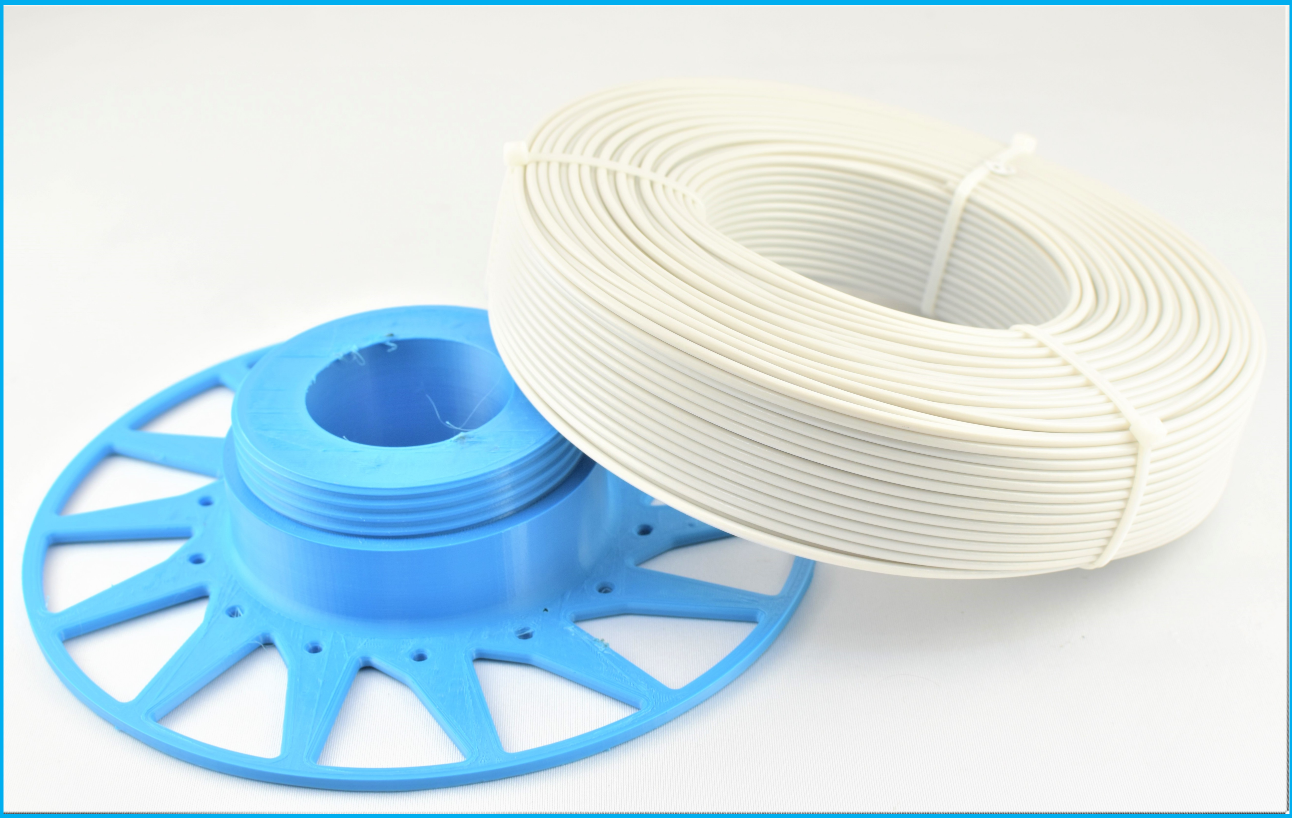
MSc Sustainable Energy Technology

Framework for sustainable recycling in automotive prototyping

The case study of Polyamide 12 in Additive Manufacturing

Ottavia Aleo
2023



MASTER'S THESIS

Framework for sustainable recycling in automotive prototyping
The case study of Polyamide 12 in Additive Manufacturing

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MSC SUSTAINABLE ENERGY TECHNOLOGY

Preface

Improving sustainability in industrial processes is a key topic to contribute to the welfare of the planet. However, sustainability is not depending just on one single factor, it can have many different forms, and they are all interconnected. The technical, environmental, economic, and social aspects of sustainability should be all taken into account when evaluating processes and innovations.

The work arises from the intention to give new life to the manufacturing waste that BMW production workers have to constantly dispose of. Every year, tons of plastic material are discarded from many facilities worldwide: recycling is an idea to attempt to turn these parts into reusable material.

This elaborate signs the end of my academic journey at the Delft University of Technology. The present work has been carried out at the BMW Additive Manufacturing Campus (AMC), in Munich, where I had the possibility to write my thesis after one year of internship. The content of this thesis is meant for readers interested in the technical, environmental, economic, and social analysis of recycling pathways as part of the integration of sustainable practices in automotive prototyping processes. With this work, I would like to combine the technical knowledge in energy technologies that I gained throughout my studies at TU Delft with the professional experience on real industrial processes that BMW offered me, together with my passion for sustainability and interest in environmental issues.

Ottavia Aleo
Munich, February 2022

Acknowledgements

In these following sentences, I would like to thank all the people that contributed to the creation of this elaborate, which was carried out between two different countries, Germany and the Netherlands, and therefore it required a joint effort from everyone involved in it to make this experience both pleasant and effective.

First of all, I would like to thank the facilities, both TU Delft and the BMW Additive Manufacturing Campus, for allowing me to take advantage of spaces, machinery, databases, and knowledge, to complete my work in the best way possible.

I would like to thank my supervisory team. I'd like to thank Paul, that offered me the possibility to stay at BMW after the end of my internship. His approach to work, and the way he makes all difficulties easy to overcome, combined with his experience, values, and global vision always provided me with new perspectives and positive energy.
Thanks to Paola, for her incredible effort in supporting me, for her availability and optimism, for being always inspirational, and for the desire for knowledge that she has transmitted to me in these months of research.
Thanks to Jun, for his help in making the whole project more clear and to the point. His comments were always very effective and meaningful.
I would also like to thank my mentor and main advisor, Zofia, for her time and support, and for her open-mindedness for having accepted my thesis request despite all the challenges that this project might have brought. It was fundamental for me to receive her remarks and points of reflection as they were a real added value to the work.

I would also like to thank all the people that helped me accomplish this work, all the BMW colleagues that gave me their professional advice, support, and feedback, with whom I spent the last year and a half. I am very grateful to have met many different people with different backgrounds and experiences.

My deepest gratitude goes to my friends spread all over the world, that made me feel always loved and never lonely, and to my amazing partner, for his fundamental support and critical eye.

I would like to thank my brothers, and in particular Ignazio, who encouraged and supported me throughout this journey, always helping me to make the right decisions.

Finally, to my parents, without whom all this would not have been possible, for always supporting and encouraging me, for never having doubted my commitment and efforts.

Enjoy reading,
Ottavia

Executive summary

Assessing the sustainability of recycling pathways is challenging. This difficulty comes from the fact that in addition to the technicalities behind the process, there is an extremely broad spectrum of factors that should be addressed, and each one of them would require an expert's point of view to be properly accounted for. The end goal of this work is not only to give a technical explanation of some possibilities to recycle a particular type of plastic, in this case, Polyamide 12 but also to provide a framework for who needs to adopt a recycling pathway in a sustainable way.

Recycling, in general, requires the addition of more processing steps, each of them resource-consuming. Therefore, it is important to find a way to mitigate such adverse effects, while still obtaining a material that has good quality to be used for further processes. The framework is created therefore for defining and selecting the most sustainable recycling pathway, among a set of alternatives, according to businesses' requirements and objectives. The idea behind the work is that for a recycling pathway to be sustainable, it should be evaluated according to technical, environmental, economic, and social criteria, which will be presented throughout the work. Together, these findings, will answer the main question of the work: *how does a framework for sustainable recycling look like and how can it be implemented in the automotive industry?*

Following the description of the framework in general, it will be then applied and therefore validated to a specific case study, which is the recycling of Polyamide 12 wastes from BMW's automotive prototyping, for automotive applications within Additive Manufacturing. For the scope of the work, alternative pathways to recycle Polyamide 12 wastes, a material widely used in the automotive industry to obtain functional parts and prototypes, will be presented. The end goal is to recycle PA12 and turn it into raw material for automotive tooling, but at the same time to perform it in the most sustainable way possible.

To start off, in Chapter 1, an introduction of the problem (on different levels) is presented, both in terms of sustainability assessment in the recycling pathways and for the BMW case. Also, the context (Additive Manufacturing and BMW's role in it) where

the problem lies is presented, to represent the environment where the work has been conducted, in order to draw the proper connections.

Subsequently, Chapter 2 served as a general overview of knowledge base information regarding Additive Manufacturing and 3D printing technologies, required to fully understand the case study.

In Chapter 3 the state of the art of the work has been presented. Here, a literature review regarding all the main three topics (sustainability assessment in recycling procedures, plastic handling, and recycling in Additive Manufacturing (AM)) discussed in the thesis is carried out. Altogether this information supported the definition of the sustainable framework itself and the recycling of Polyamide 12 (PA12) manufacturing waste in AM. With these insights, it is possible to understand where the knowledge gaps about the topic lie, and what is the added value of the work.

Following, a general overview of the framework for the evaluation of the sustainable recycling pathway is presented in Chapter 4. A systematic framework for sustainability assessment consisting of ten steps is explained in detail, step by step. From the problem definition to the potential solution of the problem, the chapter serves as a manual to be followed consistently to evaluate the most appropriate recycling pathway, among a set of alternatives.

The framework is applied to the case study of the work in Chapter 5, following all the steps presented in its general description in Chapter 4. In the context of the case study, the different indicators for each pathway are calculated to compare them. After obtaining all the key factors, the most efficient pathway is evaluated and selected in order to suggest a standard pathway that can be implemented.

To conclude, the results and the challenges encountered throughout the research will be discussed in Chapter 6, to show what it was possible to achieve, what is still open for further research, and what should be done next.

Contents

List of Abbreviations

3D Three-dimensional

ABS Acrylonitrile Butadiene Styrene

AM Additive Manufacturing

AMC Additive Manufacturing Campus

APR Association of Plastic Recyclers

As Arsenic

BBC British Broadcasting Corporation

BMW Bayerische Motoren Werke AG

BWM Best-Worst Method

BTUs British Thermal Units

CAD Computer Aided Design

CE Circular Economy

Cr Chromium

Cu Copper

4DS Four Dimensions of Sustainability

EPA Environmental Protection Agency

EU European Union

FFF Fused Filament Fabrication

FIZ Forschungs- und Innovationszentrum

GDP Gross Domestic Product

GHG Greenhouse Gas

GWP Global Warming Potential

HDPE High-density Polyethylene

LCA Life Cycle Assessment

LCSP Lowell Center for Sustainable Production

LSP Large Scale Printing

MCDM multi-criteria decision-making

MDM Multilevel Design Model

MPW Mixed Plastic Waste

PA Polyamide

PA6 Polyamide 6

PA11 Polyamide 11

PA12 Polyamide 12

Pb Lead

PC Polycarbonate

PCW Post-Consumer Waste

PE Polyethylene

PED Primary Energy Demand

PEEK Polyetheretherketone

PET Polyethylene Terephthalate

PIW Post-Industrial Waste

PLA Polylactic Acid

POPs Persistent Organic Pollutants

PP Polypropylene

PUR Polyurethane

PVC Polyvinyl chloride

rPA12 recycled Polyamide 12

SDG Sustainable Development Goals

SLS Selective Laser Sintering

TPU Thermoplastic Polyurethane

UN United Nations

vPA12 virgin Polyamide 12

WCED World Commission on Environment and Development

WHO World Health Organization

WTE Waste To Energy

WTW Wheel to Wheel

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Chapter 1

Introduction

The thesis aim is the development of a framework for assessing sustainability in recycling pathways for solid materials in the automotive prototyping process. The study has been carried out in the areas and terms that will be indicated immediately below, according to the perspectives of the fundamental issues of product efficiency, production costs, sustainability, energy savings, and conservation.
In this introductory section, a general outline of the topic of the work is presented. Subsequently, an overview of the context where the case study of the work lies will be provided, to further move on to the problem definition which is the motivation to apply the framework to the specific case study of recycling Polyamide 12 plastic automotive waste.

1.1 The general topic

The topic of this elaborate is the formulation of a framework for the design and assessment of the sustainability of recycling pathways, that can bring together the evaluation of technical, environmental, economic, and social criteria. In modern times, recycling pathways are gaining increasing popularity as sustainable processes for reusing resources and materials. Many companies throughout the world are looking for ways to manage material waste, as national and international environmental rules are becoming more stringent, and one of these ways is recycling. However, not all recycling pathways are sustainable at the same level as they involve many different steps, technologies, resources, the release of chemicals, and actors, among others. All these aspects, if not managed properly, can be the cause of potential issues, either in the short or long term. Therefore, a way to consider all the relevant factors that are involved in a recycling pathway is needed. The framework provided in this work is meant to serve for the design and evaluation of sustainable recycling pathways, by considering criteria within four dimensions of sustainability which are technical, environmental, economic, and social. This framework has been developed and is meant to be applied for the recycling of solid materials that are adopted within the automotive prototyping industry.

1.2 The case study

To assess the applicability of the framework a case study has been selected. The case study is focused on Polyamide 12 recycling from prototyping automotive waste to raw material for Additive Manufacturing technologies for automotive prototyping as well. The framework for sustainable recycling will therefore be adopted in this case study, in order to select the most appropriate recycling pathway for Polyamide 12 according to BMW's objectives.

1.2.1 The context

The Bayerische Motoren Werke AG (BMW) Group is one of the world's leading premium manufacturers of automobiles and motorcycles. The company headquarters is in Munich, while the production of motor vehicles is based in many countries: Germany, Brazil, China, India, Mexico, the Netherlands, South Africa, the United Kingdom, and the United States (BMW Group, 2021; Perillo BMW, 2022).

The origin of all BMW's vehicles takes place at a special facility located in Munich, the so-called Research and Innovation Center (in German: Forschungs- und Innovationszentrum (FIZ)). Here, the assembly and improvement of the prototypes are carried out, before the official production line of future models is subsequently launched into mass production.

As it will be discussed, in dynamic procedures such as prototyping, AM, commonly known as Three-dimensional (3D) printing, is widely used to substitute traditional manufacturing techniques.

In this regard, BMW Group is a leader in industrial-scale 3D printing, bringing together the production of prototype and series parts, research into 3D printing technologies, and associate training in tool-less manufacturing (BMW Group, 2020). Currently, AM applications in the automotive industry are multiple. They, indeed, involve the pre-production of the vehicle to tooling for the mechanics in the different prototyping phases, as well as the production of a few pieces in the actual series vehicles.

1.2.2 Problem definition

The AMC (Additive Manufacturing Campus) is where most of the Polyamide 12 (PA12) is processed among all the different BMW facilities. In 2021, 6800 kg of white PA12 powder was purchased just for its utilization in Selective Laser Sintering (SLS) technologies. All of these PA12 parts produced out of SLS, are usually ordered both internally (from other BMW departments) and externally. In 2021 as well, an amount of 46041 PA12 parts (corresponding to 679.677.961 mm^3) were dispatched just internally, to other BMW departments from the AMC. As will be discussed later, most of these parts are mainly adopted for prototyping and have a limited lifetime, ending up in leftovers. Together with the waste parts, a huge amount of plastic PA12 waste comes in the form of powder. Indeed, the powder, during SLS processes ages and therefore it can't be re-used completely for the same technology. It was calculated that the amount of powder waste coming from the SLS production (from just two printers) in the AMC, accounts roundabout for 11 tons per year.

