketable product that can result from the waste valorization solution is recycled plastic filament for 3D printers. The feasibility of recycled plastics as 3DP feedstock has been validated in the literature review presented in section 3.1. Additionally, there is currently a Dutch company, Re-Filament, that already produces recycled plastic filament at a quality comparable or superior to premium non-recycled filaments (see **Table 16**) (ReFil, 2019). The average retail price of these recycled filaments is 30€/kg, comparable to those that are non-recycled, which allows for increased profit margins since there are practically no costs associated with the raw material. Nevertheless, as seen in **Table 16,** the variety of recycled plastic filaments is still reduced since the filament extrusion process for the other plastics has not yet been optimized. Therefore, there is still a long way to go regarding the introduction of different recycled plastic filaments into the market, but once the processes have been validated, it will be possible to benefit from more types of plastic waste.

Table 16: Recycled plastic filaments on the market (retrieved from Re-filament, 2019).

RECYCLED FILAMENT RETAIL PRICES		
Polymer	Price (€/kg)	Waste Source
PET	34	Old PET bottles
ABS	28	Car dashboards, door panels and other plastic car parts

6.1.2 | 3D Printed Products

The second possible marketable outcome from the proposed solution is a wide array of 3D printed products that can be integrated into different end-use industries. Companies across multiple industries are increasingly using 3DP for more than just prototypes, as seen in **Figure 20**. The versatility of 3DP has allowed the manufacturing of almost any item. In this subsection, three different 3D printed products are proposed and discussed as an illustration of the application of 3D printed products in different markets. The three products are a wrist cast, a custom lamp, and a laser hair removal handle (see **Figure 21**). These products were chosen as they represent opposite extremes of different product design variables, as illustrated in the matrix in **Figure 22**. The matrix variables are customization, retail price and printing time. Accordingly, the wrist cast represents a highly customizable product, since it is adapted to each patient, that retails at a low price, and takes a short printing time to produce. Moreover,

Figure 21: The three 3D printed products proposed: the wrist cast, custom lamp and the laser hair removal handle.

the custom lamp represents an also a customizable product but at a higher retail price, and that takes twice as long to print compared to the wrist cast. On the other hand, the laser hair removal handle represents a standardized product, that retails at a much higher price point, and that takes six times longer to print compared to the wrist cast.

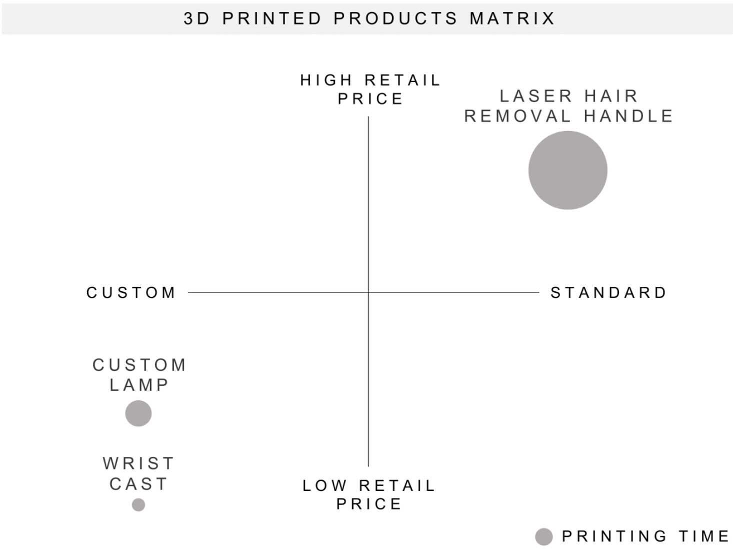

Figure 22: 3D printed products matrix with customization, retail price and printing time as product design variables.

The exact retail prices and printing times for these products are shown in **Table 17**. Additionally, this table serves as a demonstration of the potential revenue of different types of 3D printed products, in different end-use industries. Nevertheless, this table is just an example, as a 3D printer is expected to produce a mix of products, that maximizes the company's profit, instead of manufacturing one single product.

Table 17: Demonstration of the potential revenue of different 3D printed products.

3D PRINTED PRODUCTS			
	Wrist Cast	Custom Lamp	Laser Hair Removal Handle
Printing Time (h)	3	6	18
Weight (kg)	0.032	0.017	0.116
Retail Price (€)	10	25	300
Units produced by 1 Printer / Day	6	3	1
Units Produced by 10 Printer / Day	63	31	10
Units Produced by 10 Printers / Year	16466	8233	2744
Annual Filament Consumption (kg)	527	140	319
Annual Revenue (€)	164 660	205 825	823 200

Assumptions: capacity production = 80% (19h/day); 260 work days/year (5 days/week * 52 weeks/year).

6.2 | Layout and Flow

Conceptualizing the appropriate physical location of the downstream waste valorization solution is essential for the proper flow of material and information. Accordingly, the *layout and flow* process design pillar involves establishing the physical layout of the filament extrusion line and the 3D printers, which in turn dictates the flow of plastic throughout the process. To gain some notions on the most appropriate layout for the solution, informal interviews were conducted with experienced employees in both the extrusion and 3DP industries, which turned out to be essential for the development of the layout proposals. The conclusions that were drawn from the interviews revealed that most 3DP companies are organized in printing farms, such as the one in **Figure 23**.

Figure 23: An example of a printing farm (Zortrax, 2019).

Taking this information into consideration, three different layout proposals were developed with the scenarios established in section 4.3: a low, medium, and high production capacity, which have been designated as LC, MC and HC, respectively. All layout proposals consider the same equipment, the ExB and PrA (see subsections 5.1.3 and 5.2.4), and the utilization of standard racks, each with the capacity of six 3D printers, similar to a print farm set-up. Apart from the dimensions of the equipment and the rack itself, a safety distance was added to the final layout proposals.

The layout proposal for the LC scenario is illustrated in **Figure 24**, as well as the total area required for its implementation, which in this case is 57.28m_2. On the other hand, the necessary area for the implementation of the MC and HC scenario are, 100.76m_2 and 247.32m_2, respectively. The layout proposals corresponding to these scenarios can be seen in **Appendix H** and **I.**

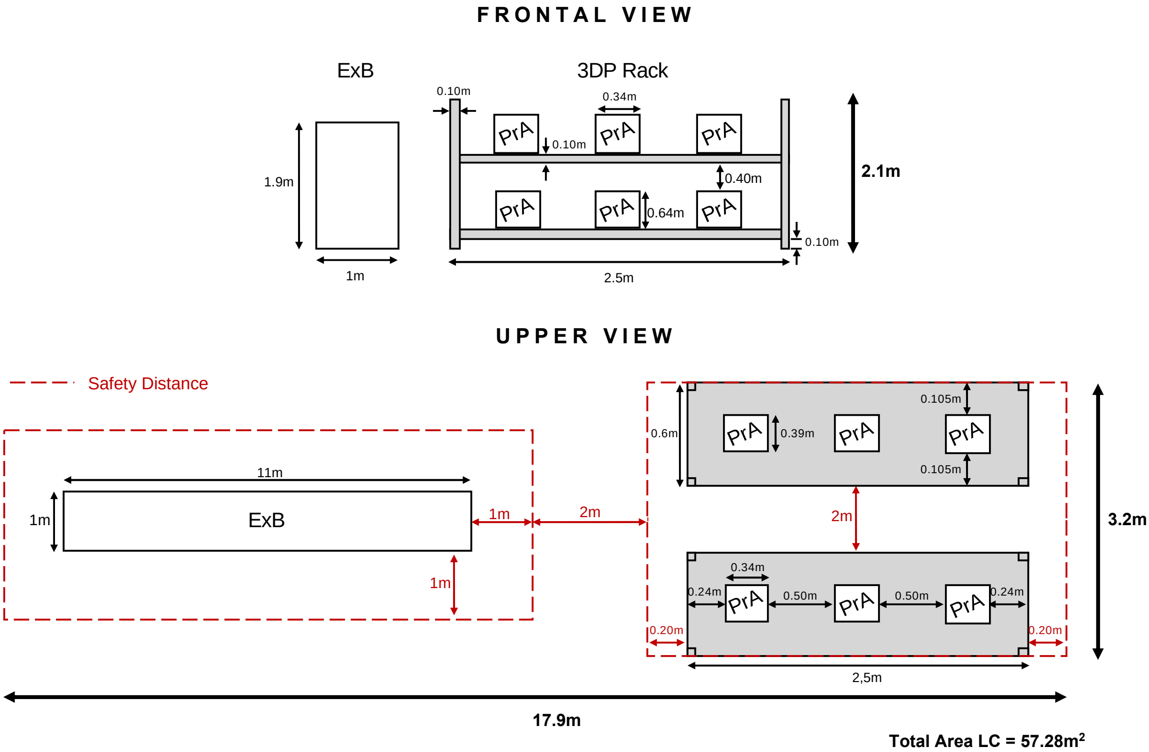

Figure 24: Layout proposal for implementing the downstream waste valorization solution with a low capacity (the diagram is not to scale).

6.3 | Job Design

The proper management of people is vital to ensure a smooth and effective operation, which is the foundation of the process design pillar that is discussed next, *job design*. Therefore, this section aims at outlining the tasks and responsibilities associated with certain parts of the process, as well as establishing the qualifications that are required to perform them.

To understand the workforce required for the waste valorization process, informal interviews were carried out with employees in both the extrusion and 3DP industries. The conclusions drawn from the interviews reveal that for each filament extrusion line, it is necessary at least one extrusion technician and one engineer, whereas, for every twenty 3D printers, one 3DP technician is enough. The technicians are required to comprehend the functioning and maintenance of the equipment, while the engineer contributes with more specialized knowledge on the operation. Accordingly, both technicians are required to have high mechanical aptitude since they need to understand how all the components of each technology work, especially in situations where the equipment requires maintenance. Moreover, they should possess strong attention to detail to guarantee both the filament and finished products are accurate. Furthermore, the ability of communication and strong organizational skills are fundamental to effectively manage all aspects of the processes and communicate rapidly in case of an error. On the other hand, the tasks of the field engineer are to identify, understand, and interpret the constraints of the process to produce successful results. In other words, the engineer is expected to be an expert in the extrusion filament process and be able to identify problems that might occur during processing that are not easily detectable, research and provide solutions, make important operational decisions, and overall ensure the process and product matches the requirements and needs.

6.4 | Supply Network Design

A process is part of a broader and interconnected network of other operations, which include suppliers and customers. The purpose of this section is to explore the final process design pillar, *supply network design*, by identifying the potential suppliers and customers of the output products of the proposed waste valorization solution, the recycled filament and diverse 3D printed products (see section 6.1), to establish a network of customer-supplier relationships. Therefore, subsections 6.4.1 and 6.4.2 discuss potential suppliers and customers, respectively.

6.4.1 | Potential Suppliers

As stated in the problem characterization (section 2.4), the target customers for the implementation of the downstream waste valorization solution are waste collectors that perform the cleaning and sorting of the plastic. In turn, these companies, that are able to integrate this solution into their process, will ultimately become the plastic waste suppliers of the process. In sum, the raw material suppliers for the solution are the plastic recycling companies that perform the upstream waste management process. Take as an example **Table 18,** which presents the main Portuguese plastic recycling companies, together with the types of waste they manage and their contact.