On the other hand, PA12 is just one of the main materials adopted by BMW, and more in general, in the automotive industry. Moreover, plastic comes in many other forms worldwide. The "plastic issue" is for sure not an isolated BMW problem; plastic pollution represents one of the most urgent environmental issues to deal with in modern society (Parker, 2019). The production of plastic has grown exponentially in just a few decades - from 1.5 million tonnes in 1950 to 359 million tonnes in 2018 worldwide (European Parliament, 2018). And numbers keep increasing: every year, more than 380 million tonnes of plastic are produced worldwide, and therefore, eliminated once the product reaches the end of its life (Ritchie & Roser, 2018). According to British Broadcasting Corporation (BBC), just 16% of plastic waste is recycled to make new plastics, while 40% is sent to landfill, 25% to incineration, and 19% is discarded (Latham, 2021). On a global level, in 2015, about 4% of Greenhouse Gas (GHG) emissions were attributed to the manufacture and use of plastics (Zheng & Suh, 2019). In the same year, 7% of all plastics were produced for the automotive industry (Geyer et al., 2017). As GHG emissions must be reduced to zero by 2050 to avoid disastrous climate disruption, it is necessary to address the situation as soon as possible and to adopt specific solutions for each issue related to plastic consumption (IPCC, 2018). Currently, in the European Union (EU), the automotive sector consumes about 25% of all aluminium, 12% of all steel and 9% of all plastics (Material Economics, 2018). Plastic has become one of the key materials required for the structure, performance, and safety of automobiles in recent years. Increasing trends of light weighting for fuel efficiency and low GHG emissions are just one of the factors that have been driving plastic consumption in the automotive sector. It is also worth mentioning the freedom in design that plastic provides compared to metals. The role of plastic in the design and manufacturing of automotive vehicles is fundamental.

Although one-third of modern vehicles' parts are made out of plastic, the consumption of it doesn't come just from the elements and inserts that are being used in the vehicles sold in the market. A high share of the automotive industry's plastic consumption comes from prototyping. Automotive prototypes, indeed, play a fundamental role in the development of a vehicle. The multiple prototyping phases are integral parts of the entire automotive engineering process, and in most of these phases, plastic is widely used for its mechanical properties/characteristics (Elverum & Welo, 2015).

However, plastic prototypes for vehicle production have a limited lifetime. Many different reasons can bring to the discard of a prototype part. First of all, at the end of the prototyping stages, when the vehicle is already in the production phases, the prototypes for that particular model are not useful anymore. Secondly, the parts could have been used for safety tests such as crash tests and thus be compromised, or damaged, if not cracked. Moreover, during prototyping, designs are analyzed, evaluated, and if needed updated. Therefore, past and outdated designs are then no longer useful. Lastly, while in the past the lifespan of a vehicle model was 12 or even 15 years, nowadays the first modifications are made after two years and a new model is produced after 4 years (MK Technology, 2022). This requires, of course, the constant production of always new designs and parts, at a much higher rate than in the past.

At this point, a solution is needed for these plastic prototypes that are no longer used. Although plastic recycling today is a very sensitive topic because of the multiple challenges that arise when it comes to turning plastic into raw material, mechanical recycling can actually represent a valid solution for most of the plastics adopted in automotive prototyping. The main challenge that always is considered when it comes to plastic recycling is indeed the sorting of the material (Stanfield, 2021). Each type of plastic has its own composition and characteristics, moreover, they might also include different chemical additives and colorants that cannot be recycled together, making it very challenging to sort all the plastic that is disposed of worldwide. On the other hand, the automotive industry represents a smaller and more organized part of this problem. More than 70% of the plastic used in the automotive sector comes from four polymers: Polypropylene (PP), Polyurethane (PUR), Polyamide (PA), and Polyvinyl chloride (PVC) (Khemka, 2019). The automotive industry is the third most important consuming sector of polymers after packaging and building and construction (OECO, 2022). That being said, the chances to have an easier process to sort the end-of-life prototypes from a particular material is definitely higher.

Lastly, the reprocessing of plastic waste is wasteful (Stanfield, 2021). All the steps involved in mechanical recycling, are at the same time energy intensive and expensive. The process itself consumes energy and resources. In most cases, recycling can be considered energy efficient because processing recycled materials uses less energy than processing new materials, but that depends also on the material. For recycling to be energy efficient, the amount of energy used for it must be less than the amount of energy used to process new materials (Enck & Dell, 2022). When it comes to plastic, it is also important to consider that this material weakens each time it is being processed, therefore there is a limit after which recycling it might not be efficient anymore (Stanfield, 2021). All this being said, the purpose of this study is to provide a framework for sustainable recycling in industrial processes, adopting as a case study a technical, economical, environmental, and social analysis on recycling Polyamide 12 parts produced via SLS, which is an AM technology mainly used for prototyping. The focus will be on turning these parts into usable materials for another AM technology (Fused Filament Fabrication) for additive applications such as tooling, to ensure the material is recycled within the automotive industry (to close the loop).

Chapter 2

Conceptual background

The aim of this work is to create a framework for designing and evaluating sustainable recycling pathways in manufacturing processes within the automotive industry. In this context, the case study will be to evaluate the adoption of recycling techniques for Polyamide 12, a material commonly used for prototyping via Additive Manufacturing in the automotive industry. Therefore, in this chapter, Additive Manufacturing technologies and the material Polyamide 12, will be discussed, to provide the reader with the basic concepts necessary to link these topics. The chapter starts with the origin and development of AM, moving then on to its role in the automotive industry. Subsequently, the specific technologies (Selective Laser Sintering and Fused Filament Fabrication) and materials (Polyamide 12) that constitute the basis of this research are investigated and discussed. The following section presents an overview with preliminary definitions, especially about Additive Manufacturing, which is essential to picture the context where the topic lies.

2.1 Additive Manufacturing

As PA12 is a material used by BMW mostly in Additive Manufacturing, it is important to provide background information regarding the technologies adopted and their breakthrough within the automotive industry. The two main AM technologies used in this research (Selective Laser Sintering and Fused Filament Fabrication) are defined, as well as the material (Polyamide 12) selected for recycling and re-purposing.

2.1.1 Context

Additive Manufacturing is referred to as an automated process for producing scaled, three-dimensional physical products from 3D Computer Aided Design (CAD) data. The process is based on the principle of layer manufacturing (Gebhardt et al., 2019). It consists in adding successive layers of material to create an object: this technique clearly differs from traditional manufacturing processes, which are determined by the subtraction of material from a solid, to obtain the desired shape (Linke, 2017). AM processes, therefore, don't require any part-dependent tool, which enables not only to save costs with respect to conventional manufacturing methods (e.g. injection molding) but also to reduce lead times. The first approaches to AM processes were released in the late '80s, where "rapid prototyping" was the most common way to denominate such practice. Nowadays the term "3D printing", as the generic term for all automated layer manufacturing processes, is accepted worldwide (Gebhardt et al., 2019). Being the technical performance of any process involved in AM exclusively based on layers, the related technology is commonly called "layer-based technology", as well as "layered technology" (Gebhardt et al., 2019); an example can be found in Figure 1.

The basic process chain (the core steps constituting most of the AM processes) can be divided into two levels: a virtual level and a physical one, as it is shown in Figure 2. The virtual level concerns the generation of mathematical layers of information, and it starts with the generation of a 3D CAD data file, which represents the part to be created. Subsequently, specific software divides the data set into slices (indeed, layers), in order to obtain contour data, thickness data, and layers number. These data files are then transmitted to a machine where the actual printing process takes place.

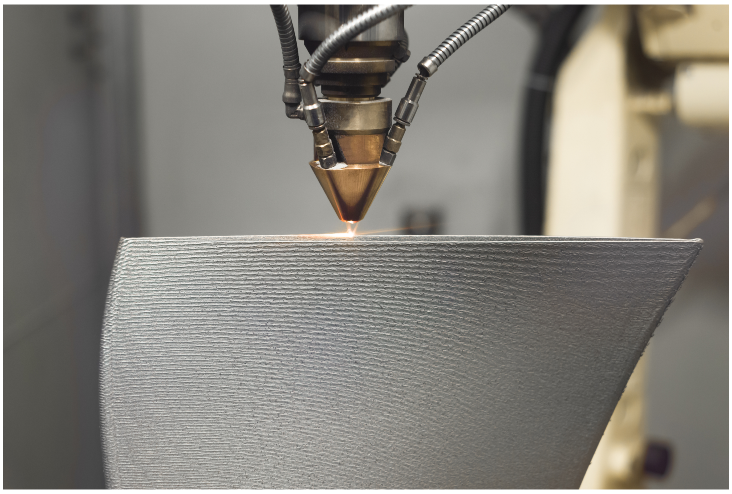


Figure 1 *Example of Layer Manufacturing (Franco, 2019)*

In the printing process is when the physical level (the generation of the physical component) begins. By first generating each layer according to the defined contour and layer thickness and then merging the layers on top of each other, the 3D printer adds layer by layer from the bottom to the top until the part is finalized (Gebhardt et al., 2019). This process chain is the same for more than 200 different AM machines. The main differences lie mainly in how a single layer is generated and how the layers are connected together (Gebhardt et al., 2019).

The selection of the most suitable additive manufacturing process is based on the requirements for a specific application. According to the type of application, AM technologies can be distinguished in ”rapid prototyping” and ”rapid manufacturing”, as it is shown in Figure 3.

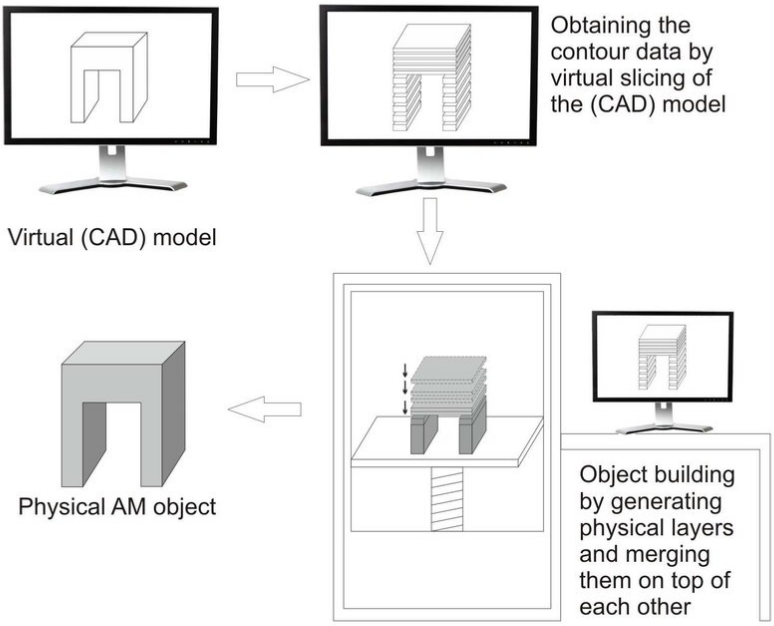


Figure 2 *Basic principle of AM process (Raos et al., 2015)*

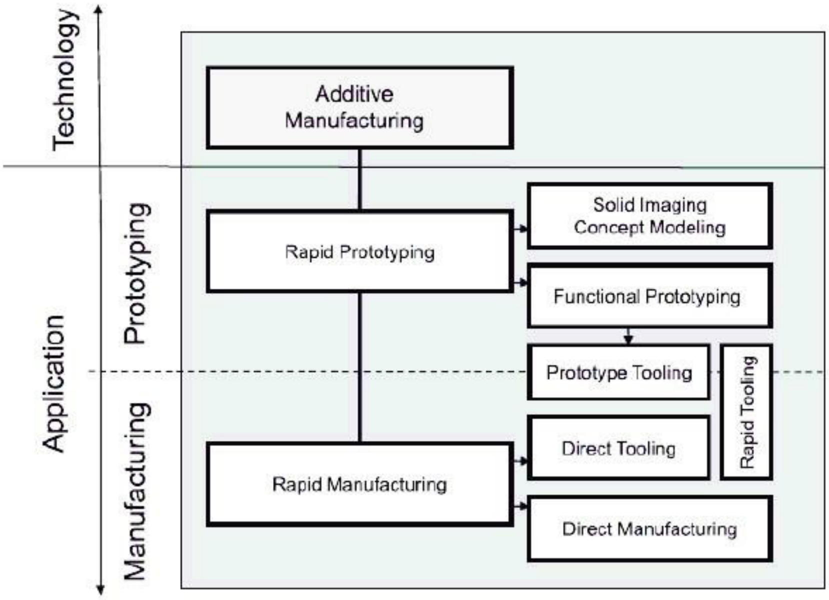


Figure 3 *Levels of application for AM technologies (Gebhardt et al., 2019)*

While rapid prototyping includes all applications that result in prototypes, models, and mock-ups, rapid manufacturing generates final products (Gebhardt et al., 2019). Rapid prototyping involves the production of parts with many different purposes, such as:

- **Visualization** - The parts are created to show the general appearance and the proportions of a model. They can be used to solve issues such as packaging problems, but can't be loaded physically.
- **Functionality** - The so-called "functional prototypes" are used to examine and verify one or multiple functions of a specific product, or to take decisions regarding the production of the latter, even if the 3D printed part can't be used as the final part. The parts generally imitate the quality of the subsequent serial manufactured ones. The reason why these parts are not used for serial manufacturing, most of the time, is due to the mechanical and thermal properties of the material used, as well as the color and the final price.
- **Fit** - Such parts are printed and then implemented in already-developed structures to prove the correct fit before starting the serial production. This is particularly important when, for example, a new design for a specific component has to be evaluated for a product that is already on the market.

Rapid manufacturing, on the other hand, involves all the processes that actually end up with a final product.

Rapid manufacturing involves two main levels:

- **Direct manufacturing** - It leads to end-products which are generated directly by AM technologies. In this case the shape and the selected material have to fulfill all the characteristics defined during the design and engineering process.
- **Direct tooling** - It involves all the processes which end up in "negatives", meaning parts used to obtain other parts. This includes for example molds, cores, cavities, and inserts.

Through rapid manufacturing, the parts generated will become final products if they show all the properties and functions that have been determined during the development process (Gebhardt et al., 2019). This is, in general, useful for the production of small batches, when the production is time and cost-consuming. If only a few parts have to be produced, or if the design is subjected to frequent modifications, it makes sense to shift to AM technologies.

2.1.2 The technologies: SLS and FFF

For the purpose of this work, two main AM technologies will be discussed and analyzed, to describe the basic path behind Polyamide 12 recycling: where the parts to be recycled come from (mainly Selective Laser Sintering) and for which technology the new material can be adopted (Fused Filament Fabrication).

Selective Laser Sintering

Selective melting of plastic and metal powders that exhibit thermoplastic behavior and re-solidification after cooling is called ”laser sintering”, ”selective laser sintering”, or in the case of metals ”laser melting”. Sintering is, indeed, the practice of using heat (below the material’s melting point) and pressure to bond and partially fuse particles together. Selective Laser Sintering (SLS) uses a high-power laser to sinter small particles of polymer powder into a solid structure based on a 3D model (Gebhardt et al., 2019). Selective laser sintering was one of the first additive manufacturing techniques adopted, developed in the mid-1980s by Dr. Carl Deckard and Dr. Joe Beaman at the University of Texas at Austin (Total Materia, 2020). Their method has, since then, been adapted to work with a range of materials, including plastics, metals, glass, ceramics, and various composite material powders. In this report, the focus will be just on plastics.

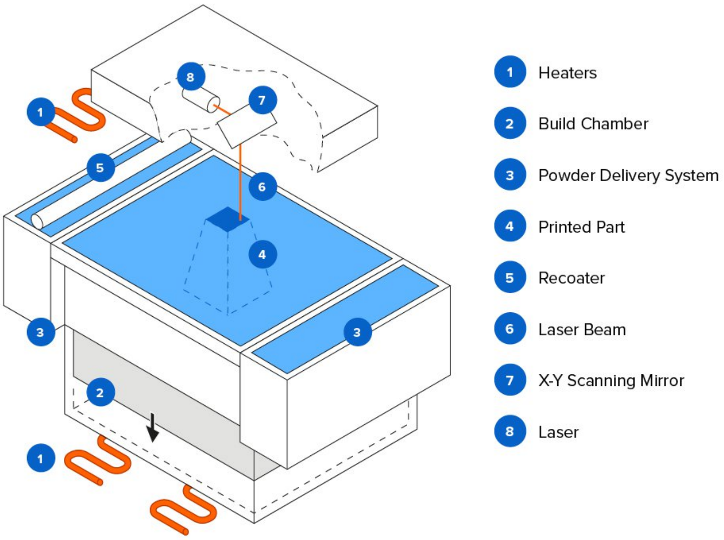


Figure 4 *Schematic of the selective laser sintering process (Formlabs, 2022)*

SLS machines (Figure 5) consist of a build space, filled with powder of grain size approximately between 20 µm and 80 µm, and a laser scanner on top that generates the contour of the part. A movable piston can be found at the bottom of the build space, which moves along the z-direction. The build area is constituted by the surface of the powder bed, which is where the current powder layer is applied. The build space (Figure 4) is heated and flooded with shielding gases (mostly nitrogen), to protect the area from oxygen, and water vapor (Gebhardt et al., 2019; Dizon et al., 2018). The process starts with the distribution of a first layer of powder, by means of a roller. Each layer is hit by a laser beam, according to the CAD model design. Where the laser beam collides with the powder surface, the particles locally melt and then solidify once the beam has moved on to a different area of the layer (Dizon et al., 2018). After the solidification of the whole layer, the piston moves down by the height of one layer thickness, and a new layer is applied onto the surface. The process then proceeds following the same steps above mentioned, until the part is finalized. After the manufacture is complete, some additional layers are applied at the top and the whole build frame is moved to cool down.

Standard plastic materials for this technology are Polyamide 11 (PA11) and PA12. Sintered plastic parts have similar properties to injection molded parts. Therefore, they are manufactured either as prototypes or even as series parts (direct manufacturing).

Figure 5 *SLS printer - EOS P770 (EOS, 2022)*

Figure 6 *FFF printer - Ultimaker S5 Pro Bundle (Ultimaker, 2022)*

Fused Filament Fabrication

While Selective Laser Sintering uses the material in the form of powder, Fused Filament Fabrication (FFF) employs, indeed, filament. An FFF machine (Figure 6) consists of a build space, than can be either sealed and heated or open, equipped with an extrusion head and a build platform. During such process, thermoplastic materials are heated to a molten state, extruded through a tip from the extrusion head, and deposited layer by layer, leaving behind a 3D object onto the printing surface (Masood, 2014). A schematic of the process is shown in Figure 7.

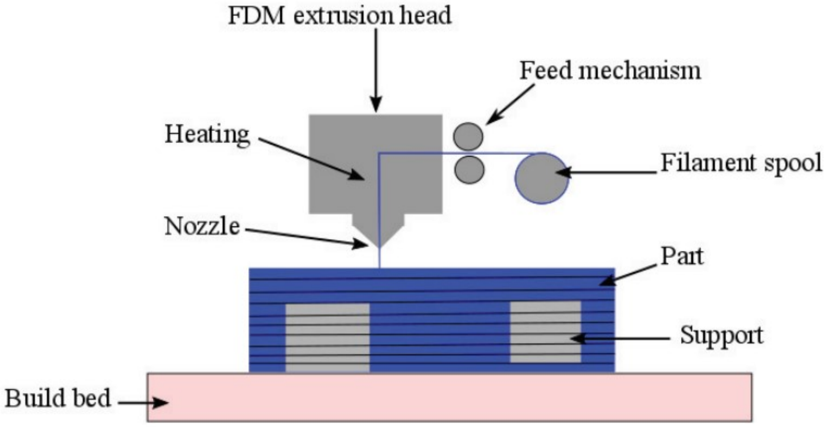


Figure 7 *Schematic of the fused filament fabrication process (Alafaghani et al., 2017)*

The build material (prefabricated in the form of filament) is continuously fed into the extrusion head. When the first layer has been applied, the material solidifies and layer after layer the build platform lowers down along the z-direction according to the thickness of the layer, to leave the nozzle space to add another layer of molten material. The process is repeated until the part is finalized (Gebhardt et al., 2019).

The parts printed through FFF generally present anisotropic behavior (they show different properties in different directions), which can be managed by adjusting printing parameters and heating conditions. For this technology, the manufactured components are mainly adopted as concept models, functional prototypes, and directly manufactured products (J. Chen et al., 2022).

Among all the AM technologies, FFF is one of the most common and widely adopted for non-industrial processes. This is due to the printers' economic accessibility, usage simplicity, and variety of materials commercially available. Materials used in FFF are primarily polymers, e.g., Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), Polyetheretherketone (PEEK), Thermoplastic Polyurethane (TPU), PA.

2.1.3 The role of Additive Manufacturing in the automotive industry

General considerations

Automotive manufacturers have been among the first adopters of AM after the technology was developed in the 1980s (Wiese et al., 2020; AMFG, 2020). As the number of vehicle models increases, as well as safety and customization requirements, being able to quickly validate new ideas, and test fit and function of parts with reduced lead times and tool costs, is for automotive companies increasingly important (AMFG, 2018). Additive Manufacturing is one of the main methods of creating automotive prototypes, for example, the support for side mirrors shown in Figure 8a. This is a crucial aspect of the study since it is from the automotive prototyping that the Polyamide 12 parts for recycling are retrieved.

(a) *Support for car side mirror printed with Polyamide via Selective Laser Sintering (Prodways, 2022)*

(b) *Customized "glove" designed to decrease the strain on limbs for BMW workers in production lines (BMW Group, 2015)*

Figure 8 *Examples of additive manufactured parts for the automotive industry*

Automotive prototyping covers the entire process of the development of a vehicle, from the concept design to the actual engineering and manufacturing (3-Dimensional, 2016). Prototyping is particularly important as it allows to save many costs, in this way manufacturers have the possibility to test their products before the beginning of mass production. Prototyping has many different functions since it enables checking the functionality of a component, selecting the most suitable material to adopt for a specific application, visualizing the structure of a part, as well as to check for mistakes, and, most important, testing safety. Such practice is also helpful to evaluate the types of equipment to be adopted to manufacture the parts. Moreover, the end product must be appealing to a potential customer, must convince the stakeholders to invest in a vehicle (or any other automotive application), and must ensure safety for the end user. All of this can be understood and therefore set up through prototyping. Any vehicle, before reaching the series production phase, has to go through a certain number of prototyping phases, such as design validation, pre-manufacturing, production, customer feedback, safety testing, and manufacturing validation (Peng, 2021; Valencia Plastics, Inc., 2019; WayKen Rapid Manufacturing, 2020).

- **Design validation** - This stage allows the visualization of the design concept. A first draft, made with rough components, is presented in front of the stakeholders. For this phase, cheap and fast manufacturing processes are generally adopted.

- **Pre-manufacturing** - During this phase, a more refined prototype is developed to validate the design and overcome any potential design challenge. It is also important because it allows understanding of how an improved part, for example, can fit into an already existing vehicle and interact with the other components, and, if needed, to evaluate possible design alternatives.
- **Production** - After the evaluation of what has to be improved, there is the transition to the actual production of the prototype. In this stage the ideal process to create the final product is developed: the most suitable manufacturing methods and materials are selected to finally start with the manufacturing of the prototype.
- **Customer feedback** - When the finished prototype is completed, manufacturers usually launch beta testing or provide their product to volunteers to collect feedback. An external point of view is important since it can bring to the surface issues never detected before.
- **Safety testing** - Exposing the prototype to extreme scenarios and conditions is a fundamental practice to test the component's durability, as well as user safety and failures. This is probably the most critical phase of the whole product development process.
- **Manufacturing validation** - This is the step where the prototype is finalized. The intended equipment and machinery are therefore officially decided, to create the final automotive part. In this phase, manufacturers make sure that the prototype is safe and operates as required, before starting the official production.

Creating a model of how the vehicle, or auto component, must be manufactured, is useful to visualize, mainly, **appearance**, **structure** and **functionality** (Peng, 2021). For these three aspects, different are the requirements and therefore different are the methods, as well as the materials, adopted.
3D printed parts can be used throughout the entire prototyping process chain, according to the requirements. Being a very fast production method, it enables testing even very complex designs, without the lead times typical of mass production, as well as the risk of delaying delivery dates. AM allows obtaining high-performance craft models, with very precise geometries, that on the other hand don't need to be particularly strong or aesthetically appealing (Mayco International, 2020). This method is used, for example, to manufacture prototypes for the production of single components, and to quickly test how such parts can fit, perform, and interact with the other elements

in already implemented vehicle structures, without interrupting the current mass production. In this regard, one of the main BMW's claims is, indeed, to be "Masters in Integration", meaning that most of the production line for a vehicle maintains the same characteristics for a long time: it is more likely within seven years to change part of it and from that the need to integrate elements, not to completely substitute the entire line.
When it comes to polymers, one of the main technologies adopted for prototyping is SLS, which can be visualized in Figure 5. Moreover, only a few AM machines are able to produce big parts (in general obtained through injection molding) in one piece. Alternatively, components manufactured through laser sintering can be virtually split into different sections, then manufactured, and finally assembled by gluing (Gebhardt et al., 2019). Laser sintering of PA makes it possible to obtain stress-resistant parts, but with a reduced surface quality compared to other techniques (Gebhardt et al., 2019).

Figure 9 *FFF Hub - BMW Additive Manufacturing Campus (Munich) (BMW's AMC, 2022)*

AM not only plays an important role in the prototyping of actual vehicles' parts but also in the production of jigs, fixtures, and tools for potential applications to improve mechanics' way to perform their job (Figure 8b). With the possibility to print many different geometries and designs in a short amount of time that can go from minutes to days, many parts can be implemented in the assembly procedure to facilitate it. The reduction of time and costs depends on many different aspects that a particular 3D printing technology can offer. For example, one of the most valuable technologies for this purpose is FFF. FFF printers, indeed, are particularly "plug and play" (Figure 9). It is possible to implement them in many different facilities so that whoever might need parts can just receive the CAD file and print its own tool. By doing so, there is no necessity anymore of ordering the parts and waiting for their delivery, which of course means fewer transportation costs, less fuel, and, in general, a more efficient process.

This practice is also valuable as it allows the users to check their tools while printing and eventually correct mistakes and identify design failures in a very short time.

2.1.4 The material: Polyamide 12

According to the ”2017 State of 3D printing”, plastic is the most widely used material for 3D printing, with a share of 88% respect to the others (Core-Baillais et al., 2017). Polyamides (PA, commonly known as Nylons), in particular, are the most adopted materials for traditional thermoplastic manufacturing. Being in the market since 1935, nylons were the first commercially successful synthetic thermoplastic polymers (Zinger, 2021; de Wargny, 2017). Among the different types of Polyamides, this study will focus on the recycling of PA12. Common applications for PA12 are mainly Injection Molding, Selective Laser Sintering, and Fused Filament Fabrication. PA12 powder is widely used in SLS to obtain components such as gear and bearings, as well as structural parts, showing very high impact strength, abrasion resistance, and chemical resistance (Fast Radius, 2022). On the other hand, its utilization for FFF printing, in the form of a filament, allows obtaining quick functional parts and prototypes such as jigs, fixtures as well as tools.

The functional parts obtained from PA12, show excellent mechanical properties. Allowing the production of very robust parts, stable for long periods of time, able to endure stress, with good chemical and thermal resistance, PA12 is a material widely used for generating mechanical parts. Some of the PA12’s main characteristics are: high strength, stiffness, resistance to cracking under stress, and long-term constant behavior (de Wargny, 2017). PA12, moreover, with respect to other types of polyamide, it absorbs less moisture, it is highly resistant to many different chemicals and it is highly processable. It allows the production of parts with a high degree of dimensional accuracy, even for complicated designs with intricate details (de Wargny, 2017). All these characteristics made PA12 usage very popular for prototype production (Fast Radius, 2022).

PA12 in its raw form, is a synthetic fine powder polymer derived from petroleum oil. Also called polylaurolactam or polydodecanolactam, PA12’s chemical formula is:

$$[-(CH_2)_{11}C(O)NH]_n$$

It is made from either ω-aminolauric acid or laurolactam, each having 12 carbon atoms (Polymer Database, 2022; Lewandowski et al., 2006).

As already mentioned, one of the main technologies in which PA12 is adopted is SLS. However, in typical SLS build jobs, only 5–20% of the powder is melted to obtain the parts; the remaining powder is not sintered but acts as a support to the parts in the building frame (Dotchev & Yusoff, 2009; He et al., 2022). Reuse of this powder amount for subsequent SLS build-jobs is challenging. Indeed, the "partcake material" (the unused powder surrounding the printed component) is recoverable, however, it is thermally degraded during the build process and its properties are altered (Wudy et al., 2014). The thermal stress that the powder during SLS process undergoes, is mainly determined by the build chamber temperature and the printing time (Pham et al., 2008). The build chamber is preheated to a temperature between the melting and the crystallization point of the thermoplastic. This can lead to both physical and chemical degradation, due to the material crystallinity (Kuehnlein et al., 2010).

In recent years, this type of plastic, has been the topic of many debates among manufacturers, regarding its sustainability. Being the main concerns of its composition, its degree of recyclability, its reusability as well as the gas emissions during its manufacturing process, research has been conducted to minimize its environmental impact (He et al., 2022; Prior, 2022). However, as it will be discussed in depth in the next chapter, most of the recycling processes for PA12 mainly involve the material in the form of powder, not parts. Like many other synthetic plastics, polyamide can't be degraded by the environment. In addition, there is no currently viable replacement for petroleum-based polyamides, despite the great potential that has been found in PA11, which is a semi-crystalline polymer that is generated from renewable raw materials derived from vegetable derivatives (mostly castor oil). However, the PA12's high resistance to chemical agents, its high processability as well as its low water absorption make it a key material with respect to all the others in advanced industries, like automotive and aeronautics. On the other hand, it is exactly because of these impressing mechanical properties that PA12 has a considerable impact on the environment. Indeed, PA12 as already mentioned is often found in functional prototypes, where resistance (mainly to fats, oils, and solvents) is one of the main requirements. Therefore, it comes clearly understandable how PA12 parts have a very long degradation lifetime if left in the environment.

To sum up, this last section has presented the main reasons why Polyamide 12 has been object of discussion regarding its degree of sustainability. It is indeed a petroleum-based polymer, often mixed with other additives to improve its properties. These additives make the material less recyclable and they increase its degradation rates. The research in recycling PA12 is still at a very early stage, after being discarded, it is often destined for incineration, which releases toxic gases in the environment (due also to the presence of the additives discussed before). Moreover, a study from 2020 about the presence of petroleum-based plastics in Marina Beach (Chennai, India), found that PA debris present in the location had a very high concentration of metals such as Arsenic (As), Chromium (Cr), Copper (Cu), and Lead (Pb) (Suman et al., 2020). As is shown in Figure 10, PA has almost always the highest concentration of such metals with respect to the other polymers tested. The analysis showed how As, Cr, Cu, and Pb were released into the marine environment, posing a severe threat to the organisms in the aquatic environment.