6.4.2 | Potential Clients

With regard to identifying the potential clients, it is important to refer to the *product design* pillar (section 6.1), where the two marketable outcomes of the waste valorization solution were established, the recycled filament itself or a wide array of 3D printed products. Appropriately, the recycled filament is targeted to 3DP companies that consume plastic filament as feedstock material. As an example of

Table 18: Portuguese recycling companies that represent potential suppliers.

PLASTIC RECYCLERS		
Company	Types of Plastic Waste	Website
ABSORVALOR, LDA.	PE, PP, ABS	www.absorvalor.pt
AMBIENTE, S.A.	PE, PP, ABS	www.ambiente-sa.com
AMBIGROUP RECICLAGEM	PE	www.ambigroup.com
ECOIBÉRIA. S.A.	PET	www.ecoiberia.pt
EVERTIS IBERICA, SA.	PET	www.evertis.com
EXTRUPLÁS, LDA.	Various	www.extruplas.com
GRIJÓTUBOS, LDA.	PE	www.grijotubos.pt
IRP, LDA.	PE	www.irp.com.pt
MICRONIPOL, S.A.	PE, PP, ABS	www.micronipol.pt
SIRPLASTE, S.A.	PE, PP	www.sirplaste.pt

potential clients for the recycled filament, **Table 19** presents the main Portuguese 3DP companies, together with their contact. On the other hand, the 3D printed products can be, and are increasingly being integrated into different industries for different applications. Therefore, the potential clients for 3D printed products are countless and are present in several end-use industries. **Table 20** indicates some of the potential applications of 3D printed products in different industries.

Table 19: Portuguese 3DP companies that represent potential customers for the recycling filament.

3D PRINTING COMPANIES	
Company	Website
CODI	www.codi.pt
IMPRESSAO 3D	www.impressao3dportugal.pt
THINK 3D	www.think3d.pt
XPIM	www.xpim3d.com
3D FACTORY	www.3dfactory.pt
3D LIFE	www.3dlife.pt
3D MAKER	www.3dmaker.pt
3D WAYS	www.3dways.pt

Table 20: The applications of 3D printed products in different industries (CODI, 2019).

3D PRINTED PRODUCTS	
Industry	Applications
Aerospace and Automobile	Rapid prototyping, parts production and tools and equipment.
Medical	Preclinical tests, clinical training models, medical manufacturing and surgical planning models.
Dentistry	Orthodontic models, crown and bridge models, surgical guides, clinical training models and implant models.
Consumer Products	Rapid prototyping and concept modelling.

6.5 | Conclusions

The findings obtained from the *product design* analysis demonstrated two possible marketable options: recycled filament and a wide array of 3DP products. Three different 3DP products have been presented to demonstrate their potential revenue. Regarding *layout and flow*, three layout proposals were presented considering different production capacity scenarios. The necessary area for the implementation of the LC, MC and HC scenarios are, 57.28m$_2$, 100.76m$_2$, and 247.32m$_2$, respectively. The results from the *job design* analysis showed that for each filament extrusion line, at least one extrusion technician and one engineer is required, whereas, for every twenty 3D printers, one 3DP technician is sufficient. Finally, when establishing the *supply network design*, the suppliers have been identified as the waste collectors that clean, sort and prepare the plastic waste for this downstream solution. Regarding the end-consumer, there are two possible targets, the 3DP filament market, and the 3DP products market.

7 | Project Appraisal

The assessment of the viability of a project is critical in determining whether it will be profitable or not, and therefore, establishing if it should be implemented or not. The following chapter aims at presenting the project appraisal that was conducted to assess the feasibility of the proposed downstream waste valorization solution. Section 7.1 describes the scenarios that were considered to perform the project appraisal, while section 7.2 presents the assumptions for this analysis. Then, section 7.3 discusses the results obtained and the sensitivity analysis that was performed to the 3DP plastic filament market.

7.1 | Scenarios

As outlined in section 4.3, the project appraisal was performed to twelve different scenarios, which were created from the findings obtained through the process design pillar analysis. These scenarios consist of three production capacity scenarios, which were then divided into four sub-scenarios, considering different marketable options. The production capacity scenarios are identical to those established for the layout proposals in section 6.2, and their full characterization is presented in **Table 21**. The number of equipment for each scenario was defined in section 4.2, while the type of equipment was chosen from those presented in subsections 5.1.3 and 5.2.4. Additionally, the employees were allocated according to the results obtained in section 6.3. The four sub-scenarios, which are shown in **Table 22**, are centered on the marketable options that were presented in section 6.1. The first sub-scenario considers retailing, exclusively, all the recycled filament that is produced by the extruder, whereas the other sub-scenarios consider the retail of the maximum amount of product that can be produced by the 3D printers, and retailing the left-over amount of recycled filament. All twelve scenarios are shown in **Figure 25.**

Table 21: The characterization of the production capacity scenarios.

		SCENARIOS		
		LOW CAPACITY (LC)	**MEDIUM CAPACITY (MC)**	**HIGH CAPACITY (HC)**
Equipment	Extruder	ExB	ExB	ExB
	# Extruders	1	1	1
	3D Printer	PrA	PrA	PrA
	# 3D Printer	12	72	144
Employees	# Extrusion Technicians	1	1	1
	# 3DP Technicians	1	4	8
	# Engineers	1	1	1

Table 22: The characterization of the sub-scenarios.

SUB-SCENARIOS			
RECYCLED FILAMENT (rFil)	**PRODUCT 1 (P1)** Wrist Cast	**PRODUCT 2 (P2)** Custom Lamp	**PRODUCT 3 (P3)** Laser Hair Removal Handle
100% rFil	Max P1 + rFil	Max P2 + rFil	Max P3 + rFil

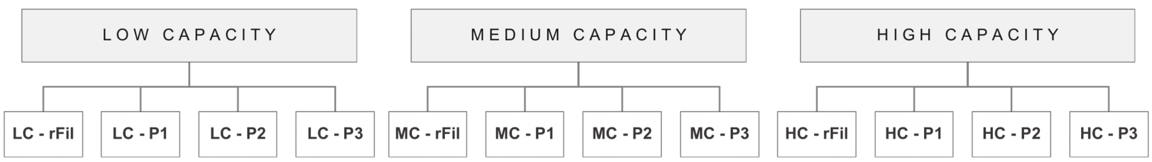

Figure 25: The twelve scenarios which were considered for the project appraisal.

7.2 | Assumptions

Project appraisals “usually build on knowledge or on assumptions of a project’s anticipated future cash flow, or inflow of income and outflow of expenses over time” (Samset, 2010). Correspondingly, the assumptions considered for the project appraisal are presented below, in **Table 23**.

Table 23: Project appraisal assumptions.

<table>
<tr><th colspan="4">ASSUMPTIONS</th></tr>
<tr><td>Investment</td><td>• The equipment retail price of ExB and PrA can be seen in 5.1.3.2 and 5.2.4.1;
• The equipment instalment price was considered to be 20% of the retail price of the equipment;
• The residual value of investment was considered to be 20% of the total investment;
• It was considered that the client has the necessary space for implementing the solution.</td><td rowspan="3">Operating Expenses</td><td rowspan="3">Raw Materials:
• The raw materials were considered to be the cost per plastic bottle (0.15€/kg) plus the cost of washing and shredding the bottle (0.7€/kg), giving a total of 0.22€/kg;
• The raw material is considered to be supplied by the client of the solution.
Salaries:
• The 3DP and extrusion technicians annual salaries were considered to be 15 739,76€, while the annual salary of the engineer was considered to be 27 752,92€, assuming:
- The technicians and engineer monthly illiquid salary is 908,5€ and 1601,9€, respectively (PORDATA, 2019);
- 14 salary months: 11 months working, 1 month of holiday, 2 months of subsidies;
- 23,57% social security tax (Segurança Social, 2019).
Energy and Water Consumptions:
• The ExB has an annual energetic and water consumption of 2 978.56€ and 18 559.84€, respectively, assuming:
- The equipment consumes 20 kW of power and 5 m^3/h of water;
- The cost per kWh is 0.0716€ (EDP, 2019) and the cost per m^3/h is 1.7846€ (EPAL, 2019).
• The PrA has an annual energetic consumption of 164.47€, considering:
- Each equipment consumes 0,6kW;
- The cost per kWh is 0.0716€ (EDP, 2019).</td></tr>
<tr><td>Income</td><td>• The ExB is considered to work at a 80% production capacity, which translates to a capacity of 24 kg/h, in 8 hour shifts/day, 5 days/week, 52 weeks/year;
• The retail price of recycled filament is considered to be 30 €/kg;
• The PrA is considered to work at a 80% production capacity, meaning 19h/day, 5 days/week, 52 weeks/year;
• The retail prices of P1, P2 and P3 can be seen in 6.1.2.</td></tr>
<tr><td>Depreciations</td><td>• The depreciation was calculated linearly according to the predicted life span of the equipment's:
- The ExB was considered to have a life span of 10 years;
- The PrA was considered to have a life span of 5 years.</td></tr>
<tr><td>Earnings Before Interests After Taxes (EBIAT)</td><td>• The tax rate considered was the Portuguese corporate income tax, equal to 21% (Deloitte, 2019).</td><td>Net Present Value (NPV)</td><td>• The discount rate considered was 10.53%, which is the sum of three different rates:
- The Portuguese risk free rate in 2019, 2.60% (Statista, 2019);
- The Portuguese risk premium rate in 2019, 7.50% (Statista, 2019);
- The Portuguese average inflation rate in 2019, 0.43% (InflationEU, 2019)</td></tr>
</table>

7.3 | Results

Having defined the scenarios and the assumptions for the analysis, three project appraisal criteria were calculated to measure the success of each scenario, the NPV, the IRR, and the payback period, which are presented in **Table 24**. The cash flow statements from which these criteria were calculated can be consulted in **Appendix J**, **K** and **L**.

Table 24: Overview of the project appraisal criteria for the different scenarios.