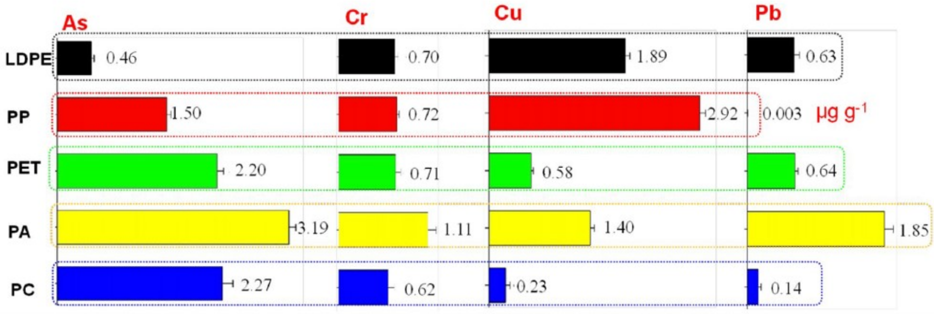
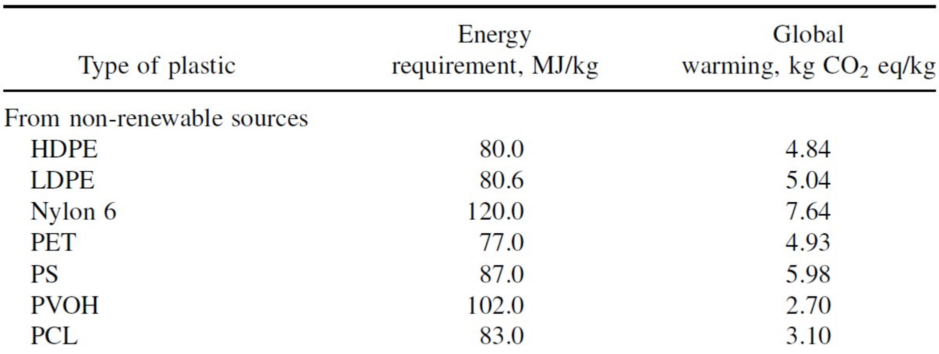


Figure 10 *The concentration of trace metals from different plastic debris in the Marina Beach (India) (Suman et al., 2020)*

Starting from its production, then to its utilization, and disposal, the overall lifetime of petroleum-based plastics such as PA12 generates a great number of carbon emissions and needs a great amount of energy as well. In Figure 11, it is possible to see the amount of energy required from non-renewable sources and carbon emissions for different types of plastics. The table is retrieved from a 2011 research where a Life Cycle Assessment (LCA) was conducted for such materials (Gironi & Piemonte, 2011). Even if it doesn't explicitly mention PA12, the study still reports the values of consumption for PA6 (which are the highest among the materials analyzed). Despite the mechanical and chemical differences between these two types of polyamides, these results still give an idea of the potential impact of PA12 on the environment, being it still a polyamide.



Type of plastic	Energy requirement, MJ/kg	Global warming, kg CO_2 eq/kg
From non-renewable sources		
HDPE	80.0	4.84
LDPE	80.6	5.04
Nylon 6	120.0	7.64
PET	77.0	4.93
PS	87.0	5.98
PVOH	102.0	2.70
PCL	83.0	3.10

Figure 11 *Energy requirement and Global warming for plastics from non-renewable sources (Gironi & Piemonte, 2011)*

Chapter 3

State of the Art

The aim of the following section is to present an overview of what has been done so far by researchers and experts in the industry, to clearly identify what is still open for further improvement and needs more investigation and research. The section has been divided into three main areas of research: frameworks for sustainability assessments, waste (in particular plastics) handling, and recycling in AM. A literature review on these three main areas has been carried out, in order to find the gaps that the present research is seeking to fill.

The chapter begins with an overview of frameworks to assess sustainability, to clearly identify the differences between them and what it is still missing.

Subsequently, the main theories behind plastic recycling are presented. Previous knowledge about the use of plastic in the automotive industry and the difference between plastic recycling and generation, represents the theoretical foundation of this research. Furthermore, the topic of recycling in AM, with particular focus on the technology FFF and the material PA12 is presented. In this case, an extensive literature review allowed to find the highest level of development that has been achieved on the recycling of materials from AM and for AM.

The chapter is concluded with a discussion on the knowledge gaps found in the literature regarding these three main areas that have been discussed so far, to show why this new framework for assessing sustainability in recycling pathways (especially PA12 for AM), represents a novelty.

3.1 Frameworks for sustainability assessment

Many studies throughout the years, from early 2000, analyzed the concept of circular economy from the perspective of sustainable development (Purvis et al., 2019). The common idea behind sustainable development is that it is based on the so-called ”three-pillars” approach, meaning that it should be assessed according to three dimensions of sustainability: environmental, economic, and social. An extensive literature review has been conducted by Purvis et al. to understand the theoretical foundations of the three-pillars concept. They showed how popular this concept is among the majority of academics addressing sustainability (Purvis et al., 2019). They justify its great diffusion in sustainability science with a growing emergence of techniques to integrate economic growth with social and ecological issues.

Based on the outcome of the 2005 UN World Summit, the World Commission on Environment and Development (WCED) reported an overall agreement among the parties involved that sustainability should be assessed through the reconciliation of environmental, social, and economic criteria, which cannot be exclusive, but should be linked to reinforce each other (Thomsen, 2013). Moreover, when it comes to the creation of frameworks to assess the sustainability of innovation and practices, the common trend is to base those on the three pillars of sustainability. Korhonen et al. in 2016, reputed the concept of Circular Economy (CE) until that moment as too diverse and confusing (Korhonen et al., 2018). Despite a new business idea of CE has been given in Korhonen's work, its definition still maintained the three-pillars approach of sustainability, according to the definition of sustainable development given by the WCED. By their definition, to cite the authors: "[...] Successful circular economy contributes to all the three dimensions of sustainable development [...]" (Korhonen et al., 2018).

Following this paradigm, many frameworks have been developed to assess sustainability. In 2011, the Lowell Center of Sustainable Production (LCSP) developed a framework to evaluate the effect of sustainability indicator systems in companies. The LCSP framework mainly concerns the environmental, health, safety, social and economic aspects of sustainable production (Veleva & Ellenbecker, 2001). Bianchini et al. in 2022, proposed a framework to assess social indicators to measure the relationship between managers' opinions and the level of incorporation of social issues in companies (Bianchini et al., 2022). The validation of the model has been conducted in a medium-size footwear industry. It was concluded that the evaluation of social indicators in such a broad spectrum of categories, together with the economic and environmental impacts should be the basis for a circular economy transition (Bianchini et al., 2022).

Following the same approach of three dimensions of sustainability, and moving towards the application in waste management and recycling, Menikpura et al. in 2012 evaluated the effect of recycling procedures on the sustainability of the current waste management in Thailand (Menikpura et al., 2012). Again, various indicators have been used for the evaluation, associated with environmental, economic, and social aspects. The authors argued in their paper that most of the LCA studies on waste management were mainly focused on environmental issues (presumably due to the lack of data and difficulties in performing quantitative assessments), therefore, for the scope of the work, more attention has been given to economic and social matters (Menikpura et al., 2012).

A research focused on the sustainability of recycling processes has been conducted by Cuc and Vidovic in 2011. In the paper, they examined the process of recycling textile wastes and quantified potential ecological and social benefits and economical effects of such practice (Cuc & Vidovic, 2014). Even in this case, a three-pillar approach has been followed for the creation of the model. What is relevant is that they clearly show what is considered within the environmental dimension. Conservation of resources, energy consumption, greenhouse gas production, and land preservation are all evaluated under it. However, the technical aspects of recycling, such as material quality and overall efficiency of the procedure are not involved in the assessment.

To conclude this overview on frameworks for sustainability assessment, another work that is important to mention is the study that has been conducted by Kumar et al. in 2019. They developed a framework for selecting a sustainable location for Waste Electrical and Electronic Equipment recycling plants (A. Kumar et al., 2020). They argue that for a recycling pathway to be effectively sustainable, also the recycling plant location should be aligned with the sustainability principles (A. Kumar et al., 2020). It is interesting, moreover, that together with social, environmental, and economic, also a technical dimension is considered for the evaluation. Within the latter, the authors mention many important technical factors that must be considered when selecting a recycling plant site. Such technical criteria mainly concern the level of equipment and quality of the infrastructures, together with the potential benefits that closeness with other facilities can bring. However, the technical aspects of recycling pathways such as the quality and properties of the end material, not just the production plants, should be more considered when assessing their sustainability. The present work will provide a new paradigm for sustainability evaluations based on four dimensions that are technical, environmental, economic, and social. By collecting information regarding each of these dimensions, divided as it was shown among several works, a comprehensive evaluation will be conducted to obtain as complete a framework as possible.

3.2 Plastic handling

With the development of AM technologies and their quick adoption on an ever increasing scale, new challenges are arising that need to be addressed and overcome as soon as possible. One of them is, for sure, to avoid as well as reduce material waste. Despite AM already allowing to save material with respect to traditional production technologies, additive applications such as prototyping bring short use of the products. This is mainly because the part is created, tested throughout a series of prototyping phases, and then discarded. Therefore, a way to manage these manufacturing wastes is needed. Currently, there are several ways to handle waste (landfilling, incineration

with or without energy recovery, and recycling). This work will focus on achieving sustainable pathways for recycling practices.
This section presents an overview of plastic use and management in the automotive industry. To follow up, as many studies argue that recycling plastics is wasteful, a literature review has been conducted also to identify how sustainable is this process with respect to virgin plastic production.

3.2.1 Plastic use in the automotive industry

To start this section, it is important to provide the reader with an overview of plastic utilization within the area context of this research: the automotive industry. Plastic, together with steel and aluminum, is one of the main materials adopted in car manufacturing. Plastic is widely used for many different purposes, from car prototyping to series vehicle components. According to Geyer et al., in 2015 the automotive sector consumed globally around 27 million tonnes of plastics (Geyer et al., 2017). Many different types of plastic can be found in a single vehicle, in more than 2000 different forms. Plastics currently account for roundabout 10-15% of a vehicle's weight, with a much higher share in terms of volume, even constituting half the volume of a car. Becoming the emission standards stricter year after year, manufacturers are focusing even more on achieving fuel efficiency, by decreasing vehicles' weight. This is one of the reasons why plastics are increasingly substituting other materials in car parts. Other reasons are the low level of corrosion that plastic has with respect to other materials like steel, ensuring vehicles' longevity, freedom in design, and flexibility in integrating components (Becqué & Sharp, 2020). Therefore, plastic utilization in vehicles is likely to increase in the next years. Digitalization is also a significant driver for the increase of plastic components in cars to support electronics (Becqué & Sharp, 2020).
As per 2016, PP (Polypropylene), PUR (Polyurethane), PVC (Polyvinyl chloride), ABS (Acrylonitrile butadiene styrene) and fiberglass accounted for almost 80% of the plastics used in cars. The rest was constituted by Polyethylene (PE) (Polyethylene), PA (Polyamide), polyacrylates, and PC (Polycarbonate). PP is the main type of plastic used in the design and manufacture of cars, with a share of 26%, followed by PUR (15%) (Plastics Europe, 2020).

3.2.2 Plastic generation VS Plastic recycling

According to Environmental Protection Agency (EPA), ”one ton of recycled plastic saves 5,774 KWh of energy, 16.3 barrels of oil, 98 million British Thermal Units (BTUs) of energy, and 30 cubic yards of landfill space” (EPA, 2018). Whether recycling is the most sustainable way to dispose of plastic, in terms of energy consumption, with respect to others, is still an open topic that has long made academics and experts debate. However, it seems widely agreed that recycling has considerable potential in saving energy with respect to plastic production from scratch. Recycling plastic conserves fossil fuels used to manufacture it. Plastic is indeed produced from crude oil and natural gas, both non-renewable fossil fuels. Producing one kilogram of plastic from crude oil requires 62-108 MJ (North American Forest Foundation, 2020). Moreover, the steps that consume the highest amount of energy when it comes to plastic production are the extraction and refining of oil and gas, which are of course avoided in the case of recycling plastic (U.S. EIA, 2021). The Association of Plastic Recyclers (APR) in December 2018, examined the life cycle impacts of post-consumer recycled plastic pellets compared to virgin plastic pellets from petrochemical sources for resins such as Polyethylene Terephthalate (PET), High-density Polyethylene (HDPE), and PP. It was concluded that the energy for transportation and processes for virgin plastic production is 1.7 (PET), 3.0 (HDPE), and 3.0 (PP) times higher than for recycled plastic. Recycling plastic is more conserving (from a transportation and process standpoint) with respect to producing it. Indeed, according to current practices, plastic recycling is overall less energy-consuming than synthesizing plastic resins from basic chemicals. For the scope of the study, the steps adopted within the pathway to produce/recycle the plastic were analyzed individually: starting from the extraction of petroleum and natural gas for virgin plastic, and from the collection process for used plastics, ending with the creation of granulate for both of the processes. The calculations were made for 100% virgin plastic and 100% recycled plastic, leaving the mixtures outside of the research.

The following histograms (Figures 12 and 13), retrieved from the APR 2018 report, show that, overall, for energy consumption and global warming potential, recycled plastics create fewer expenses with respect to virgin plastics (The Association of Plastic Recyclers, 2018).

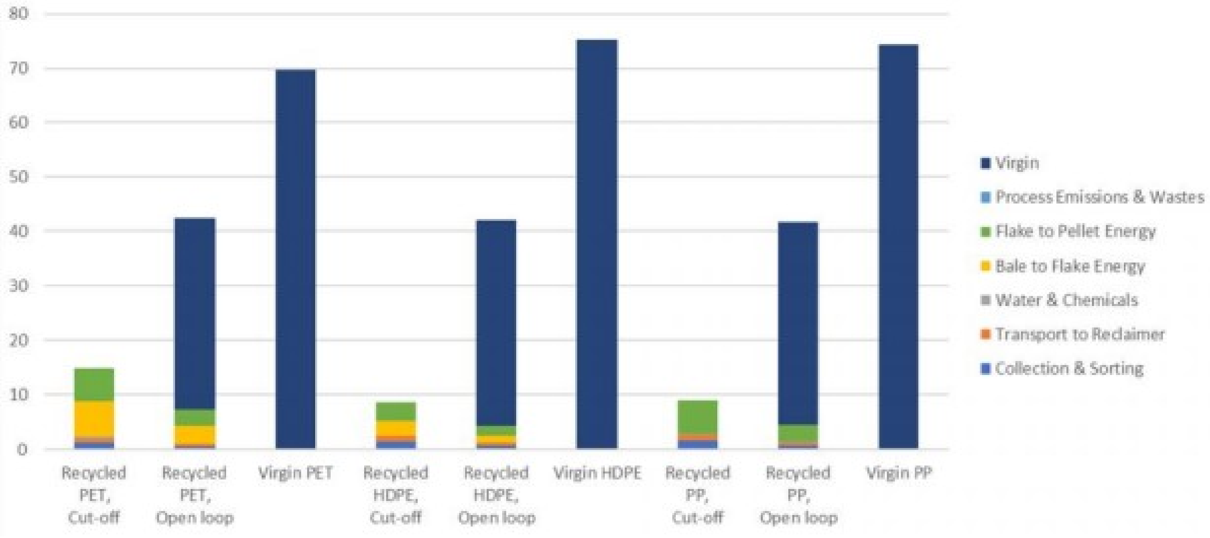


Figure 12 *Total Energy Results for Recycled and Virgin Resins (MJ/kg) (The Association of Plastic Recyclers, 2018)*

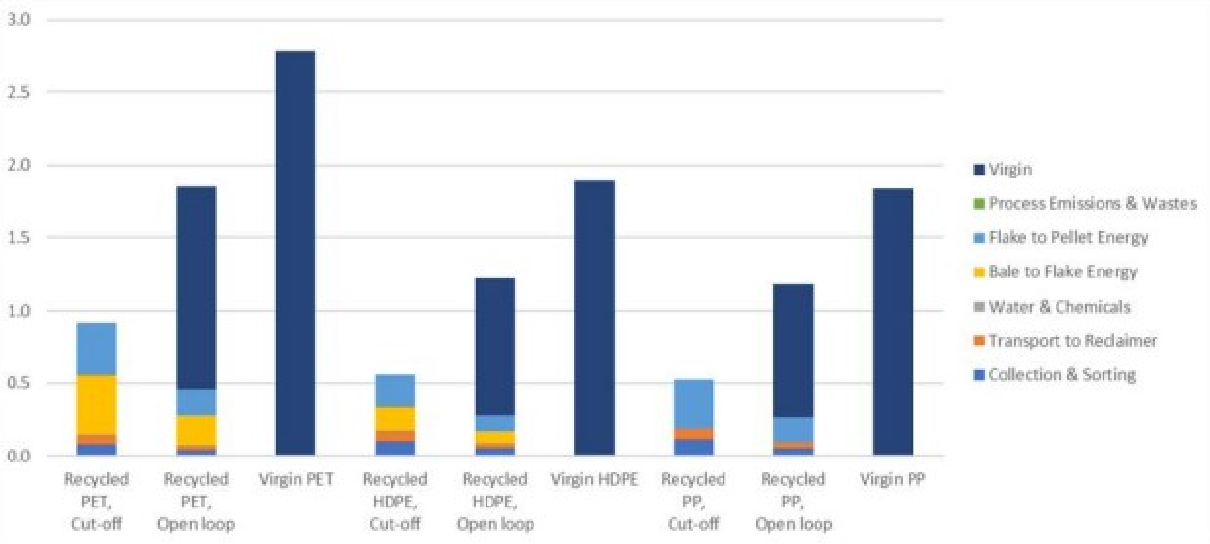


Figure 13 *Global Warming Potential Results for Recycled and Virgin Resins (kg CO2 eq/kg resin) (The Association of Plastic Recyclers, 2018)*

As a final observation, in a 2020 report published by the Imperial College London, it is argued that ”recycling wins over virgin production on all environmental measurements, especially when it comes to carbon emissions” (Voulvoulis et al., 2020). It was demonstrated that, according to the type of recycling process, the allocation method (open- or closed-loop), and the amount of non-renewable energy used, recycling and re-manufacturing plastic save between 30% and 80% of the carbon emissions that original processing and manufacturing produce (Voulvoulis et al., 2020).