LOW CAPACITY (LC)

Project Appraisal Criteria	LC - rFil	LC - P1	LC - P2	LC - P3
Net Present Value (NPV)	€6 074 820,00	€6 728 630,39	€7 197 207,49	€10 154 466,93
Payback Period (Years)	0,034	0,073	0,070	0,048
Payback Period (Months)	0,406	0,874	0,841	0,582

MEDIUM CAPACITY (MC)

Project Appraisal Criteria	MC - rFil	MC - P1	MC - P2	MC - P3
Net Present Value (NPV)	€6 074 820,00	€10 132 840,30	€11 764 312,24	€30 687 859,54
Internal Rate of Return (IRR)	2956,58%	538,09%	622,01%	1595,47%
Payback Period (Years)	0,034	0,186	0,161	0,063
Payback Period (Months)	0,406	2,230	1,929	0,752

HIGH CAPACITY (HC)

Project Appraisal Criteria	HC - rFil	HC - P1	HC - P2	HC - P3
Net Present Value (NPV)	€6 074 820,00	€14 190 860,61	€17 453 804,48	€55 300 899,08
Internal Rate of Return (IRR)	2956,58%	402,40%	491,03%	1519,11%
Payback Period (Years)	0,034	0,249	0,204	0,066
Payback Period (Months)	0,406	2,982	2,444	0,790

The first criterion that was calculated, the NPV, represents the discounted present value of the sequence of cash flows over the lifetime of the project, which in this case is 10 years. A positive NPV indicates that the projected earnings generated by the project exceed the anticipated costs, translating into a profitable project. Additionally, the higher the NPV, the more profitable the project is (Samset, 2010). By observing **Table 24**, it is clear that, according to this criterion, all scenarios are extremely profitable. The scenarios that consider only retailing rFil have the same values, since removing the 3DP factor of the scenario results in three identical situations. Within each production capacity scenario, the NPV increases throughout sub-scenarios P1, P2, and P3, as expected, since the retail price of the product increases, even though fewer units are sold. It is also possible to conclude that the HC scenarios, excluding the rFil, are the most profitable. The second criterion that was computed, the IRR, is the interest rate that returns a zero NPV and is a direct expression of the anticipated yield of the project. Similarly, to the NPV, the higher the project's IRR, the more desirable it becomes (Samset, 2010). It is apparent from **Table 24** that all scenarios are highly profitable since the IRR values are extremely high. Comparably to what occurred with the NPV, within each production capacity scenario, the IRR increases throughout sub-scenarios P1, P2, and P3. However, it appears as the IRR is in conflict with the NPV since the IRR of the LC scenarios are higher than the IRR of the MC and the HC scenarios, and the IRR of the MC scenarios is higher than those of the HC scenario. This conflict may arise when dealing with mutually exclusive projects, in this case, scenarios, where the goal is to select the best scenario, eliminating the others from consideration. In this situation, the conflict may result from the difference in the scale of the scenarios or from the difference of the cash flow distribution over time (Smirnov, 2019). Considering that the scenarios represent different production capacities, it seems likely that the size difference between them is responsible for this conflict. When conflicts arise, it is generally accepted that the NPV method is the preferred technique since it assumes that the future cash flows are reinvested at the discount rate (cost of capital), a more realistic and conservative assumption, when compared to the IRR method which considers the future cash flows are reinvested at the IRR (Smirnov, 2019). Finally, the payback period was calculated, which indicates the amount of time required to recuperate the cost of the investment or to reach the breakeven point. Therefore, shorter payback periods translate into more attractive investments (Samset, 2010). Looking into the results, all scenarios reveal very short payback periods, all under one month, except from scenarios MC-P1, MC-P2, HC-P1, HC-P2, whose payback periods are under one year, which is also considered a short period time.

All in all, the project appraisal criteria are very optimistic and validate all the scenarios considered for the downstream waste valorization solution. However, these results need to be interpreted with caution. For example, in the scenarios which involve P3, 1 ExB produces roughly 49.9 ton of rFil annually, while 12, 72, and 144 PrA produce respectively, 3293, 19760 and 39520 units of P3, which consume respectively, 382, 2292, and 4582 kg of filament annually. The left-over amount of rFil is respectively, 49.5, 47.6, 45.3 ton per year, which translates into only 0.8, 4.6, and 9.2% of annual rFil consumption, and this is regarding P3, the product which consumes the most filament. Therefore, the optimistic results obtained through this project appraisal are highly reliant on the 3DP plastic filament market, *i.e.*, are subject to the capacity of retailing all the remaining rFil. For this reason, it was decided to perform a sensitivity analysis on the NPV by varying the 3DP filament market. The responsiveness of the LC scenarios is shown in **Figure 26.** Looking into the LC-rFil scenario, a market fluctuation of -5, -10, and -15%, results in the decrease of the NPV by 321 498.70€, 642 997.40€, and 964 496.09€, respectively. **Appendix M** contains the sensitivity analysis of the MC and HC scenarios.

The conclusion is that the optimistic results are subject to the 3DP filament market, and therefore, can be associated with a future scenario when the 3DP industry has expanded, as expected.

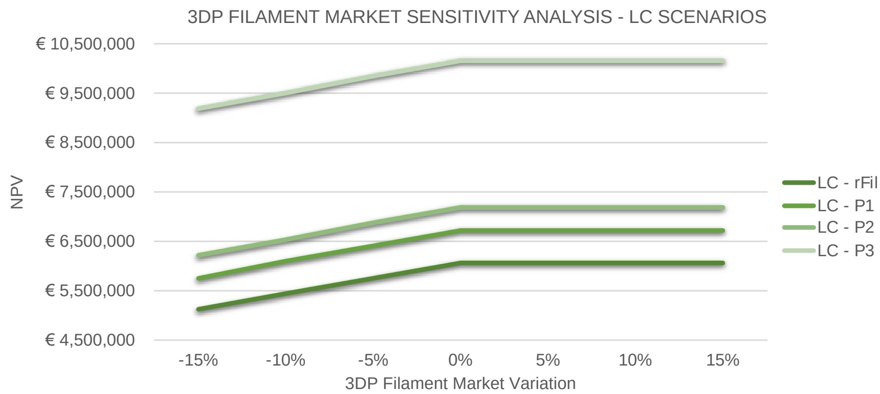

Figure 26: 3DP filament market sensitivity analysis for the low capacity scenarios.

8 | Final Conclusions, Limitations and Future Work

The exponential growth of the plastic industry has been fueled by its inexpensiveness, versatility, lightweight and durability. However, this revolutionary material has faced a significant shift in production from durable and reusable plastics towards single-use and disposable products which has led to a "throwaway" society that is potentially one of the greatest threats to the environment. The current plastic age has been aggravated by mankind's inability to cope with end-of-life plastics, resulting in mismanaged waste and unexploited recycling processes. In this context, the main waste management approaches have been analyzed as well as the externalities related to plastic. To provide a better understanding of this material, a thorough analysis of the different thermoplastics along with their applications was provided. Furthermore, a waste valorization solution has been developed by Company A as a strategy to cope with the excessive volumes of plastic. The solution involves the extrusion and 3DP of plastic waste into marketable products. However, the complexity of the process integration of this solution at an industrial scale is standing in the way of its current implementation. Under these circumstances, the problem characterization was described.

3DP has gained popularity as a low-cost and sustainable alternative to conventional manufacturing. Emphasis was given on FDM, one of the most commonly used 3DP technologies. In this sense, achieving sustainability of FDM feedstock is of utmost importance to manage the projected growth of the 3DP market and as a strategy to deal with plastic waste. A detailed literature review on recycled plastic extrusion and 3DP validated the feasibility of these materials as FDM feedstock. The literature review enabled an in-depth understanding of the behavior of the different types of plastics when subjected to either operation, as well as the critical process parameters that should be controlled. Furthermore, a theoretical analysis of process design, along with its five pillars was presented.

Two main literature gaps were identified, the lack of research on a flexible integrated process and studies on extrusion and 3DP as a whole and how they can work as a process. Therefore, an integrated process design of plastic waste valorization with extrusion and 3DP was developed, at an industrial scale, by adopting a methodology centered on Slack *et al.* (2007) approach. The primary concern of the dissertation was to assess the *process technology* pillar of process design. The data collected from the literature review together with the fieldwork findings, through interviews and experimental testing, enabled the characterization of 4 and 26 critical operational parameters for the filament extrusion and 3DP processes, respectively. Moreover, the most common quality problems of each technology were studied, and a troubleshooting process was provided to solve and improve these issues. Finally, examples of each equipment which are currently available in the market were introduced.

Turning to the secondary process design pillars, the findings obtained regarding *product design* indicated two possible marketable products: the recycled filament itself or a vast range of 3D printed products. Three different 3DP products have been presented to demonstrate their potential revenue. Concerning *layout and flow*, three layout proposals were conceptualized considering a low, medium, and high capacity. The results obtained from the *job design* analysis showed that for one filament extrusion line, at least one extrusion technician and one engineer is required, whereas, for every twenty 3D printers, one 3DP technician is enough. Finally, when establishing the *supply network design*, the suppliers have been identified as the waste collectors that clean, sort and prepare the plastic waste for this downstream solution. Regarding the end-consumer, as mentioned earlier there are two possible targets, the 3DP filament market, and the 3DP products market.

To conclude the research, a project appraisal was conducted to assess the viability of the proposed downstream waste valorization solution. Twelve different scenarios were considered a low, medium, and high production capacity scenario, which were then divided into four sub-scenarios considering different marketable products. The project appraisal criteria point to the profitability of all the scenarios and the results are considerably optimistic. However, these results should be read with attention since they are highly reliant on the availability of the 3DP plastic filament market. Accordingly, a sensitivity analysis was conducted to this market to demonstrate the responsiveness of the results to the ability of retailing the large quantities of recycled filament that is produced and not consumed for products. The conclusions that were drawn revolve around the idea that the results can be considered as a future scenario when the 3DP industry will have expanded, as well as the demand for 3DP filament.

The main limitations of this research were the inability of conducting experimental testing with recycled plastics, due to the lack of appropriate recycled raw material. Moreover, the extrusion experimental testing was also compromised, sometimes due to inexplicable malfunctions of the equipment, mainly due to the worn-out and old extruder that was used, but also due to the puller system which was not optimal for the experiment.

Future work that is suggested involves further experimental testing with recycled polymers since optimal parameters for these types of plastics, both in filament extrusion and 3DP, have not yet been achieved. Further work should focus on the process design of the upstream stages of the valorization process, which were not approached in this research, namely, plastic waste cleaning, sorting, shredding and drying. The prospect of being able to implement a fully integrated plastic waste valorization solution, and stimulate sustainability and plastic circularity, serves as a continuous incentive for research.

In conclusion, this dissertation has contributed to filling out the literature gap on the development of an integrated process design of waste valorization with extrusion and 3DP at an industrial scale by adopting the methodology proposed by Slack *et al.* (2007). Additionally, this research has contributed to a sustainable solution in reducing the excessive volumes of plastic waste which are threatening life as we know on planet Earth.

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Appendix A: Plastics Classification Summary Table

Table A1: Plastics classification summary table.

RIC	Abbreviation	Resin	Physical and Chemical Properties							Common Uses [1]	Recyclable[1]
			Overview[1]	Density (g.cm^{-3})[3]	Melting Temperature (ºC)[4]	Máx CST* (ºC)[5]	Toughness** (J.m^{-2})[5]	Young's Modulus (GPa)[5]	Tensile Strength (MPa)[4]		
1	PETE or PET	Polyethylene Terephthalate	Clear, strong and lightweight	1.370	260	140	140	2.8 - 3.5	152***	 • Plastic bottles (water, soft drinks, cooking oil)	**Yes** Widely recycled
2	HDPE	High-Density Polyethylene	Stiff and hardwearing; Hard to breakdown in sunlight	0.944 - 0.965	130	120	20 - 220	0.5 - 1.1	20	 • Milk containers • Cleaning agents • Shampoo bottles • Bleach bottles	**Yes** Widely recycled
3	V or PVC	Polyvinyl Chloride	Rigid or flexible (via plasticizers)	1.380	100 - 260	80	*Rigid:* 20 - 110	*Rigid:* 2.4 - 4 *Flexible:* 0.001 - 1.8	*Rigid:* 34 - 62 *Flexible:* 6.9 - 25	 • Plastic piping • vinyl flooring • cabling insulation • roof sheeting	**Sometimes** Often not recyclable due to chemical properties
4	LDPE or PE-LD	Low-Density Polyethylene	Lightweight, low-cost, versatile; Fails under mechanical and thermal stress	0.917 - 0.930	110	100	999	0.13 - 0.3	7	 • Plastic bags • Food wrapping (bread, fruit, vegetables)	**No** Failure under stress makes it hard to recycle
5	PP	Polypropylene	Tough and resistant; Effective barrier against water and chemicals	0.905	191 - 232	130	*Copolymer:* 60 - 500 *Homopolymer:* 20 - 60	*Copolymer:* 1 - 1.2 *Homopolymer:* 1.1 - 1.6	*Copolymer:* 25[3] *Homopolymer:* 33[3]	 • Bottle lids • Food tubs • Furniture • Houseware • Medical • Rope • Automobile parts	**Sometimes** Complex process
6	PS	Polystyrene	Lightweight, structurally weak, easily dispersed	1.050	210 - 249	122**	11 - 150***	10***	53	 *Rigid Polystyrene*[6]: • CD cases • Disposeable cutlery *Formed Polystyrene*[6]: • Food containers • Packaging • Egg cartons • Building insulation	**No** Rarely recycled
7	OTHER or O	Polycarbonate, Polyctide, ABS, Fiberglass, Nylon	Diverse in nature with various properties	-	-	-	-	-	-	 • Water cooler • Bottles • Baby cups • Fiberglass	**No** Diversity of materials risks contamination of recycling
-	ABS	Acrylonitrile Butadiene Styrene	Glossy, tough and chemically and thermally stable; Properties vary according to the proportion of each monomer[2]	1.0 - 1.05	204 - 238	89	200 - 215	1.79 - 3.2	46	 • Safety helmets[3] • Luggage shells[3] • Pipes[3] • Automotive interior[3]	**Yes** Not widely[6]

[1] Ritchie and Roser, 2018; [2] 3D Insider, 2019 [3]; BPF ,2019;[4] CM,2019; [5] Omnexus ,2019 , [6] 3D Printing Era, 2019.
*CTS (Continuous Service Temperature), the maximum acceptable temperature above which mechanical/electrical properties of a plastic part are significantly degrading, over the reasonable life time of the tested product.
**Values obtained using the Notched Izod Impact test performed at room temperature (23°C).
***With 30% glass fiber

Appendix B: Literature Overview on Recycled Plastic Extrusion

Table B1: Literature overview on recycled plastic extrusion.

PLASTIC	REFERENCE	APPROACH	RESULTS	REMARKS
PETG with rPET	Lehrer and Scanlon (2017)	Analysed the feasibility of extruding a mixture of PETG and rPET.	• Successful extrusion of the filament.	• Importance of proper mixture of both polymers before extrusion as glycol has a fundamental role in improving PET properties, and because mixing will improve the low intrinsic viscosity associated to PET.
rPET	Byiringiro *et al.* (2018)	Evaluated the feasibility of extruding a filament made from PET water bottles.	• Successful extrusion of the filament; • rPET filament had similar thermal and mechanical properties to those made from PLA and ABS.	• Puller speed, the distance between the puller and the die and the cooling method during extrusion are key factors that influence filament quality.
	Zander *et al.* (2018)	Assessed the feasibility of extruding a filament made from PET bottles and packaging without additives or modification of the polymer.	• Successful extrusion of 100% recycled and unmodified PET filament; • Successful 3DP of small and long lead time samples with the filament.	• rPET has the capability for replacing commercial filament in printing provided the material is properly cleaned and dried; • Additives can improve mechanical properties of rPET and expand its applications; • TS of rPET samples comparable to those made from COTS PET and PC-ABS filament.
PP with tire waste	Domingues *et al.* (2017)	Examined the feasibility of extruding a blend of 60% tire waste and 40% rPP using a twin-screw extruder.	• Successful extrusion of the filament blend; • Successful 3DP of large parts with the filament.	-
rPP	Iunolainen (2017)	Studied the feasibility of extruding rPP.	• Inconsistent diameters and an elliptical shape; • rPP filament extrusion with unsatisfactory quality; • Great discrepancy between rPP properties and those from commercially available filaments.	• Key factors that improve rPP filament quality: - Use a cooling water bath during extrusion; - Extruding at higher temperatures; - Cleaning extruder with virgin PP before extruding the rPP. • Rarity of PP as 3DP material because of warping and poor adhesion during printing.
rHDPE	Baechler *et al.* (2013)	Developed a extruder and assessed the feasibility of extruding rHDPE.	• Successful extrusion of the filament; • Increasingly successful part printing with the filament.	• Filament extrusion 40x more economical in terms of energy compared to purchasing COTS filaments. • Parts printed with rHDPE did not match ABS quality. • Limitations of extruding with HDPE: - Physical assistance was required to draw the filament from the extruder; - Inconsistent rate of extrusion; - Heterogeneous waste feedstock. • Cutting the HDPE into small and homogeneous pieces greatly increased the extrusion rate.
	Hamod (2015)	Evaluated the feasibility of extruding rHDPE by comparing it to ABS and PLA filament.	• rHDPE goes along with PLA data with respect to melt flow, yield strain, melt temperature and extruding temperature while tensile strength and Young's modulus values are not comparable to either PLA or ABS; • The data relationship to PLA confirms the suitability of rHDPE as a filament.	• Puller speed, extruding temperature and distance between the die and puller are key factors in optimizing the filament extrusion process.
	Chong *et al.* (2017)	Examined the feasibility of rHDPE as a filament by comparing it to ABS in terms physical characterization.	• Physical characterization testing showed that extruding rHDPE filaments is a viable option.	• rHDPE pellets had favorable water rejection, with extrusion rate and thermal stability comparable to those of the filament made of ABS pellets.
	Angatkina (2018)	Studied the feasibility of extruding rHDPE filament from MSW.	• Successful extrusion of the filament although it was inconsistent and oval shaped; • Successful 3DP with the filament.	• A heated water bath during the extrusion process was found to be crucial in producing the most round and homogeneous filament; • Main issue during extrusion was material flow stoppage that could be caused by blockage of the die, melting instability or unsuitability of the extrusion screw since rHDPE consists of various blends of HDPE polymers with different molecular weight, molecular weight distribution and chain branching; • The non-uniformity and inconsistency of the filament diameter could be also caused by those factors.
rPVC	Janajreh *et al.* (2015)	Analysed the mechanical recycling of PVC plastic waste stream from the cable industry using a twin-screw extruder.	• The thermal stability and the composition of the extruded rPVC were not affected proving the viability of reprocessing PVC; • Tensile testing showed that the extruded samples became tougher compared to untouched ones.	• The variability between rPCV and pristine PVC is reasonable considering the scaled up extrusion, aging, and post curing that the sample of the cable material experiences at the plant.
rPP/rPET rPP/rPS	Zander *et al.* (2019)	Evaluated the feasibility of extruding rPP/rPET and rPP/PS blends, with or without compatibilizers.	• Successful extrusion of the filament blends.	• TS of the filament was comparable to lower-end commercial filaments such as HIPS

Appendix C: Extrusion Experimental Results - ABS

Table C1: ABS extrusion experimental results.

Experiment	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	Extruder Speed (RPM)	Puller Speed	Remarks
ABS 1	228	239	248	245	5	30	• polymer bubbling as it exits the extruder: due to high temperatures; • some smoke is also noticeable exiting the extruder: also due to the high temperatures; • since there are bubbles, there might be voids; • irregular shape (not round); • high diameter fluctuation; • texture is not smooth; • filament is brittle (cannot be spooled);
ABS 2	228	239	248	245	5	40	• same issues; • diameter decrease;
ABS 3	228	239	248	245	5	50	• same issues; • diameter decrease;
ABS 4	228	239	248	245	10	30	• polymer bubbling as it exits the extruder: due to high temperatures; • some smoke is also noticeable exiting the extruder: also due to the high temperatures; • since there are bubbles, there might be voids; • irregular shape (not round); • diameter fluctuation less noticeable to naked eye; • texture is not smooth • filament is brittle (cannot be spooled); • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed;
ABS 5	228	239	248	245	10	40	• same issues; • diameter decrease;
ABS 6	228	239	248	245	10	50	• same issues; • diameter decrease;
ABS 7	218	229	238	235	5	30	• polymer bubbling as it exits the extruder (less than with higher temperatures): due to high temperatures; • some smoke is also noticeable exiting the extruder (less than with higher temperatures): also due to the high temperatures; • since there are bubbles, there might be voids; • irregular shape (not round); • high diameter fluctuation; • texture is not smooth; • filament is brittle (cannot be spooled);
ABS 8	218	229	238	235	5	40	• same issues; • diameter decrease; • very high diameter fluctuation;
ABS 9	218	229	238	235	5	50	• same issues; • diameter decrease; • very high diameter fluctuation;
ABS 10	218	229	238	235	10	30	• polymer bubbling as it exits the extruder (less than previsouly): due to high temperatures; • since there are bubbles, there might be voids; • irregular shape (not round); • high diameter fluctuation; • texture is not smooth; • filament is brittle (cannot be spooled); • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed;
ABS 11	218	229	238	235	10	40	• same issues; • diameter decrease; • very high diameter fluctuation;
ABS 12	218	229	238	235	10	50	• same issues; • diameter decrease; • very high diameter fluctuation;
ABS 13	208	219	228	225	5	30	• polymer bubbling as it exits the extruder (less than previsouly): due to high temperatures; • visible voids; • irregular shape (not round); • very high diameter fluctuation; • texture is not smooth; • filament is brittle (cannot be spooled); • stringing;
ABS 14	208	219	228	225	5	40	• same issues; • diameter decrease;
ABS 15	208	219	228	225	5	50	• same issues; • diameter decrease;
ABS 16	208	219	228	225	10	30	• polymer bubbling as it exits the extruder (less than with higher temperatures): due to high temperatures; • visible voids; • irregular shape (not round and less than previously); • very high diameter fluctuation; • texture is not smooth; • filament is brittle (cannot be spooled); • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • stringing;
ABS 17	208	219	228	225	10	40	• same issues; • diameter decrease;
ABS 18	208	219	228	225	10	50	• same issues; • diameter decrease; • noticeable diameter fluctuation;
ABS 19	198	209	218	215	5	30	• polymer bubbling as it exits the extruder (less than with higher temperatures): due to high temperatures; • visible voids; • irregular shape (not round and less than previously); • very high diameter fluctuation; • texture is not smooth; • stringing; • filament is less brittle;
ABS 20	198	209	218	215	5	40	• same issues; • diameter decrease;
ABS 21	198	209	218	215	5	50	• inconsistent results: the polymer had very different behaviours, large throughput then small, and so, very high diameter fluctutions;
ABS 22	198	209	218	215	10	30	• few bubbles; • more regular shape; • less diameter discrepancy; • texture is not smooth; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • stringing;
ABS 23	198	209	218	215	10	40	• same issues; • diameter decrease; • stringing;
ABS 24	198	209	218	215	10	50	• same issues; • diameter decrease; • stringing;
ABS 25	188	199	208	205	5	30	• no issues;
ABS 26	188	199	208	205	5	40	• no issues; • decrease of diameter
ABS 27	188	199	208	205	5	50	• no issues; • decrease of diameter
ABS 28	188	199	208	205	10	30	• no issues; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed;
ABS 29	188	199	208	205	10	40	• no issues; • decrease of diameter
ABS 30	188	199	208	205	10	50	• no issues; • decrease of diameter

Appendix D: Extrusion Experimental Results - HDPE

Table D1: HDPE extrusion experimental results.