However, most of the studies presented so far regarding plastic recycling, have focused on common plastics such as PP, PET, HDPE. These latter are materials found in a very broad variety of applications, from clothing to food and beverage containers as well as general packaging. Being the production and disposal of these types of plastics very diffused in humans' everyday life, they were the main materials evaluated for recycling throughout history. Research on recycling more niche materials like less common plastics adopted in the automotive industry as well as materials adopted for Additive Manufacturing is starting to gain momentum. However, there are still many polymers not yet tackled for recycling, one of these being Polyamide 12.

3.3 Recycling in Additive Manufacturing

One of the aims of this study is to develop a mechanical recycling pathway for PA12, therefore, further research should be conducted to understand the actual impact of mechanical recycling not just in a general context of industrial processes, but specifically regarding AM technologies. This section will provide an overview of the main materials evaluated for recycling within FFF as an AM technology, present in literature. The section will end by moving further on the current ways adopted by researchers and experts to reuse Polyamide 12.

3.3.1 Recycling and FFF

Being the case study of this project the transformation of PA12 automotive waste into filament for FFF printing technologies, it is important to understand the current research status in terms of the production of FFF filaments from recycled materials. Sustainable processes are rapidly taking hold in every aspect of industrial and technological production. AM is among those industries that are trying to make processes more compatible with the environmental standards imposed by various national and international protocols and agreements. Nowadays, many different materials are available in the market out of recycled and/or compostable materials. This last section is therefore meant to discover the relationship between the recycling of polymeric materials and FFF printing. Current practices to produce recycled filament are presented, as well as which type of materials are used the most for this type of process.

Natural materials

It is possible to recognize many different types of filament as ”sustainable”. Several scientific researchers have worked on the development of sustainable materials for FFF: there is a very broad range of discoveries that have been done in recent years. Filament out of natural material is without any doubt a sustainable filament, but also a material (even if not natural) that is for example recyclable (and/or recycled), has its

own degree of sustainability. PA12 is definitely not biodegradable or natural. Whether it is recyclable depends on the type of application selected, as well as the nature of the material in its waste form.
Many companies have worked in the utilization of natural and compostable materials for filament production, as the main material, or as fillers mixed with other polymers. Among the most common natural materials adopted, it is possible to mention: wood from different plant species, cellulose, cork, bamboo powder, rice straw, as well as hemp (Fico et al., 2022). Moreover, recent studies showed that it is possible to use less common natural materials for the production of filament, by mixing them mainly with PLA and ABS. For example, Tran et al. in their study utilized cocoa shell waste as filler and a single-screw extruder to obtain the filament (Tran et al., 2017), while Velarde et al. produced filament for FFF based on PLA and fibers from Agave leaves, a waste material for the production of tequila (Velarde et al., 2021). Tran et al. conducted thermal characterization and scanning electron microscopy measurements on the parts obtained via FFF and found good properties with their cocoa shells material, such as well-defined structure, good adhesion between layers and fine resolution. Velarde et al., on the other hand, obtained filament by extrusion using a twin-screw extruder and conducted Differential Scanning Calorimetry tests on it. After obtaining the filament, some samples have been also printed via FFF. They witnessed changes in the mechanical and thermal properties of the material with increasing concentration of Agave fibers, ending up with a low-cost and compostable material for FFF, very lightweight, suitable for the fabrication of molds and supports. A very interesting discovery was made by Rahimizadeh et al. who used wind turbine waste as filler for the production of filament for 3D printing, based on PLA (Rahimizadeh et al., 2021). The materials used in wind turbines are mainly copper, steel, and glass fibers, allowing therefore to obtain, as the author demonstrated, a filament with higher tensile strength and E-modulus, compared with pure PLA. Furthermore, several companies (such as Marble EcoDesign) have been trying to obtain filament for FFF, by adopting marble residues (Fico et al., 2022), testing its mechanical properties in comparison with pure materials.

This section has presented some types of filaments obtained for FFF technologies with recycling techniques for natural materials. Such FFF filaments were all obtained via grinding the waste and extruding it in the form of filament (either mixing it with other additives or leaving it in its pure form). Most of the researchers cited in this last section witnessed changes in the mechanical and thermal properties of the new material. However, none of them evaluated the environmental impact, energy consumption, and economic aspect of such recycling processes for natural materials. Moreover, adopting natural and bio-materials for the production of recycled filament doesn't solve the problem of plastic pollution in industrial processes. As will be presented in the next section many studies attempted to obtain recycled filament out of non-natural and polymeric materials. However, what has been found to be missing in both the production of natural and non-natural recycled filament, is their potential for automotive applications, which is also the object of this study about PA12 recycling.

Polymeric materials

There are many non-natural materials, exactly like PA12, that are existing in the environment as waste, and therefore no longer used, that could be given new life as FFF filament, minimizing their harmful effect on the environment. This is the reason why, the following section presents many recycled filaments (especially from polymeric waste), created indeed to maximize the economic value of such materials and at the same time minimize their harmful environmental impact.

To start with this overview about recycling polymeric material for filament production, Ferrari et al. studied the production of filament from PET bottles found in the sea. Such bottles were collected, processed, and turned into filament (PET bottles were cut and milled, then desiccated and finally single-screw extruded in the form of filament) (Ferrari et al., 2020). The samples obtained via FFF through this recycled material were compared with samples obtained by commercial PET. After tensile testing, overall, good mechanical behavior was found for the recycled samples (Ferrari et al., 2020). Farina et al. developed filament from recycled Nylon 6, mixed with ABS and titanium dioxide (Farina et al., 2019). The filament was obtained through a dedicated extrusion line with a twin-screw extruder. The rheological and thermal properties, as well as the tensile strength, wear resistance, and printability of the new recycled material, were investigated. The main tests conducted on the materials were: Melt-Flow-Index (MFI), Differential Scanning Calorimetry (DSC), and tensile tests. The results showed that the recycling of Nylon-6 enables to obtain of a filament with high physical and mechanical properties. Furthermore, Wei et al. adopted aluminum-plastic packaging waste (APPW) for their filament (Wei et al., 2021). The 3D printed parts (via FFF) showed excellent mechanical and heat transfer performance, but also high tensile strength and thermal conductivity when considering a composite material containing also EG (expandable graphite). These results were obtained by conducting both tests on the materials such as tensile testing and theoretical calculations based on the dimensions of the geometries obtained via FFF (Wei et al., 2021).

It is particularly worth mentioning the review that Mikula et al. provided regarding the recycling of polymeric materials (Mikula et al., 2021). Figure 14 shows a table retrieved from Mikula's review, where the authors report a series of works related to the recycling of many different polymers.

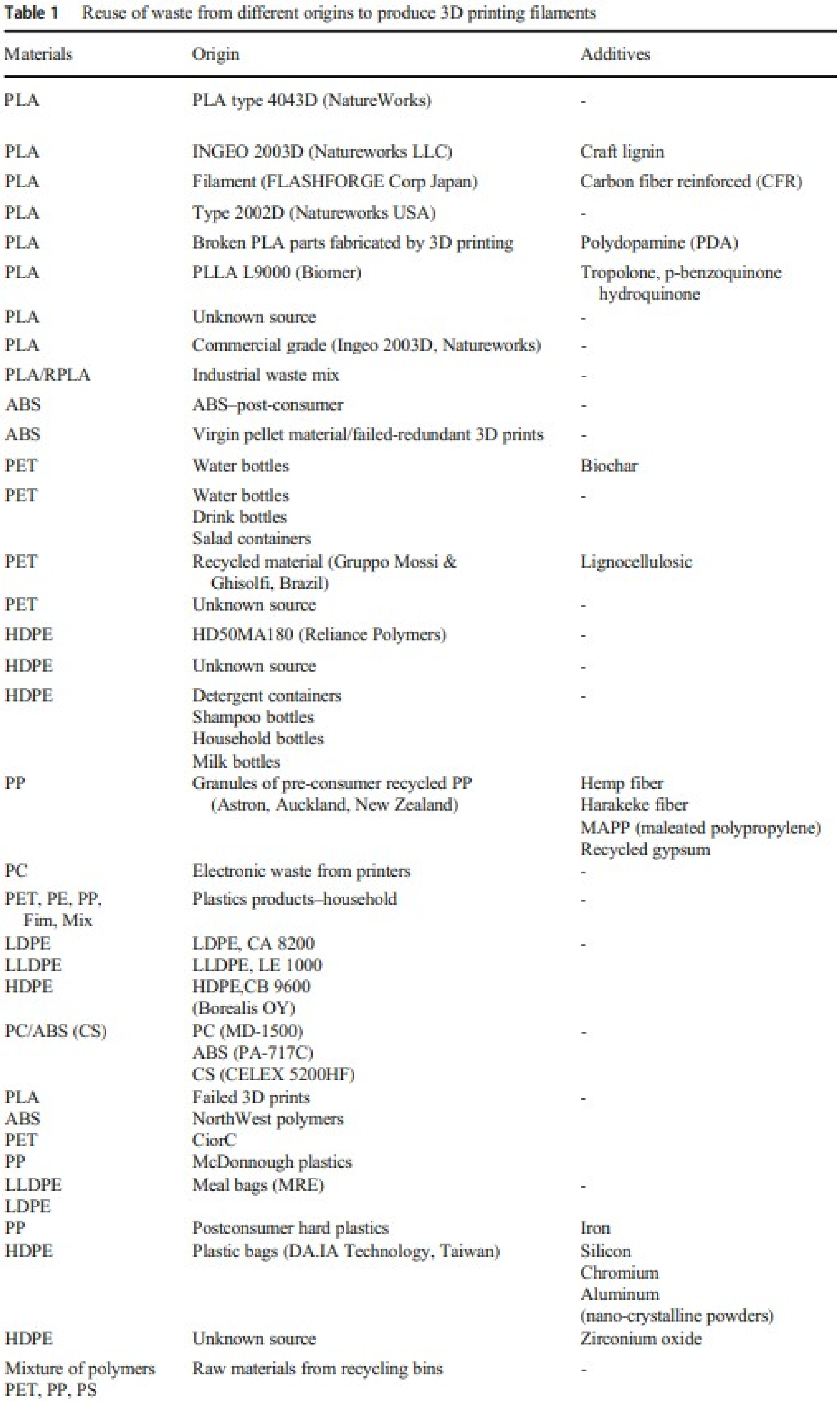


Table 1 Reuse of waste from different origins to produce 3D printing filaments

Materials	Origin	Additives
PLA	PLA type 4043D (NatureWorks)	-
PLA	INGEO 2003D (Natureworks LLC)	Craft lignin
PLA	Filament (FLASHFORGE Corp Japan)	Carbon fiber reinforced (CFR)
PLA	Type 2002D (Natureworks USA)	-
PLA	Broken PLA parts fabricated by 3D printing	Polydopamine (PDA)
PLA	PLLA L9000 (Biomer)	Tropolone, p-benzoquinone hydroquinone
PLA	Unknown source	-
PLA	Commercial grade (Ingeo 2003D, Natureworks)	-
PLA/RPLA	Industrial waste mix	-
ABS	ABS–post-consumer	-
ABS	Virgin pellet material/failed-redundant 3D prints	-
PET	Water bottles	Biochar
PET	Water bottles Drink bottles Salad containers	-
PET	Recycled material (Gruppo Mossi & Ghisolfi, Brazil)	Lignocellulosic
PET	Unknown source	-
HDPE	HD50MA180 (Reliance Polymers)	-
HDPE	Unknown source	-
HDPE	Detergent containers Shampoo bottles Household bottles Milk bottles	-
PP	Granules of pre-consumer recycled PP (Astron, Auckland, New Zealand)	Hemp fiber Harakeke fiber MAPP (maleated polypropylene) Recycled gypsum
PC	Electronic waste from printers	-
PET, PE, PP, Fim, Mix	Plastics products–household	-
LDPE LLDPE HDPE	LDPE, CA 8200 LLDPE, LE 1000 HDPE,CB 9600 (Borealis OY)	-
PC/ABS (CS)	PC (MD-1500) ABS (PA-717C) CS (CELEX 5200HF)	-
PLA ABS PET PP	Failed 3D prints NorthWest polymers CiorC McDonnough plastics	-
LLDPE LDPE	Meal bags (MRE)	-
PP HDPE	Postconsumer hard plastics Plastic bags (DA.IA Technology, Taiwan)	Iron Silicon Chromium Aluminum (nano-crystalline powders)
HDPE	Unknown source	Zirconium oxide
Mixture of polymers PET, PP, PS	Raw materials from recycling bins	-

Figure 14 *Reuse of waste from different origins to produce 3D printing filaments (Mikula et al., 2021)*

As it is possible to notice, not only PA is missing but also none of the materials tested come from automotive industry wastes. Also in this case most of the materials are from common usage applications such as drink and food containers, household products, and bags. Plastic recycling within the automotive industry needs more research. According to Wards Intelligence, as of 2019, 1.4 billion motor vehicles were estimated to be in use worldwide; 0.4 billion more than eight years before (2011) (Wards Intelligence, 2022). With the increase of motor vehicles present on the road, the problem of plastic consumption for the automotive industry becomes increasingly urgent as well. Indeed, like for packaging and household tools, also plastic use in vehicles has definitely become prevalent in the modern world.

As the authors state, the recycling pathway followed to obtain most of these filaments is somehow common. Cleaning, grinding, melting, extruding, and measuring the properties of the filament is the general practice to turn waste polymers into filament for FFF (Mikula et al., 2021). However, as we discussed so far, most of the works are mainly focused on the quality of the material in comparison to its virgin counterpart and its properties. Very little research has been conducted until now to understand the actual environmental, energetic, and economic impact of such recycled materials. This is due to the fact that often the recycled material is likely to be degraded, risking obtaining poor mechanical, thermal, and rheological properties. Therefore, prior to analyzing the impact of recycling processes and materials for FFF, the most important factor to study has been considered the quality of the recycled material. Indeed, obtaining a good quality material is a necessary but not sufficient condition to move further in the process. The inability to obtain a valuable material makes the recycling process useless in the first place. On the other hand, it is also important to understand how to recycle it in the most sustainable way possible, something that no one has studied yet. All the studies so far have stopped at obtaining a good material and analyzing its qualities.

In order to increase the final properties of the 3D printed parts, as already mentioned before, several polymer-based composites and nanocomposites have been developed for FFF process (Fico et al., 2022). However, as Fico et al. argue, these materials are not all biodegradable. Consequently, even if they solve the problem of reusing waste material, they might represent a future issue for the environment in terms of their disposal.

In order to make their materials further recyclable, many companies are working on the production of materials without the addition of chemicals and other supplements. Zander et al. generated filament from 100% recycled PET from bottles and packaging (Zander et al., 2018). Recycled PET has been shown to be a suitable material for FFF printing, prior to proper processing. The best application for such material proposed by the authors is distributive manufacturing, especially in rural and remote locations in both developed and developing countries (Zander et al., 2018).