Experiment	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	Extruder Speed (RPM)	Puller Speed	Remarks
HDPE 1	191	208	228	228	5	30	• no issues;
HDPE 2	191	208	228	228	5	40	• no issues; • diameter decrease;
HDPE 3	191	208	228	228	5	50	• no issues; • diameter decrease;
HDPE 4	191	208	228	228	10	30	• some swiling: as temperature is high and the extruder speed increased, the cooling time is not enough, causing swirling at the downstream of the puller; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • potentially due to inefficient puller equipment: if it would be followed directly into a spool this issue probably would not occur due to traction;
HDPE 5	191	208	228	228	10	40	• swirling; • diameter decrease;
HDPE 6	191	208	228	228	10	50	• swirling; • diameter decrease;
HDPE 7	181	198	218	218	5	30	• no issues;
HDPE 8	181	198	218	218	5	40	• no issues; • diameter decrease;
HDPE 9	181	198	218	218	5	50	• no issues; • diameter decrease;
HDPE 10	181	198	218	218	10	30	• some swiling: as temperature is high and the extruder speed increased, the cooling time is not enough, causing swirling at the downstream of the puller; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • potentially due to inefficient puller equipment: if it would be followed directly into a spool this issue probably would not occur due to traction;
HDPE 11	181	198	218	218	10	40	• swirling; • diameter decrease;
HDPE 12	181	198	218	218	10	50	• swirling; • diameter decrease;
HDPE 13	171	188	208	208	5	30	• no issues;
HDPE 14	171	188	208	208	5	40	• no issues; • diameter decrease;
HDPE 15	171	188	208	208	5	50	• no issues; • diameter decrease;
HDPE 16	171	188	208	208	10	30	• some swiling: as temperature is high and the extruder speed increased, the cooling time is not enough, causing swirling at the downstream of the puller; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • potentially due to inefficient puller equipment: if it would be followed directly into a spool this issue probably would not occur due to traction;
HDPE 17	171	188	208	208	10	40	• swirling; • diameter decrease;
HDPE 18	171	188	208	208	10	50	• swirling; • diameter decrease;
HDPE 19	161	178	198	198	5	30	• no issues;
HDPE 20	161	178	198	198	5	40	• no issues; • diameter decrease;
HDPE 21	161	178	198	198	5	50	• no issues; • diameter decrease;
HDPE 22	161	178	198	198	10	30	• some swirling (less than with higher temperatures): as temperature is high and we increased the exrtuder rpm, the cooling time is not enough and swirls in the downstream of the puller; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • potentially due to inefficient puller equipment: if it would be followed directly into a spool this issue probably would not occur due to traction;
HDPE 23	161	178	198	198	10	40	• swirling; • diameter decrease;
HDPE 24	161	178	198	198	10	50	• swirling; • diameter decrease;
HDPE 25	151	168	188	188	5	30	• no issues;
HDPE 26	151	168	188	188	5	40	• no issues; • diameter decrease;
HDPE 27	151	168	188	188	5	50	• no issues; • diameter decrease;
HDPE 28	151	168	188	188	10	30	• some swirling (less than with higher temperatures): as temperature is high and we increased the exrtuder rpm, the cooling time is not enough and swirls in the downstream of the puller; • diameter increase (compared to 5 RPM, all else constant): due to higher throughput caused by the increase of extruder speed; • potentially due to inefficient puller equipment: if it would be followed directly into a spool this issue probably would not occur due to traction;
HDPE 29	151	168	188	188	10	40	• swirling; • diameter decrease;
HDPE 30	151	168	188	188	10	50	• swirling; • diameter decrease;

Appendix E: 3DP Experimental Results - PET/PETG Cylinders

Table E1: Experimental 3DP input parameters for PET and PETG. Printer X and Y are Bowden extruders, while printer Z is direct drive

	Experiments								
3D Printer	**X**	**X**	**X**	**X**	**Y**	**Y**	**Z**	**Z**	**Z**
3DP Parameters	PETG (B)	PETG W300 (B)	PETG_1.1	PETG_1.2	PETG_1.3	PETG_1.4	PET_Virgin_1.1	PET_Virgin_1.2	PET_White_1.1
Nozzle Diamater (mm)	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4
Extrusion Multiplier	1	1,1	1,1	1,1	1,1	1,1	1	1	1
Extrusion Width (mm)	0,48	0,45	0,48	0,48	0,48	0,48	0,48	0,48	0,48
Retraction Distance (mm)	0,8	6	0,5	0,5	0,5	0,5	1,5	1,5	1,5
Retraction Speed (mm/s)	20	60	30	30	30	30	20	20	20
Coast at End	Yes	No	Yes	Yes	Yes	Yes	yes	yes	yes
Coasting Distance (mm)	1	-	1	1	1	2	1	1	1
Extruder Temperature (ºC)	235	230	230	230	230	230	250	250	250
Bed Temperature (ºC)	60	Layer 1 - 60 Layer 2 - 80	70	70	70	70	Layer 1 - 80 Layer 2 - 85	Layer 1 - 80 Layer 2 - 85	Layer 1 - 80 Layer 2 - 85
Ambient Temperature (ºC)	30	30	30	30	30	30	30	30	30
Printing Speed (mm/s)	50	50	50	50	50	50	40	40	40
Outline Underspeed (%)	70	80	80	80	80	80	70	70	70
Top Layer	6	2	6	3	3	4	2	4	4
Bottom Layer	3	2	3	3	3	3	2	3	3
Outline Shells	3	3	2	2	2	2	2	2	2
Infill (%)	20%	20%	20%	20%	20%	20%	10%	10%	10%

Table E3: PET/PETG cylinder samples results.

	3DP Most Common Issues																											
Experiment	Not extruding at start	Not sticking to bed	Under-extrusion	Over-extrusion	Gaps in top layers	Stringing/Oozing	Overheating	Layer shifting	Layer seperation/splitting	Grinding filament	Clogged extruder	Stops extruding mid print	Weak infill	Blobs and zits	Gaps between infill and outline	Curling/rough corners	Scars on top surface	Gaps in floor corners	Lines on the side of print	Vibrations and ringing	Gaps in thin walls	Small features not printed	Inconsistens extrusion	Warping	Poor surface above supports	Dimensional accuracy	Poor Bridging	**Remarks**
PETG (B)														x	x													• defect on the bottom: due to misaligned build plate; • noticeable line along the side as each layer has the same starting point
PETG W300 (B)					x																							• few top layers; • good connection between infill and outfill; • small extrusion excess on top layers;
PETG_1.1		x																										• poor bottom layers that did not stick properly to the bed: due to misaligned build plate and nozzle far from the build plate • poor bottom balyers led to top layers not extruding the shole diameter of the cylinder and so, the nozzle eventually got stuck and created an accumulation of plastic;
PETG_1.2		x																										• poor bottom layers: due to build plate misaligned;
PETG_1.3					x																							• small gaps no top layer;
PETG_1.4																												• great results;
PET_Virgin_1.1					x						x																	• difficulties in the print at first: extruder got clogged (at 230ºC, so the temperature was increased to 250ºC); • top layer broke: due to very few and thin layers; • few bottom layers; • cylinder not completely solid as a a consequence of the above; • rough surface (compared to PETG);
PET_Virgin_1.2		x																										• defect on the bottom: due to misaligned build plate; • rough surface (compared to PETG);
PET_White_1.1																												• great results; • smooth surface (compared to PET_Virgin);

Figure E1: PETG cylinder samples obtained from the 3DP experimental work.

Appendix F: Ishikawa Diagrams

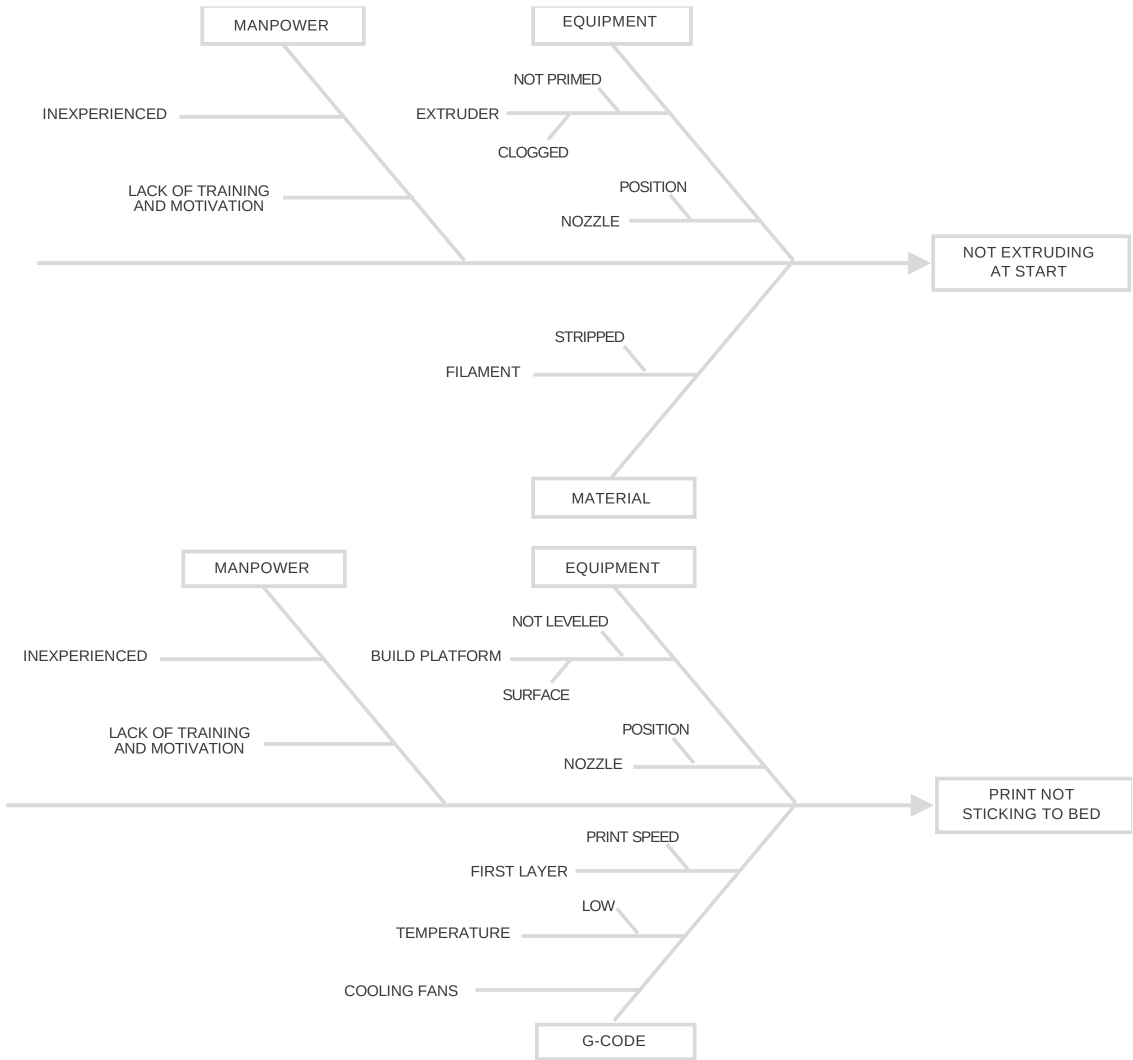

Figure F1: Ishikawa diagrams for 3DP quality problems 5.2.2.1. and 5.2.2.2.