As already discussed, most of the research that involved recycled filament focuses mainly on the quality of the recycled by-product and on its mechanical, thermal, and rheological properties. However, a significant work about recycled filament for FFF that seems to differ from the others in the literature, has been conducted by Kreiger and her colleagues from the Michigan Technological University. The aim of their research was to determine whether the production of recycled HDPE filament via MakerBot (a particular waste plastic extruder) was an environmentally friendly alternative to conventionally centralized recycling HDPE (Kreiger et al., 2014). They conducted a LCA for such distributed recycling of HDPE and demonstrated that it uses less embodies energy than the best-case scenario for centralized recycling. Indeed, the reduction of energy use just for transportation and collection of the waste material (required for the centralized recycling) was found to be over the 80% for the distributed recycling by the placement of machines like MakerBot in various facilities. Even in this case, the material object of the study was indeed a common polymer, with a very broad range of applications, for which the recycling procedure is already implemented in many facilities. It would be interesting to understand whether a niche material like PA12, whose waste parts have never been recycled before, would have the same results when studying its energy use. Moreover, an environmental and economic evaluation should be also added to the assessment to obtain complete results.

3.3.2 Polyamide 12 recycling in literature

In this section, most of the current ways to re-use PA12 found in the literature are presented. As already mentioned, being PA12 a petroleum-based polymer, it can't be degraded in the environment. Throughout the years, many studies tried to find ways to improve PA12 sustainability, however, this material presents a very low degree of recyclability as well as long degradation times. Most of the practices concerning PA12 reusability involve the re-utilization of the material in the form of powder, not parts. Indeed, as previously presented in Chapter 2, PA12 powder during SLS processes ages, and it can't be fully re-used in the same process. Many studies were conducted to understand PA12 aging and the powder's structural evolution during SLS. Chen et al. studied systematical mechanisms of PA12 aging and its microstructural evolution during SLS. It was found that the effect of solid-state poly-condensation reduces the crystallinity of the powder by 6% after three recycling cycles (P. Chen et al., 2018). Pham et al. found that in SLS, the PA12 powder undergoes molecular chain entanglement to form grains (Pham et al., 2008). The higher the temperature and the longer the powder is exposed to high temperatures, the more likely is that the molecular chains become larger, which eventually leads to an increase in molecular weight, a decrease in fluidity, and ultimately the deterioration of the powder's mechanical and thermal properties (P. Chen et al., 2018; Dotchev & Yusoff, 2009). Molecular weight is, indeed, a fundamental parameter when studying the stress on a material. Virgin powder has the lowest molecular weight. Furthermore, this parameter increases with build time and build chamber temperature and it is directly proportional to another important parameter which is viscosity (Wudy & Drummer, 2019). Viscosity also influences the molecular mobility of the powder (Wudy et al., 2014). Due to an increase in the molecular weight, there is also a growth in the linear macro-molecular chain. The longer the chain, the less will be its mobility, and, indeed, the powder after an SLS process turns out lumpy (Pham et al., 2008). For this reason, the reuse of the non-sintered powder (which accounts for 80-90% of the total weight used for one process) is limited. The most common practice for re-using the powder is to blend the virgin powder with the recovered one, to refresh its properties. Most of the studies recommend a refreshing rate of 70% virgin powder and 30% aged powder, even if it has been demonstrated that, with a ratio of 50% each, it is possible to obtain parts with good properties (Josupeit et al., 2013). What can determine the failure of the print job can be directly visible in the quality of the parts, for instance, the shrinkage rate will be higher, and the surface roughness will be greater, a phenomenon referred to as "orange peel" (Dotchev & Yusoff, 2009).

Until now the studies concerning PA12 old powder re-utilization in SLS were presented. However, adopting refreshing rates for the powder in SLS means that there is still leftover powder not re-sintered at all. Not re-using PA12 old powder from SLS, not only would be a waste of resources but also could generate environmental pollution (He et al., 2022). He et al. in 2022 quantified the environmental impact of recycling PA12 powder, compared to a base case scenario with no recycling procedure. The life cycle Primary Energy Demand (PED) and Global Warming Potential (GWP) of recycling PA12 powder from the SLS process were calculated considering the case study of an injection-molded automotive fuel-line clip. The results showed that recycling of PA12 powder brings overall PED and GWP benefits into the industry (He et al., 2022). Even if the properties of the old powder are not suitable anymore to be fully used in SLS processes, the aged powder still keeps sufficient quality to be potentially adopted for other processes. Recent studies have found new ways for recycling the waste PA12 powder from SLS processes. Feng et al. have analyzed the recycling of old PA12 powder from SLS into filament production for FFF. They found out that turning SLS powder residues into polymer filaments for FFF can be one of the solutions to its successful reuse (Feng et al., 2019). The mechanical properties of the 3D printed samples with the recycled Polyamide 12 (rPA12) filament were comparable to those with the virgin Polyamide 12 (vPA12) in the x-direction of printing (Feng et al., 2019). In other studies, rPA12 from the SLS process is mixed with reinforcement fibers to produce granulate/filaments for injection molding/extrusion-based AM processes (Wang et al., 2018). In 2019, PA12 powder designed for SLS costed around \$150/kg, while the cost of PA12 granulate (pellets) for conventional plastics processing was below \$3/kg (Feng et al., 2019). The cost of PA12 filament for FFF was approximately \$100/kg (Feng et al., 2019). This is the first step to link together two separate processes (i.e. SLS and FFF) to make AM more cost-effective, economical, and environmentally friendly.

Regarding PA12's reprocessing, it is worth mentioning other studies that demonstrate its potential for circular use in 3D printing. Kumar and Czekanski tried to connect SLS and FFF as well, obtaining filament for FFF, out of used PA12 powder from SLS, both keeping it pure and mixing it with different shares of tungsten carbide. Their study demonstrated that an inexpensive filament compatible with FFF and with adequate mechanical properties can be fabricated (S. Kumar & Czekanski, 2018, 2017).

The literature research presented so far about PA12 recycling, covers just the reutilization of the material in the form of powder, not parts. Some studies attempted to re-use the PA12 powder for its circular adoption on SLS. Chemical studies were therefore conducted on the aged powder itself, to understand its adaptability for re-sintering processes. Other studies tried to link SLS and other 3D printing technologies, with the adoption of melting and extrusion processes to turn the powder into pellets (for Injection Molding) and filaments (for FFF). However, none of these evaluations involved the recycling of the PA12 in the form of parts out of SLS. Research on the influence of the shredding procedure for mechanically recycling PA12 parts on both the quality and the impact of the material should be therefore carried on.

It is therefore interesting to show the results that Vidakis et al. obtained in their study in 2021. They didn't recycle just the powder but moved further in recycling already re-melted PA12. They demonstrated that PA12 can be successfully mechanically recycled for a certain number of cycles, without a decrease in the mechanical properties compared to the virgin material (Vidakis et al., 2021). The results were obtained by starting with virgin PA12 filament, shredding it into pellets, and re-extruding them many times to always obtain new filament. 3D-printed samples in the form of tensile bars were also produced in the context of the study. However, even if they added the shredding phase to the recycling procedure, they extruded and re-melted the materials in the form of filament (not yet printed). It is still left to understand whether the addition of the 3D printing phase and therefore the shredding of already printed parts, can modify these results.

3.4 Knowledge gaps

This section provided an overview of the main studies that have been conducted so far, for a better understanding of the topic, but also to find knowledge gaps to attempt to take a step forward with this research. Such knowledge gaps have been found in all the three main areas introduced in this chapter: frameworks for assessing sustainability, waste handling (and recycling), and recycling in AM.

According to the literature review conducted, there is a common trend when creating sustainable frameworks following the so-called ”three-pillars approach”. In most of the studies reviewed in this regard, it is considered efficient to evaluate just three dimensions of sustainability: environmental, economic, and social. All the indicators regarding resource use are mainly considered within the environmental dimension, as the literature analysis conducted in Section 3.1 demonstrated. However, the scope of this research is to evaluate the sustainability of recycling pathways. An analysis in depth of the quality and characteristics of the material obtained via recycling is fundamental to make worthwhile the recycling process. For this reason, a new dimension of sustainability will be suggested in the following chapters of this research: the technical dimension. As will be demonstrated later on, this dimension is meant to comprehend all the indicators linked to the overall efficiency and quality of resources, being clearly separated from the environmental dimension.

If most of the frameworks regarding sustainability consider influential just the environmental, economic, and social aspects of processes and services, on the other hand, the research on recycling materials is mainly focused on studying the quality of such materials, not the other aspects. When it comes to recycled filament production for FFF, the research has been focusing on understanding the mechanical, thermal, and rheological characteristics of the materials (Section 3.3.1). An evaluation considering both quality and other indicators should be considered. Evaluating the quality of the materials is for sure what makes it worth the most to recycle them. Obtaining low-quality material would obviously make the recycling process futile. But on the other hand, the recycling process must be worth it also from an environmental, economic, and social point of view. Exploration in this regard is, for their time being, still in a primordial stage, and needs to be developed further. Conversely, other studies regarding recycling in AM, just focused on the environmental impact of such practices, not on the quality of the recycled material. And even in this case, the environmental impact was studied on recycling practices to turn the material into pellets, not filament.
The present study is meant to consider all these aspects in one unique multi-factorial assessment. The new framework proposed will be based on four dimensions of sus-

tainability (technical, environmental, economic, and social), to gather together all the most important elements, as no one ever attempted before.

On the other hand, concerning material recycling, from the literature review performed and reported in Section 3.3.1, it was found that most of the research on this topic mainly concerns the recycling and reprocessing of common polymers such as polypropylene (PP), polyethylene (PE), polyurethane (PU), poly(vinyl chloride) (PVC) and poly (ethylene terephthalate) (PET). Recycling of PA is still a very little addressed topic, being the usage of this thermoplastic less common and more of a niche with respect to the materials that have been presented so far. By focusing on what has been done so far in AM for the production of recycled filament, it is possible to notice how most of the recycled filaments studied in literature are either composites (hence not recyclable anymore), or natural materials. Despite research in obtaining FFF filament from polymeric materials is spreading really fast, as Mikula et al. showed, PA12 is still missing in the list of the main works conducted on this topic (Mikula et al., 2021). Moreover, most of the materials recycled for filament production were not coming from the automotive industry and were not meant for automotive applications. As another consideration on recycling of PA12 in AM (Section 3.3.2), while many studies demonstrated the possibility to turn old PA12 powder into filament for FFF printing, or into granulate for other 3D printing technologies (Large Scale Printing (LSP) for instance), on the other hand, literature is still lacking a study that actually extrudes not just old powder but PA12 parts. The most similar work found in literature in this regard, concerns the attempt to shred and re-extrude many times PA12 filament, to test its recyclability, but not the parts printed out of it. The case study of the present work will therefore be focused on taking a step further as in mechanically recycling old PA12 parts.

The creation of a framework for assessing the sustainability of recycling under four dimensions (technical, environmental, economic, and social) is therefore the topic of this work. After being presented and explained in depth, this framework will be applied to a precise case study. Recycling Polyamide 12 parts to turn them into usable filament for FFF, without the addition of any composite in the mixture is the real-world application selected to verify the usefulness of this new framework. The aim of this thesis is to conduct a comprehensive analysis of the technical, environmental, economic, and social impact of adopting such sustainable practices in the automotive industry, in the context of AM. The analysis of the literature presented in this chapter, was, indeed, meant to show how many studies focused on just some of these four dimensions of sustainability, but not on all of them. Also, it was demonstrated as the conversion (via mechanical recycling) of PA12 printed parts into filament for FFF, still needs research, both in terms of sustainability assessment and also of the feasibility of the process.

Chapter 4

Definition of the framework

4.1 Introduction to the systematic framework

The aim of this work is to define a framework for the introduction of sustainable recycling practices for solid materials in automotive prototyping processes. This chapter is meant to answer the main research question of the work: *how does a framework for sustainable recycling look like and how can it be implemented in the automotive industry?*
The focus of this chapter is therefore the development of a concrete framework for measuring the sustainability of recycling pathways. Such a framework can be adopted to facilitate the decision-making process for the evaluation of different alternative possibilities to manage solid material waste. The framework can be applied to many different materials as well as many different processes. Indeed, within the automotive industry, there are many materials adopted that can be successfully sustainably recycled and reprocessed.
Throughout the chapter, the general approach, and the steps followed to answer the following research sub-questions are also discussed.

SB1. *What are the main factors that influence the sustainability of recycling?*

SB2. *How can sustainability in recycling be assessed?*

SB3. *How to compare in a standard and consistent way different recycling pathways?*

SB4. *How the implementation of the framework can help design the most sustainable recycling pathway for PA12 in automotive prototyping?*

As can be observed, the last sub-question is related to the implementation of the framework to a selected case study, which will be further discussed in Chapter 5.

4.1.1 Sustainable production

Nowadays, "sustainability" is still an unclear concept, to which everyone gives a different interpretation. Above all, it is a multifaceted concept, in which a multitude of variables, as well as options, have an influence. However, for a process to be sustainable there is a set of unavoidable factors to take into account. Especially for suppliers of products and services, it is a common opinion among experts and academics that it is necessary to overcome old paradigms of evaluation just based on economy and finance (Veleva & Ellenbecker, 2001). The financial standpoint is for sure necessary, but conservation of resources, care for the environment, safety, and social development should constitute as well the basis for sustainable innovation.

The framework proposed in this section intends to match both general paradigms that should be implemented in any automotive industrial process, together with a sufficient degree of individuality according to the differences between each firm, their objectives, and the recycling practices. Considering that standardizing sustainability is a very hard, if not impossible task, this work supports the idea that it is possible to find general spheres (that will be called then "dimensions") for every company or organization that works with materials to choose the most appropriate recycling pathway to adopt. This gives the decision-makers some freedom in their choices, according to their objectives, needs, and standards. Overall, this chapter describes the methodology followed to obtain such a framework and to answer the research questions. Furthermore, the framework will be then applied to the case study of this work, which is the implementation of a recycling pathway for PA12 wastes from automotive prototyping for automotive applications.
To make the framework easier to understand, and to improve its usability, the latter has been divided into ten steps, each one with its own characteristics, as will be described in the following sections. By doing so, the framework will be defined as a sequence of tasks that must be addressed in a systematic way to fully succeed in obtaining a sustainable recycling pathway for the management of solid waste.

The basic concept behind the framework is that for a recycling pathway to be sustainable four dimensions have to be considered in the evaluation. These dimensions are: technical, environmental, economic, and social, which will be called from now on as 4DS. Each one adds some necessary factors to the evaluation, as will be discussed in the following section.

4.1.2 Four Dimensions of Sustainability (4DS)

Every industrial process involves the presence of distinct resources, technologies, stakeholders, as well as regulations. However, for any practice to be sustainable, it should take into account four different dimensions which are: technical, environmental, economic, and social, that together constitute a sufficient set of factors to evaluate the impact of procedures such as recycling. This section describes such dimensions, their relevance, and how they can be evaluated.

First element to point out is that most of the practices that involve the recycling of materials as a waste disposal method just consider as an influencing factor the quality of such materials after the recycling pathway. However, demonstrating that it is possible to successfully recycle material is just the first of many other stages that need to be addressed to define a standard recycling pathway for it. Throughout the years, many studies have been conducted to recycle materials, without however focusing on the actual environmental impact of these practices. Being the recycling process already more sustainable with respect to the utilization of virgin material, most of the studies stopped at defining just the recycling pathway and understanding whether the new material is satisfactory or not. However, when recycling materials, in order to properly post-process them, more steps must be added to the chain (e.g. sorting, shredding, and melting in the case of mechanical recycling). Each of these steps consumes therefore more energy as well as other resources that must be taken into account when defining a pathway. What this research wants to evaluate is how every industrial process can be further improved to be more efficient from a technical, environmental, economic, and social standpoint. Moreover, instead of improving the recycling process after it is already implemented, it can be more efficient to analyze these dimensions beforehand and start with the adequate groundwork for where to build the recycling pathway.