Appendix G: Print Quality Troubleshooting Guide Diagram

PRINT QUALITY TROUBLESHOOTING GUIDE

5.2.2.1 | NOT EXTRUDING AT START

EXTRUDER NOT PRIMED BEFORE PRINT	- INCLUDE SKIRT IN G-CODE
NOZZLE STARTS TOO CLOSE TO BED	- MANUALLY ADJUST BED OR - INCREASE Z-AXIS G-CODE OFFSET
FILAMENT HAS STRIPPED AGAINST DRIVE GEAR	- CHECK "GRINDING FILAMENT"
CLOGGED EXTRUDER	- UNCLOG EXTRUDER

5.2.2.2 | PRINT NOT STICKING TO BED

BED IS NOT LEVELED	- LEVEL BED PROPERLY
NOZZLE STARTS TOO FAR FROM THE BED	- MANUALLY ADJUST BED OR - INCREASE Z-AXIS G-CODE OFFSET
FIRST LAYER PRINT TOO FAST	- DECRESE PRINT SPEED OF THE FIRST LAYER
TEMPERATURE OR COOLING SETTINGS	- INCREASE BED TEMPERATURE - DISABLE COOLING FAN FOR FIRST LAYERS
BUILD SURFACE	- USE A SUITABLE MATERIAL FOR THE BED - STICK TAPE TO BED - APPLY HAIR SPRAY OR GLUE TO BED
WHEN ALL ELSE FAILS	- ADD A BRIM OR A RAFT

5.2.2.3 | UNDER-EXTRUSION || 5.2.2.4 | OVER-EXTRUSION

INCORRECT FILAMENT DIAMETER	- CHECK IF FILAMENT DIAMETER VALUE IS CORRECT IN THE SOFTWARE
EXTRUSION MULTIPLIER	- INCREASE/DECREASE EXTRUSION MULTIPLIER

5.2.2.5 | HOLES AND GAPS IN TOP LAYERS

FEW TOP SOLID LAYERS	- INCREASE TOP SOLID LAYERS
INFILL % TOO LOW	- INCREASE INFILL %
UNDER-EXTRUSION	- CHECK 5.2.2.3

5.2.2.6 | STRINGING

RETRACTION DISTANCE	- INCREASE RETRACTION DISTANCE BY 1 MM
RETRACTION SPEED	- IDEAL BETWEEN 1200-1600 MM/MIN - FINE-TUNE ACCORDING TO FILAMENT
EXTRUDER TEMPERATURE TOO HIGH	- DECREASE TEMPERATURE BY 5-10 DEGREES
X-Y AXIS MOVEMENT SPEED	- INCREASE X-Y-AXIS MOVEMENT SPEED

5.2.2.7 | OVERHEATING

INSUFFICIENT COOLING	- INSTALL EXTERNAL COOLING FAN - INCREASE COOLING FAN SPEED
PRINT TEMPERATURE TOO HIGH	- DECREASE TEMPERATURE
PRINT SPEED TOO FAST	- DECREASE PRINT SPEED
WHEN ALL ELSE FAILS	- PRINT MULTIPLE PARTS AT ONCE

5.2.2.8 | LAYER SHIFTING OR MISALIGNMENT

TOOLHEAD MOVING TOO FAST	- DECREASE PRINTING SPEED - DECREASE X-Y AXIS MOVEMENT SPEED

5.2.2.9 | LAYER SEPARATION

LARGE LAYER HEIGHT	- DECREASE LAYER HEIGHT (SHOULD BE 20% SMALLER THAN NOZZLE DIAMETER)
PRINT TEMPERATURE TOO LOW	- INCREASE TEMPERATURE BY 10 DEGREES

5.2.2.10 | GRINDING FILAMENT

AGGRESSIVE RETRACTION SETTINGS	- DECREASE RETRACTION SPEED BY 50%
EXTRUDER TEMPERATURE	- INCREASE TEMPERATURE BY 5-10 DEGREES
PRINT SPEED TOO FAST	- DECREASE PRINT SPEED
CLOGGED NOZZLE	- CHECK 5.2.2.11

5.2.2.11 | CLOGGED EXTRUDER

- MANUALLY PUSH FILAMENT INTO EXTRUDER
- RELOAD FILAMENT
- CLEAN NOZZLE

5.2.2.12 | STOPS EXTRUDING MID-PRINT

OUT OF FILAMENT	- LOAD NEW SPOOL
FILAMENT STRIPPED AGAINST DRIVE GEAR	- CHECK 5.2.2.10
CLOGGED EXTRUDER	- CHECK 5.2.2.11
OVERHEATED EXTRUDER MOTOR DRIVE	- TURN OFF PRINTER TO ALLOW ELECTRONICS TO COOL DOWN

5.2.2.13 | WEAK INFILL

- CHANGE INFILL PATTERNS
- LOWER PRINT SPEED

5.2.2.14 | BLOBS AND ZITS

RETRACTION AND COASTING SETTINGS	- *DEFECT AT BEGINNING:* INSERT A NEGATIVE VALUE FOR EXTRA RESTART DISTANCE - *DEFECT AT THE MID-END:* DECREASE COASTING DISTANCE (SHOULD BE BETWEEN 0.2-0.5 MM)
SELECT LOCATION OF START POINTS	- MANUALLY INSERT XY COORDINATES FOR STARTING POINTS

5.2.2.15 | GAPS BETWEEN INFILL AND OUTLINE

NOT ENOUGH OUTLINE OVERLAP	- INCREASE OUTLINE OVERLAP
PRINT SPEED TOO FAST	

5.2.2.16 | CURLING OR ROUGH CORNERS

PRINT NOT STICKING TO BED	- DECREASE PRINT SPEED BY 50% - CHECK 5.2.2.2
OVERHEATING	- CHECK 5.2.2.7

5.2.2.17 | SCARS ON TOP SURFACE

EXTRUDING TOO MUCH PLASTIC	- CHECK 5.2.2.4

5.2.2.18 | HOLES AND GAPS IN FLOOR CORNERS

NOT ENOUGH PERIMETERS	- INCREASE NUMBER OF OUTLINE SHELLS
NOT ENOUGH TOP SOLID LAYERS	- INCREASE NUMBER OF TOP SOLID LAYERS
INFILL % TOO LOW	- INCREASE INFILL %

5.2.2.19 | LINES ON THE SIDE OF PRINT

INCONSISTENT EXTRUSION	- CHECK 5.2.2.23
TEMPERATURE FLUCTUATION	- RECALIBRATE PID CONTROLLER

5.2.2.20 | VIBRATIONS AND RINGING

PRINT SPEED TOO FAST	- DECREASE PRINTING SPEED - DECREASE X-Y AXIS MOVEMENT SPEED

5.2.2.21 | GAPS IN THIN WALLS

- CHANGE EXTRUSION WIDTH TO FIT BETTER

5.2.2.22 | VERY SMALL FEATURES NOT BEING PRINTED

- REDESIGN MODEL TO HAVE THICKER FEATURES
- INSTALL A NOZZLE WITH A SMALLER SIZED TIP

5.2.2.23 | INCONSISTENT EXTRUSION

FILAMENT IS GETTING STUCK OR TANGLED	- GUARANTEE SPOOL ROTATES FREELY AND THAT PLASTIC IS EASILY UNWOUND
CLOGGED EXTRUDER	- CHECK 5.2.2.11
VERY LOW LAYER HEIGHT	- INCREASE LAYER HEIGHT
INCORRECT EXTRUSION WIDTH	- SHOULD BE WITHIN 100-150% OF THE NOZZLE DIAMETER
POOR QUALITY FILAMENT	- REPLACE SPOOL WITH A NEW, UNOPEN, HIGH-QUALITY FILAMENT

5.2.2.24 | WARPING

- USE A HEATED BED
- DISABLE FAN COOLING
- USE A HEATED ENCLOSURE
- ADD BRIMS AND RAFTS

Figure G1: Print quality troubleshooting guide diagram.

Appendix H: Layout Proposal - Medium Capacity

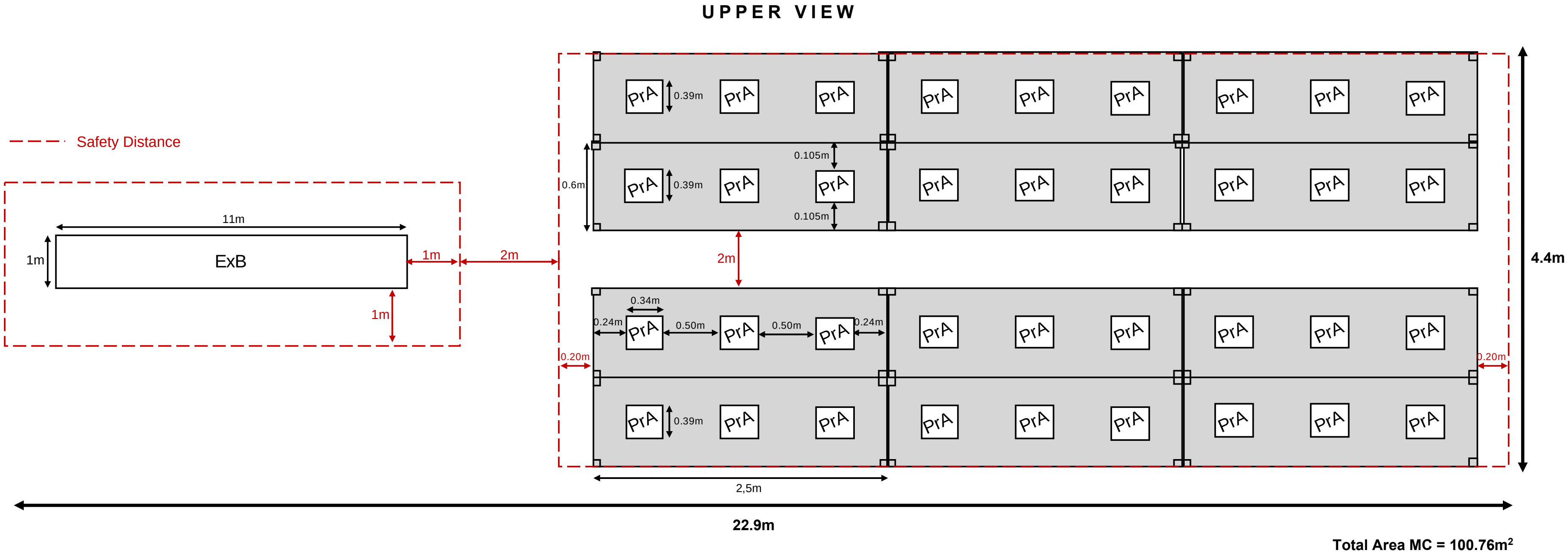

Figure H1: Layout proposal for implementing the downstream waste valorization solution with a medium capacity (the diagram is not to scale).