As surfaced from the analysis of the literature, no one ever attempted to consider all these dimensions together. In general, just one of these aspects is always evaluated in the studies presented so far, whether it is technical, environmental, or economical. However, what is really missing when it comes to the evaluation of recycling processes for the sustainable management of resources, is their social impact. This factor must be always included in any evaluation, as most materials' management procedures involve, although to varying degrees, the release of chemicals or pollutants that can really harm populations' health and well-being. But the effect on society doesn't stop just at the air quality. Noise pollution, the hazardousness of processes and machinery, together with other factors that will be discussed later on, can potentially constitute a danger to populations. Every (recycling) practice has always a certain degree of social impact, both for positive and negative reasons.

For a recycling pathway to be considered sustainable, as this study will try to demonstrate, all four dimensions of sustainability (4DS in Figure 15) should be evaluated. By not taking into account even just one of them, there are risks to consider. In fact, it is possible that some problems, not considered in the initial phase, will be present in the future. Therefore it is important to try to tackle most potential issues beforehand, not to have to deal with them in a successive moment: that is how a process is really sustainable when it brings advantages in the present, but does not constitute dangers for the future. Otherwise, by just considering the short-term, the real sense of the improvement is lost.

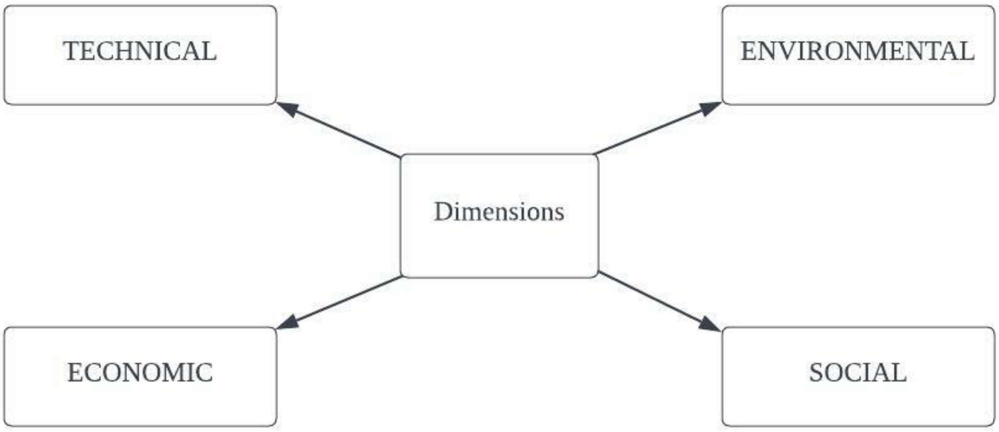


Figure 15 *Four Dimensions of Sustainability (4DS)*

Dimension I: TECHNICAL

The first dimension to take into account is the technical aspect of the process. The term ”technical” for the evaluation of recycling pathways involves all the variables related to the conservation and efficiency of resources, such as energy, water, and materials. Moreover, it is also connected to materials’ characteristics and quality, as well as technologies adopted for the recycling pathway.

Resource efficiency is a big branch of sustainability and sustainable development. For an innovation to be sustainable it absolutely should involve an efficient use of resources, by consuming less or even by producing them as well. However, companies should be aware that improving energy efficiency for instance, often requires an initial investment to switch technologies to more efficient ones, before potentially saving finances in the long term. This practice might therefore require capital as well as long times for its actual implementation. Energy consumption is crucial to define the impact of the practice. Some energy is consumed in all of the steps of the potential recycling pathway. Addressing and calculating all of them would be practically impossible. First of all, because the number of indicators that can be considered is almost unlimited, and second because, within the same indicator, there would be an unlimited number of variables as well. In the next sections, a methodology for selecting the most efficient set of indicators for recycling pathways will be presented and discussed.

The technical dimension of a recycling pathway involves also the characteristics of the recycled material itself. Understanding whether it is possible to obtain an acceptable quality for the new recycled material is undeniably essential. Fully discerning the strengths and the weaknesses of recycled material in terms of its quality allows also to be able to define potential applications for it. Otherwise, even the inverted processes can be adopted: starting from the selection of the application and then checking if the material meets the requirements to be successfully utilized. Depending on the application of the material, certain characteristics must be considered. Many different properties (mechanical characteristics, ease of design, degree of usability) can be looked at, according to the end-use of the material. Therefore, it is fundamental to define the requirements that the new material must have to be successfully recycled, otherwise, it is clear that the whole implementation of the recycling pathway would be futile.

Dimension II: ENVIRONMENTAL

The second aspect of sustainable production to analyze when adopting recycling pathways is the environmental dimension. It involves all the elements that first of all could generate emissions in the environment in any form such as greenhouse gases, polluting substances, acid gases, and chemicals. Waste and harmful byproducts resulting from a recycling pathway should be examined and managed in an efficient way. Environmental impacts are defined as changes in the environment, resulting directly from an activity, product, or service, that can have adverse effects on the ecosystem (Abdallah, 2017). Therefore, pollution, contamination, or destruction that occurs as a consequence of a recycling pathway, which can have short-term or long-term ramifications should be considered as environmental impacts and properly addressed. Any recycling process, whether it is mechanical or chemical, alongside its benefits to society as the reduction of wastes, can bring potentially harmful issues, and all of them must be evaluated before the actual implementation of the process, to avoid any risk to the environment and the society. Potential issues include air pollution, greenhouse gas emissions, noise, vibrations, waste disposal, and water discharges for instance. Moreover, it is important also to consider that not all of these impacts can show up immediately in the short term. The long term is generally where the actual environmental effect of a practice arises (Tchounwou et al., 2012).

A key goal of sustainable recycling practices is to reduce waste and manage efficiently its disposal, as well as reduce consumption of fossil fuels, to contain overall pollution, and global warming and contribute to the welfare of lands, oceans, forests, and populations.

Dimension III: ECONOMIC

Finances are and have been in history, one of the biggest drivers of innovation within any industry. The long-term economic performance of a process is, of course, a mandatory element to evaluate when to look at innovation. However, when it comes to recycling processes, with respect to the other dimensions, the boundaries between what it is worth to pay or not, are more blurred. The economic aspect of a recycling pathway is part of its sustainability asset, but while it is for example clear that environmental issues should be avoided, on the other hand, any company can deliberately decide where and how to invest the capital. The financial aspect, of course, greatly affects decisions about the recycling route. Moreover, a sustainable process such as recycling can be economically efficient, perhaps even saving or generating capital. It is also true that most of the time, an initial investment might be required for the success of a sustainable recycling pathway. Adopting new and more efficient machinery, hiring more staff, and investing in advertisements, are all examples of steps than involve capital expenses. Whether it is possible to invest in them or not of course depends on the budget and willingness of the single company. Nowadays, especially in the manufacturing industry, making processes more sustainable (e.g. with the adoption of recycling pathways) is a very efficient way to gain more customers and stand out from the competitors, which ultimately translates into more revenue.

The environmental aspect is for sure significant in contributing to the achievement of the climate goals, but it is also significant in terms of reputation and even media coverage that a company can benefit from, and this will then reflect in economic benefits as well (Clarke et al., 1994). In general, for a process to be sustainable from an economic standpoint, there are many possibilities. First of all, it is possible that it does not either produce or save money but it is affordable in the long-term; then in this case it is worth it if it brings advantages under any other sustainable dimension. An expensive process that on the other hand allows to improve populations' well-being, or other environmental benefits, or save materials and energy, can be seen as an investment for the future. All the sustainable dimensions are interconnected with each other (Clarke et al., 1994). Improving one aspect of them might be effective also to improve another one. Investing in expensive technologies, but less harmful to air quality, for example, prevents diseases, which can translate into fewer deaths, meaning, in a properly functioning economy, fewer people spending money on medicines and doctors but also more people available to work, make new discoveries and move the economy. That being said, a more sustainable company puts itself at a great advantage over the others, which calls inevitably more consumers.

What has been discussed so far is to point out that the risk of not making revenue from a recycling process within the manufacturing industry, as well as just adding costs, is real. Most of the time sustainable practices are more expensive, leading to more expensive products. The common opinion is that recycling tends to be more expensive than producing raw materials (Ettehadieh, 2011). In the current market ”recycled” products are always more expensive than their common counterpart, which brings first of all the consumer not to consider them (despite being intrigued by such sustainable products), and subsequently the supplier not to produce them anymore. However, recycling can bring benefits from other aspects, and in this case, as long as it is affordable for a company, it can anyways be worth the cost and the risk.

Dimension IV: SOCIAL

Another necessary dimension to consider, which is sometimes the least valued for the feasibility of recycling pathways, is the social dimension. According to the United Nations (UN), social sustainability is about identifying and managing business impacts, both positive and negative, on people (UN Global Compact, 2022). The social impact of a recycling practice for a company can be evaluated on many levels (with respect to the community, to other companies, and to the employees). The quality of a company’s relationships and engagement with other stakeholders is crucial. Even in this case, a company that takes care of the employees, for instance, gives value to work and follows ethical principles, might then convert all of it into revenues as well.
As Braveman and Gruskin argue equity and human rights are often seen as abstract concepts with little practical application (Braveman & Gruskin, 2003). However, the link between poverty and health has been examined in literature and it has been pointed out that together these factors are necessary elements to take into account for the society’s development (Braveman & Gruskin, 2003). Manufacturing industries can contribute to this development by adopting practices and methods that are respectful of human rights and health. The Nobel Laureate Amartya Sen defined five dimensions of social sustainability: quality of life, equity, diversity, social cohesion, and democracy and governance (Sen, 2013). A company that considers these dimensions for the determination of a recycling process can be considered socially sustainable. Moreover, according to the UN Global Compact, many are the advantages for businesses in aiming for social sustainability (ADEC Innovations, 2022). First of all, companies are more willing to make agreements with others that are more ethical. Secondly, social sustainability can mitigate risks. Providing safe working conditions, living wages, and job security, for instance, creates a more secure supply chain, together with higher em-

ployee happiness and engagement. Another important aspect of social sustainability is its role in culture, civilization, and education. Intellectual, ethical, and imaginative commitment is necessary to achieve the goals of sustainability and greater and progressive social justice.

Social sustainability must be considered in any recycling pathway. Materials recycling can have both advantages and disadvantages with respect to society. Some advantages are improved public health, an improved sense of global awareness, and a sense of community. Reusing and re-purposing wastes minimizes pollution. Also, by recycling material the need for new raw material is cut down, and with that natural resources are conserved (Kukreja, 2022). Recycling spreads environmental awareness. By sorting waste and adopting recycled products, it creates a chain reaction in which people become more conscious of environmental issues. Recycling also creates more jobs, since new recycling plants, together with a long chain of collection and delivery, should be set up, and these latter all involve human-made activities. It helps preserve a cleaner environment, and it can be a driver for scientific advancements and innovations (Kukreja, 2022). Scientific advances are producing less natural resource-intensive products making it easier to recycle numerous products (Kukreja, 2022). However, recycling can lead to potential issues for society. First of all, recycling sites are mostly unhygienic and unsafe. These can release pollutants in the air that can damage workers' and communities' health. Moreover, even if recycling creates jobs, the steps required for the most common recycling techniques (ex. sorting, washing, bleaching of wastes and byproducts) create low-quality jobs, that can lead to low morale and poor quality of life, together with low salaries (Kukreja, 2022). It is clear at this point that particular attention must be put to avoiding such potential issues, in order to obtain sustainable recycling pathways, that respect communities, and workers.

4.2 Overview of the framework

The methodology presented in this section has been developed on the basis of the principles of sustainable production as defined in different works of the Lowell Center for Sustainable Production (LCSP) at the University of Massachusetts Lowell. The Center since 1996 has been working on sustainable systems of production, subsequently developing the so-called Lowell Center Indicator Framework, a tool to enable companies to evaluate the effectiveness of sustainability indicator systems and to evaluate the ability of a set of indicators to inform decision-making and measure progress towards more sustainable systems of production (Veleva & Ellenbecker, 2001; Veleva et al., 2001). The LCSP defines sustainable production as: "the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and, socially and creatively rewarding for all working people" (Veleva & Ellenbecker, 2001; Veleva et al., 2001).

On the basis of such principles, the following framework has been developed to provide a tool for automotive companies for the adoption of sustainable recycling practices, according to the 4DS (technical, environmental, economic, and social) previously discussed. The main idea behind the framework is to help companies in the decision-making process for the selection of the most efficient and sustainable recycling pathway, through the analysis and evaluation of different potential alternatives.

The framework presented in this work aims to be fast to adopt, easy to use, and dynamic. In the automotive industry, there is a great variety of already developed processes and technologies that adopt different principles, as well as materials. However, the increasingly stringent national and international sustainability agreements and targets are pushing companies to become greener and to quickly shift towards sustainable production. Nowadays the industry is developing so fast that by the time a recycling method to improve technology is created, a new technology that can substitute completely the old one has been developed. On the other hand, economically, in the short term, it can be sometimes better to improve the current process and in the long term to substitute it with a new one. This means that, in any case, a fast implementation procedure is therefore needed and can be useful to quickly adopt sustainable improvements within the processes in the short term.

That being said, the fastest solution might appear to be the development of a standard pathway to adopt for any process. However, such a standard pathway for recycling doesn't exist and it is strongly argued by experts that it will never exist (Veleva & Ellenbecker, 2001). Sustainability involves many different aspects and each process has its own characteristics and materials. Some elements of sustainability that may apply in one context, may not apply as well in another one. Let's for example think about a recycling pathway that moves materials through many different countries. While working on reducing the distance between the different facilities, in this case, might be a very efficient improvement in terms of sustainability, for a company that has a recycling process established in one single facility the same procedure is not similarly useful. As for the second company, there might be a lack of sustainability in some other aspects of the recycling chain. In the end, it is clear that a tool for adopting sustainable recycling practices should not only be fast and easy to use but also should be dynamic and able to adapt to many different needs.

The ten-step framework for defining and selecting appropriate recycling pathways in automotive prototyping processes, developed for this work, is shown in Figure 16.