Appendix I: Layout Proposal - High Capacity

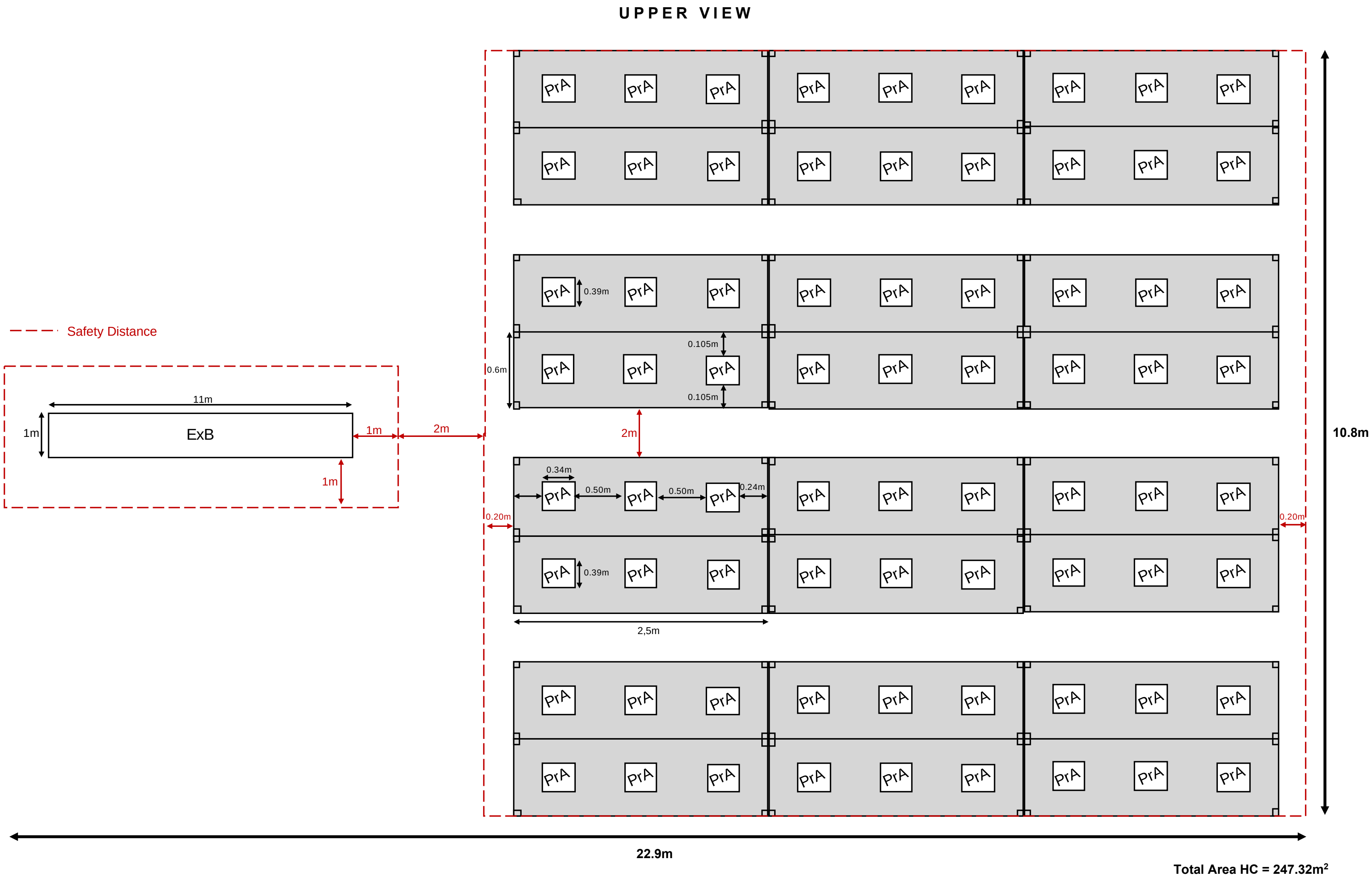

Figure I1: Layout proposal for implementing the downstream waste valorization solution with a high capacity (the diagram is not to scale).

Appendix J: Project Appraisal - Low Capacity

Table J1: Cash flow statement of the LC - rFil scenario.

LC - rFil

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 38 004,00										
	Extruders	- 31 670,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											7 600,80
3	**Investment Cash Flows**	- 38 004,00										7 600,80
4	**Income**		1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00
5	**Operating Expenses**		- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44
8	**EBIAT**		1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45
9	**Operating Cash Flows**		1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85
10	**Total Cash Flows**	- 38 004,00	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 131 218,65

Table J2: Cash flow statement of the LC - P1 scenario.

LC - P1

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 91 284,00										
	3D Printers	- 44 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 8 880,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											18 256,80
3	**Investment Cash Flows**	- 91 284,00										18 256,80
4	**Income**		1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40	1 676 230,40
5	**Operating Expenses**		- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23
	3DP Printers		- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		1 567 751,41	1 567 751,41	1 567 751,41	1 567 751,41	1 567 751,41	1 578 407,41	1 578 407,41	1 578 407,41	1 578 407,41	1 578 407,41
8	**EBIAT**		1 238 523,61	1 238 523,61	1 238 523,61	1 238 523,61	1 238 523,61	1 246 941,85	1 246 941,85	1 246 941,85	1 246 941,85	1 246 941,85
9	**Operating Cash Flows**		1 252 980,01	1 252 980,01	1 252 980,01	1 252 980,01	1 252 980,01	1 250 742,25	1 250 742,25	1 250 742,25	1 250 742,25	1 250 742,25
10	**Total Cash Flows**	- 91 284,00	1 252 980,01	1 252 980,01	1 252 980,01	1 252 980,01	1 252 980,01	1 250 742,25	1 250 742,25	1 250 742,25	1 250 742,25	1 268 999,05

Table J3: Cash flow statement of the LC - P2 scenario.

LC - P2

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 91 284,00										
	3D Printers	- 44 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 8 880,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											18 256,80
3	**Investment Cash Flows**	- 91 284,00										18 256,80
4	**Income**		1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20	1 739 561,20
5	**Operating Expenses**		- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23
	3DP Printers		- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		1 631 082,21	1 631 082,21	1 631 082,21	1 631 082,21	1 631 082,21	1 641 738,21	1 641 738,21	1 641 738,21	1 641 738,21	1 641 738,21
8	**EBIAT**		1 288 554,95	1 288 554,95	1 288 554,95	1 288 554,95	1 288 554,95	1 296 973,19	1 296 973,19	1 296 973,19	1 296 973,19	1 296 973,19
9	**Operating Cash Flows**		1 303 011,35	1 303 011,35	1 303 011,35	1 303 011,35	1 303 011,35	1 300 773,59	1 300 773,59	1 300 773,59	1 300 773,59	1 300 773,59
10	**Total Cash Flows**	- 91 284,00	1 303 011,35	1 303 011,35	1 303 011,35	1 303 011,35	1 303 011,35	1 300 773,59	1 300 773,59	1 300 773,59	1 300 773,59	1 319 030,39

Table J4: Cash flow statement of the LC - P3 scenario.

LC - P3

		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 91 284,00										
	3D Printers	- 44 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 8 880,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											18 256,80
3	**Investment Cash Flows**	- 91 284,00										18 256,80
4	**Income**		2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20	2 474 139,20
5	**Operating Expenses**		- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59	- 94 022,59
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44	- 59 232,44
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23	- 4 952,23
	3DP Printers		- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67	- 1 973,67
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 14 456,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00	- 10 656,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		2 365 660,21	2 365 660,21	2 365 660,21	2 365 660,21	2 365 660,21	2 376 316,21	2 376 316,21	2 376 316,21	2 376 316,21	2 376 316,21
8	**EBIAT**		1 868 871,57	1 868 871,57	1 868 871,57	1 868 871,57	1 868 871,57	1 877 289,81	1 877 289,81	1 877 289,81	1 877 289,81	1 877 289,81
9	**Operating Cash Flows**		1 883 327,97	1 883 327,97	1 883 327,97	1 883 327,97	1 883 327,97	1 881 090,21	1 881 090,21	1 881 090,21	1 881 090,21	1 881 090,21
10	**Total Cash Flows**	- 91 284,00	1 883 327,97	1 883 327,97	1 883 327,97	1 883 327,97	1 883 327,97	1 881 090,21	1 881 090,21	1 881 090,21	1 881 090,21	1 899 347,01

Appendix K: Project Appraisal - Medium Capacity

Table K1: Cash flow statement of the MC - rFil scenario.

	MC - rFil										
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 38 004,00										
	Extruders	- 31 670,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											7 600,80
3	**Investment Cash Flows**	- 38 004,00										7 600,80
4	**Income**		1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00
5	**Operating Expenses**		- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44
8	**EBIAT**		1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45
9	**Operating Cash Flows**		1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85
10	**Total Cash Flows**	- 38 004,00	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 131 218,65

Table K2: Cash flow statement of the MC - P1 scenario.

	MC - P1										
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 357 684,00										
	3D Printers	- 266 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 53 280,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											71 536,80
3	**Investment Cash Flows**	- 357 684,00										71 536,80
4	**Income**		2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40	2 569 382,40
5	**Operating Expenses**		- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57
	3DP Printers		- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		2 350 535,78	2 350 535,78	2 350 535,78	2 350 535,78	2 350 535,78	2 414 471,78	2 414 471,78	2 414 471,78	2 414 471,78	2 414 471,78
8	**EBIAT**		1 856 923,27	1 856 923,27	1 856 923,27	1 856 923,27	1 856 923,27	1 907 432,71	1 907 432,71	1 907 432,71	1 907 432,71	1 907 432,71
9	**Operating Cash Flows**		1 924 659,67	1 924 659,67	1 924 659,67	1 924 659,67	1 924 659,67	1 911 233,11	1 911 233,11	1 911 233,11	1 911 233,11	1 911 233,11
10	**Total Cash Flows**	- 357 684,00	1 924 659,67	1 924 659,67	1 924 659,67	1 924 659,67	1 924 659,67	1 911 233,11	1 911 233,11	1 911 233,11	1 911 233,11	1 982 769,91

Table K3: Cash flow statement of the MC - P2 scenario.

	MC - P2										
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 357 684,00										
	3D Printers	- 266 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 53 280,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											71 536,80
3	**Investment Cash Flows**	- 357 684,00										71 536,80
4	**Income**		2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20	2 949 367,20
5	**Operating Expenses**		- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57
	3DP Printers		- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		2 730 520,58	2 730 520,58	2 730 520,58	2 730 520,58	2 730 520,58	2 794 456,58	2 794 456,58	2 794 456,58	2 794 456,58	2 794 456,58
8	**EBIAT**		2 157 111,26	2 157 111,26	2 157 111,26	2 157 111,26	2 157 111,26	2 207 620,70	2 207 620,70	2 207 620,70	2 207 620,70	2 207 620,70
9	**Operating Cash Flows**		2 224 847,66	2 224 847,66	2 224 847,66	2 224 847,66	2 224 847,66	2 211 421,10	2 211 421,10	2 211 421,10	2 211 421,10	2 211 421,10
10	**Total Cash Flows**	- 357 684,00	2 224 847,66	2 224 847,66	2 224 847,66	2 224 847,66	2 224 847,66	2 211 421,10	2 211 421,10	2 211 421,10	2 211 421,10	2 282 957,90

Table K4: Cash flow statement of the MC - P3 scenario.

	MC - P3										
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 357 684,00										
	3D Printers	- 266 400,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 53 280,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											71 536,80
3	**Investment Cash Flows**	- 357 684,00										71 536,80
4	**Income**		7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20	7 356 835,20
5	**Operating Expenses**		- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22	- 151 110,22
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73	- 106 451,73
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05	- 62 959,05
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57	- 14 820,57
	3DP Printers		- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01	- 11 842,01
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 67 736,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00	- 63 936,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		7 137 988,58	7 137 988,58	7 137 988,58	7 137 988,58	7 137 988,58	7 201 924,58	7 201 924,58	7 201 924,58	7 201 924,58	7 201 924,58
8	**EBIAT**		5 639 010,98	5 639 010,98	5 639 010,98	5 639 010,98	5 639 010,98	5 689 520,42	5 689 520,42	5 689 520,42	5 689 520,42	5 689 520,42
9	**Operating Cash Flows**		5 706 747,38	5 706 747,38	5 706 747,38	5 706 747,38	5 706 747,38	5 693 320,82	5 693 320,82	5 693 320,82	5 693 320,82	5 693 320,82
10	**Total Cash Flows**	- 357 684,00	5 706 747,38	5 706 747,38	5 706 747,38	5 706 747,38	5 706 747,38	5 693 320,82	5 693 320,82	5 693 320,82	5 693 320,82	5 764 857,62

Appendix L: Project Appraisal - High Capacity

Table L1: Cash flow statement of the HC - rFil scenario.

	HC - rFil											
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 38 004,00										
	Extruders	- 31 670,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											7 600,80
3	**Investment Cash Flows**	- 38 004,00										7 600,80
4	**Income**		1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00	1 497 600,00
5	**Operating Expenses**		- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16	- 76 309,16
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68	- 43 492,68
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44	1 417 490,44
8	**EBIAT**		1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45	1 119 817,45
9	**Operating Cash Flows**		1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85
10	**Total Cash Flows**	- 38 004,00	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 123 617,85	1 131 218,65

Table L2: Cash flow statement of the HC - P1 scenario.

	HC - P1											
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 677 364,00										
	3D Printers	- 532 800,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 106 560,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											135 472,80
3	**Investment Cash Flows**	- 677 364,00										135 472,80
4	**Income**		3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80	3 641 164,80
5	**Operating Expenses**		- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58
	3DP Printers		- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		3 283 581,12	3 283 581,12	3 283 581,12	3 283 581,12	3 283 581,12	3 411 453,12	3 411 453,12	3 411 453,12	3 411 453,12	3 411 453,12
8	**EBIAT**		2 594 029,08	2 594 029,08	2 594 029,08	2 594 029,08	2 594 029,08	2 695 047,96	2 695 047,96	2 695 047,96	2 695 047,96	2 695 047,96
9	**Operating Cash Flows**		2 725 701,48	2 725 701,48	2 725 701,48	2 725 701,48	2 725 701,48	2 698 848,36	2 698 848,36	2 698 848,36	2 698 848,36	2 698 848,36
10	**Total Cash Flows**	- 677 364,00	2 725 701,48	2 725 701,48	2 725 701,48	2 725 701,48	2 725 701,48	2 698 848,36	2 698 848,36	2 698 848,36	2 698 848,36	2 834 321,16

Table L3: Cash flow statement of the HC - P2 scenario.

	HC - P2											
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 677 364,00										
	3D Printers	- 532 800,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 106 560,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											135 472,80
3	**Investment Cash Flows**	- 677 364,00										135 472,80
4	**Income**		4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40	4 401 134,40
5	**Operating Expenses**		- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58
	3DP Printers		- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		4 043 550,72	4 043 550,72	4 043 550,72	4 043 550,72	4 043 550,72	4 171 422,72	4 171 422,72	4 171 422,72	4 171 422,72	4 171 422,72
8	**EBIAT**		3 194 405,07	3 194 405,07	3 194 405,07	3 194 405,07	3 194 405,07	3 295 423,95	3 295 423,95	3 295 423,95	3 295 423,95	3 295 423,95
9	**Operating Cash Flows**		3 326 077,47	3 326 077,47	3 326 077,47	3 326 077,47	3 326 077,47	3 299 224,35	3 299 224,35	3 299 224,35	3 299 224,35	3 299 224,35
10	**Total Cash Flows**	- 677 364,00	3 326 077,47	3 326 077,47	3 326 077,47	3 326 077,47	3 326 077,47	3 299 224,35	3 299 224,35	3 299 224,35	3 299 224,35	3 434 697,15

Table L4: Cash flow statement of the HC - P3 scenario.

	HC - P3											
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
1	**Investment**	- 677 364,00										
	3D Printers	- 532 800,00										
	Extruders	- 31 670,00										
	Install 3D printers	- 106 560,00										
	Install Extruder	- 6 334,00										
2	**Residual Value of Investment (20%)**											135 472,80
3	**Investment Cash Flows**	- 677 364,00										135 472,80
4	**Income**		13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40	13 216 070,40
5	**Operating Expenses**		- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28	- 225 911,28
	Raw Materials		- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08	- 11 278,08
	Salaries		- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78	- 169 410,78
	Engineers		- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92	- 27 752,92
	3DP Technician		- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10	- 125 918,10
	Extrusion Technician		- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76	- 15 739,76
	Energy Consumption		- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58	- 26 662,58
	3DP Printers		- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02	- 23 684,02
	Extruders		- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56	- 2 978,56
	Water Consumption		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
	Extruders		- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84	- 18 559,84
6	**Depreciation**		- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 131 672,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
	3D Printers		- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00	- 127 872,00					
	Extruders		- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40	- 3 800,40
7	**EBIT**		12 858 486,72	12 858 486,72	12 858 486,72	12 858 486,72	12 858 486,72	12 986 358,72	12 986 358,72	12 986 358,72	12 986 358,72	12 986 358,72
8	**EBIAT**		10 158 204,51	10 158 204,51	10 158 204,51	10 158 204,51	10 158 204,51	10 259 223,39	10 259 223,39	10 259 223,39	10 259 223,39	10 259 223,39
9	**Operating Cash Flows**		10 289 876,91	10 289 876,91	10 289 876,91	10 289 876,91	10 289 876,91	10 263 023,79	10 263 023,79	10 263 023,79	10 263 023,79	10 263 023,79
10	**Total Cash Flows**	- 677 364,00	10 289 876,91	10 289 876,91	10 289 876,91	10 289 876,91	10 289 876,91	10 263 023,79	10 263 023,79	10 263 023,79	10 263 023,79	10 398 496,59

Appendix M: Project Appraisal - Sensitivity Analysis

Figure M1: 3DP filament market sensitivity analysis for the MC scenarios.

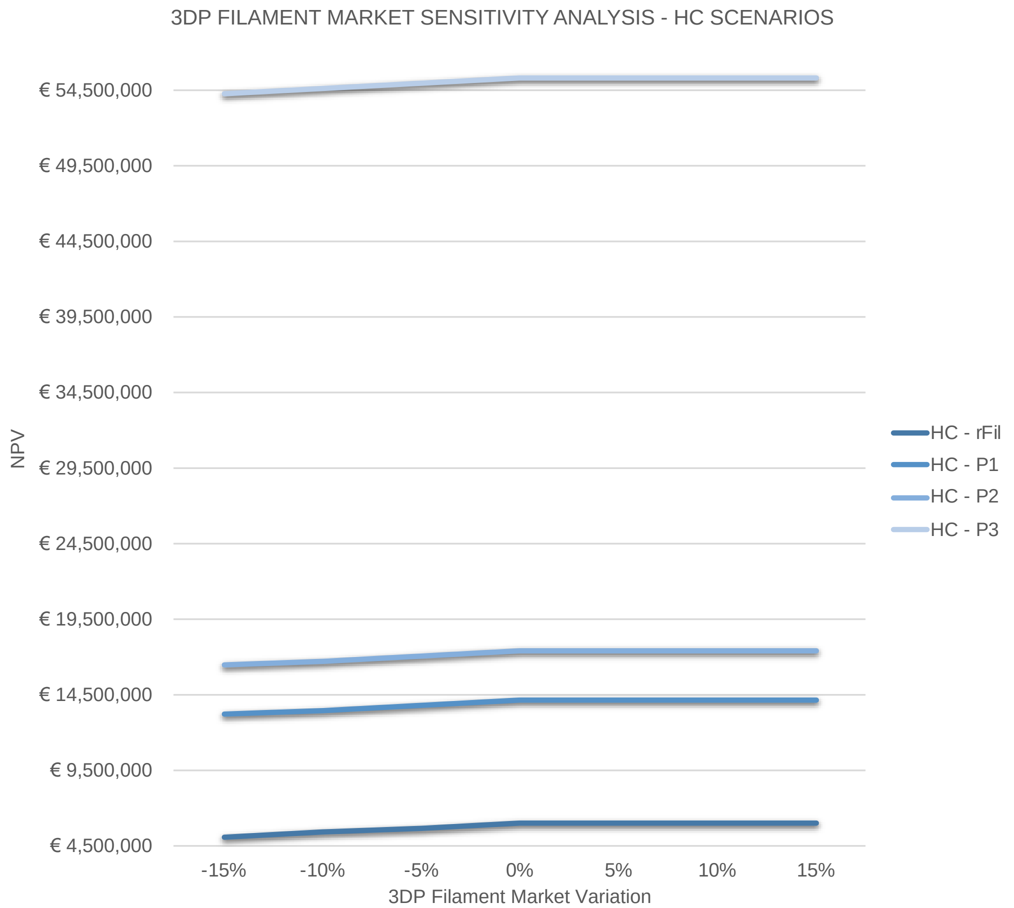

Figure M2: 3DP filament market sensitivity analysis for the HC scenarios.