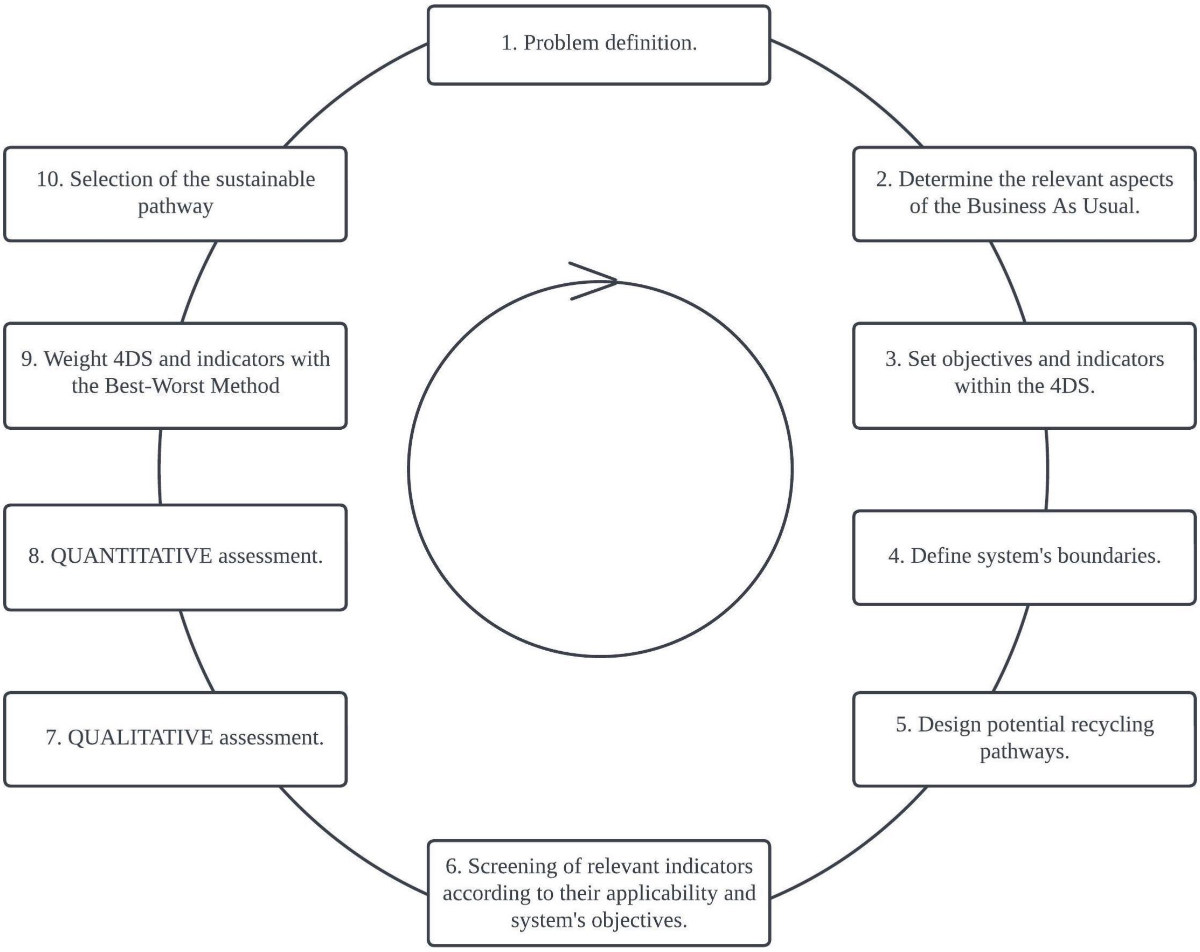


Figure 16 *Framework for evaluating sustainable recycling pathways in automotive prototyping processes*

4.2.1 Step 1: Problem definition

The first step of the framework presented in this work is the problem definition. The decision of improving the sustainability of automotive prototyping processes by developing a recycling pathway, in general, comes from an issue to be solved. Whether it is on a large scale such as to comply with new governmental policies or on a smaller scale such as waste accumulation or workers' complaints in a singular facility, this should be the first element to identify. Understanding the reason behind the need for developing a recycling pathway, will also help visualize the extent of the issue to tackle, therefore, it is necessary to obtain a consistent solution.

4.2.2 Step 2: Determine the relevant aspects of the Business As Usual

After the identification of the problem, an up-to-date description of the current system is needed. Having an idea of how the system (in which the recycling pathway should be implemented) currently works is the basis of the evaluation.

Relevant aspects to understand the current system can be multiple, depending on the single case. In general, the three main aspects to consider are certainly: **current waste management**, **data information**, and **stakeholders involved**.

For the implementation of a recycling pathway, it will be useful to understand how waste is currently disposed of for that particular material to recycle, whether they are destined for landfilling, incinerated for energy production, or simply incinerated. This information can be important when comparing the advantages and disadvantages of a recycling pathway over the current management system.

A key element for the success of the framework is data availability. Therefore, what information is being produced, who is using the information and how, how to access data, and which type of data resources are being used are some of the elements to look at when defining the current system. In this step just the way data is managed and accessed should be looked at, not the numbers themselves.
Specific questions to be answered can be:

- **What** type of data are adopted?
- **Who** is in charge of organizing the data?
- **Where** are the data stored?
- **How** to retrieve the data?
- **How often** are the data updated?

Key people involved and the type and status of technologies currently adopted are other elements that can help in understanding and collecting other relevant information for the design of potential recycling pathways. Determining who within the company itself (for example a project leader or a sustainability board) makes decisions about the recycling process, and what kind of information, is a cardinal element of this step. A stakeholders analysis, where it is clearly defined the degree of power/interest of the different actors, is important also to understand who can benefit/suffer from the implementation of a potential recycling pathway.

Moreover, other important information can be strengths and limitations of the system. Which elements of the Business As Usual can be kept as they are, and which others can or must be changed. In Step 1, described in Section 4.2.1, the issue causing the need for a recycling pathway has been defined, however, together with it, many other problems can arise from this analysis. Obtaining a recycling pathway that solves not only the already defined problem but also others, would just be an added value. Understanding what and if there is something else that must be improved can be helpful in defining the objectives in the next step (Section 4.2.3).

4.2.3 Step 3: Set objectives and indicators within the 4DS

Set objectives

The next step after the description of the current system is setting objectives. Meaningful objectives are necessary as they provide structure and direction to the work to be done, show progress and room for improvement, and communicate impact. Defining objectives that the recycling pathway must assess is a key step to reaching the goal, which is to solve the issue from Step 1, through the implementation of a sustainable recycling pathway on a realistic time scale. Setting specific, measurable, achievable, relevant, and time-bound (SMART) objectives is a useful way to plan the steps that the potential sustainable recycling pathway should meet (Doran, 1981). Objectives for a specific recycling pathway are proper to each company according to their goals and needs, for instance, for recycling pathways, some objectives might be common to many, for example, minimize waste, conserve energy, recover resources, save on disposal costs, and generate revenue. Objectives of the company as a whole should be considered too. These can be various, from a more general point of view like to meet national or international targets (like the EU goals), to a more specific one, unique for each company and process. Defining such objectives will give a clearer overview of how to reach the goal through a successful sustainable recycling pathway.

Select indicators within the 4DS

The selection of a substantial set of indicators that align with the objectives previously defined is essential to select the most sustainable recycling alternative, as they will provide real data on which to base the assessment.
As Krajnc et al. argue, indicators ”compress large amounts of information from different sources into a format easier to understand, compare and manipulate” (Krajnc & Glavič, 2003). Indicators enable the identification of more sustainable options through comparison of similar products made by different companies, comparison of different processes producing the same product, bench-marking of units within corporations, rating of a company against other companies in the sector, assessing progress towards sustainable development of a sector (Azapagic & Perdan, 2000). It is clear at this point that for the scope of this study, the selection of indicators is fundamental as it enables the comparison of the different recycling pathways.

However, it is not possible to set up sustainability indicators that are applicable to any company or organization, even if many different approaches for standardization have been proposed in the years. Each company has its own targets, objectives, and areas of expertise for instance for which an ad hoc selection of indicators must be performed. Most of the literature regarding sustainable indicators supports the idea that the indicators should address environmental, social, and economic sustainability (the so-called ”three pillar approach” (Iglesias, 2008)) (Veleva & Ellenbecker, 2001; Fan et al., 2010; Pavlovskaia, 2014; Krajnc & Glavič, 2003; Amantova-Salmane, 2018). However, as already mentioned in the overview of the systematic framework, for the comparison and selection of the most sustainable recycling pathway a fourth dimension is defined: the technical dimension. Indicators for the evaluation of recycling pathways within manufacturing processes should address all the four dimensions previously discussed (4DS: technical, environmental, economic, and social). Within each dimension, the indicators can be chosen according to the company's standards and goals, as well as main activities and targets. As Veleva and Ellenbecker argue, the approach of using indicators is dynamic, since businesses, companies, and technologies constantly evolve, and with them also the tools for sustainability assessment should as well (Veleva & Ellenbecker, 2001).

Being, indeed, variables, and indicators should be clearly formulated, easy to apply, and transparent. They should be linked with the sustainability goals and the objectives of the company. As Veleva and Ellenbecker show, indicators should have a **unit of measurement** and be considered in a **specific period of measurement** (Veleva & Ellenbecker, 2001).

Technical indicators

The indicators from the technical dimension involve all those indicators related to resource (energy, material, water) use, quality of the material, and technologies adopted. According to the differences within the companies and the procedures, different indicators should be chosen.

Resource indicators concern material use (raw material, recycled material, material from non-renewable sources), but also energy use (energy consumption, energy from renewables, energy savings) (Fan et al., 2010). Water use is another important aspect of resource utilization, as refineries, industries, and electric utilities use tons of water. Moreover, common recycling steps can be the washing and purification of the waste, therefore, water consumption can be potentially adopted as an indicator.

Every industrial process has its own particular set of resources to look at, however, some of them (especially energy use and recycled material use) should always be considered. It is possible to look at resource consumption in the form of the amount of energy consumed, electricity used, amount of virgin material saved and/or utilized, and expenses of fuel for transportation, among many other factors.

Being the scope of the recycling process to turn material into another form, it is also important to define some indicators that can assess the quality of the material obtained via recycling. These indicators can be related to the mechanical properties of the material (tensile strength, elongation at break for instance). Based on the potential application of the material it is indeed possible that some properties are relevant while others are not.

Technologies are another aspect to look at within the technical dimension, as they allow using and managing the resources in different ways. In this regard, it is important to understand if the aim is resource conservation and resource efficiency. While resource efficiency involves a shift toward technologies and processes that can perform the same functions as the ones before, while using fewer resources and still achieving the same (if not better) performance (European Commission, 2022). On the other hand, resource conservation is the practice to use fewer resources with the same technologies, it is about changing some behaviors or adopting practices that can save or even re-use the resources (Ahmad et al., 2022).

Environmental indicators

Indicators from the environmental dimension are mainly linked with the major key global issues (e.g. global warming, ozone depletion, acidification, nitrification, and so on) (Krajnc & Glavič, 2003). Amount of waste, air emissions, and pollution are aspects that are considered within the environmental dimension. Environmental indicators should reflect all elements that link the recycling pathway to its environmental impact (Smeets & Weterings, 1999). These can be in terms of emissions, such as CO_2, GHG. Moreover, they can be connected to the phenomena potentially originating from a recycling pathway, such as temperature, and level of noise. National and international policy targets can also set up some particular indicators to take into account when selecting a recycling pathway.

Economic indicators

Economic indicators are all those indicators related to economic data, that allow performing measurements to understand current and future activities and opportunities within a recycling pathway (Barone, 2021). Economic indicators can come from many different fields of analysis such as finances, prices, Gross Domestic Product (GDP), and profits. Employees' salaries for working in a recycling chain, the cost of materials and compounds, and the amount invested per recycling pathway are just some of the economic indicators that can be selected. Moreover, economic indicators are not related just to costs directly, but they can be considered in other forms, such as the number of employees or stakeholders involved, the percentage of the material sold, as well as the amount of space adopted for the recycling process chain.

Social indicators

Indicators from the social dimension are always the most challenging to define, for two main reasons. First of all, as Krajnc et al. suggested, the social aspect of sustainability in some cases cannot be easily quantitatively expressed (Krajnc & Glavič, 2003). Most of the social indicators are based on questionnaires and people's preferences. However, some indicators that reflect people's (populations, communities, employees) well-being can be considered in more objective terms. Some of these indicators can be payment ratios for employees from different social categories, promotion rates, community population growth, the number of jobs that the recycling pathway can create, and employee turnover, just to mention a few. Social indicators involve also the safety of the workers in the workplace. Most of the recycling pathways involve steps such as shredding in the case of mechanical recycling or the use of solvents in the case of chemical recycling, which can be potentially dangerous for the employees. Therefore other important indicators that can be considered are for instance lost workdays due to illness or injury, or the number of accidents in the workplace.

As shown, many different indicators can be chosen in this step. To facilitate the process, some reports that provide lists of potential indicators can be found in Appendix A.

The result of this step should be, together with the objectives, a set of at least five indicators per each of the 4DS, selected according to what has been discussed so far, to compare them in the next steps, among the different recycling pathways.

4.2.4 Step 4: Define system's boundaries

After the definition of the objectives that must be considered to reach the final goal, is necessary to define and distinguish system boundaries and factors. Defining system boundaries highly influences the analysis as they separate what should be part of the system and what should be left outside. On the other hand, factors define what can be done and what cannot be done within a potential recycling pathway. Understanding in which direction it is possible to move towards will make the decision-making process and the following steps faster and more efficient. Indeed, while some limitations are very noticeable and can stop the process in an early stage, some others are invisible, and they can arise in successive moments. These can not only pose an obstacle to overcome, but also a real impediment that can cause to go back to the starting point of redefining the pathways. Therefore it is important to understand most (if not all) the potential limitations, as well as possibilities, of the process, to have afterwards a clearer route. Possibilities and limitations, in this case, depend on many different factors. For the scope of the framework, these factors have been divided into two categories: *direct factors* and *indirect factors*.

Direct factors are all those aspects in which real limitations might occur, which do not depend on the company or the decision-makers within it. These are tangible and in some cases also measurable. From the research conducted and the experience within industrial and automotive production processes, seven categories have emerged that cover the possible direct factors: geographical, temporal, economical, ecological, safety, health and well-being, and regulations.

1. **Geographical**: geographical limitations that can interrupt or impede the implementation of a recycling process can be for natural reasons such as the appearance of the landscape or climate conditions or human-made such as the presence of wars. Such conditions change from land to land, therefore they can shift the decision of adopting one practice or another, one step or another, and where. For example, the option of a recycling pathway that involves the movement of material into a land where there is a war ongoing can inhibit the process. Moreover, it is important to point out that geographical limitations cover any extent of land, even on the small scale. For example, a company having scarce storage space in a facility can have a reason to adopt one more step over another.

2. **Temporal**: Temporal limitations are mainly due to any type of deadline, especially when working with projects for big companies it is most of the time difficult, and in any case inefficient, to shift time limits for a particular goal. Planning, whether it is for the short-term or the long-term, for example for reaching EU goals, can influence the decisions on what to consider within the system.

3. **Economical**: Economical constraints are of course always considered in any decision-making process. Having enough budget to implement practices and pursue them, is most of the time the element that allows making certain decisions in the first place.

4. **Ecological**: Respect for plants and wildlife, as well as natural habitats and any kind of organism is in general an underrated limitation. Aside from the fact that the most urgent environmental issues are regulated to a certain degree by agreements and legislation, it is important to draw a boundary between what is still within the respect of the environment and what already overcomes the boundaries (or is borderline) and can potentially result into exploitation, in the present or future production.

5. **Privacy**: Privacy involves all the limitations that can result in protection issues, either for workers or information. Information security and protection of confidential data within companies and processes are regulated. Being aware of how and which kind of information to convey before the implementation of a process and arranging a proper security system, can mitigate, if not avoid, many risks for the future.

6. **Health and well-being**: Health and well-being involve the protection of populations, and personnel, from being harmed in any way. Safety in the workspace is a very relevant aspect of social sustainability, therefore it has to be taken into account from the very beginning of the procedure, even before evaluating the different alternative solutions. A socially sustainable company should discard in the first place all the solutions that might put in danger the safety of the employees, especially in the manufacturing industry, where most of the process involves manual work and the adoption of tools and machinery, this is a very crucial part of the evaluation. It is possible to define health and well-being requirements on many levels. For a recycling pathway, these levels can be society as a whole, communities, and the production line of the recycling chain. This aspect covers mainly all those practices that implicate the release of chemicals and toxic gases, as well as any kind of byproduct in the environment. Such an aspect of production is another one of those whose effect could be mainly seen in the long term. By acting on it in an early stage of development the risk of harmful effects in the future can be alleviated. Mitigating such risks not only will help to improve the quality of life for people but also can be seen as a way for preventing future losses. Tardily realizing after the implementation of a recycling pathway that this is causing not foreseen diseases for the personnel, will constitute a reason to change it again and restart the process.

7. **Regulations**: Despite some regulations are actually involved to a certain degree in most of the factors discussed so far, the subject of the Law covers many other aspects that according to the particular single case or the specific country can be taken into account. Countries' regulations play a big role in the definition of the system, not ending up in illegal pathways and procedures is a quite straightforward concept which, however, must be considered.

All these factors just presented cover circumstances in which the decision-maker is not completely free to choose; his decision is conveyed by these factors that must be respected. The direct factors can be arranged in a wheel scheme, as shown in Figure 17. The shaded gray section should include all the elements that are outside of the system definition, according to the different factors considered. Such factors are defined in this step of the framework and they will be considered throughout the whole selection of the sustainable pathway, starting from the design of potential recycling pathways in the next step of the framework (Step 4.2.5). The selection of the factors that are considered or not in the system will make the process of definition of the recycling pathways easier and quicker as it will be already visualized what can or cannot be done.

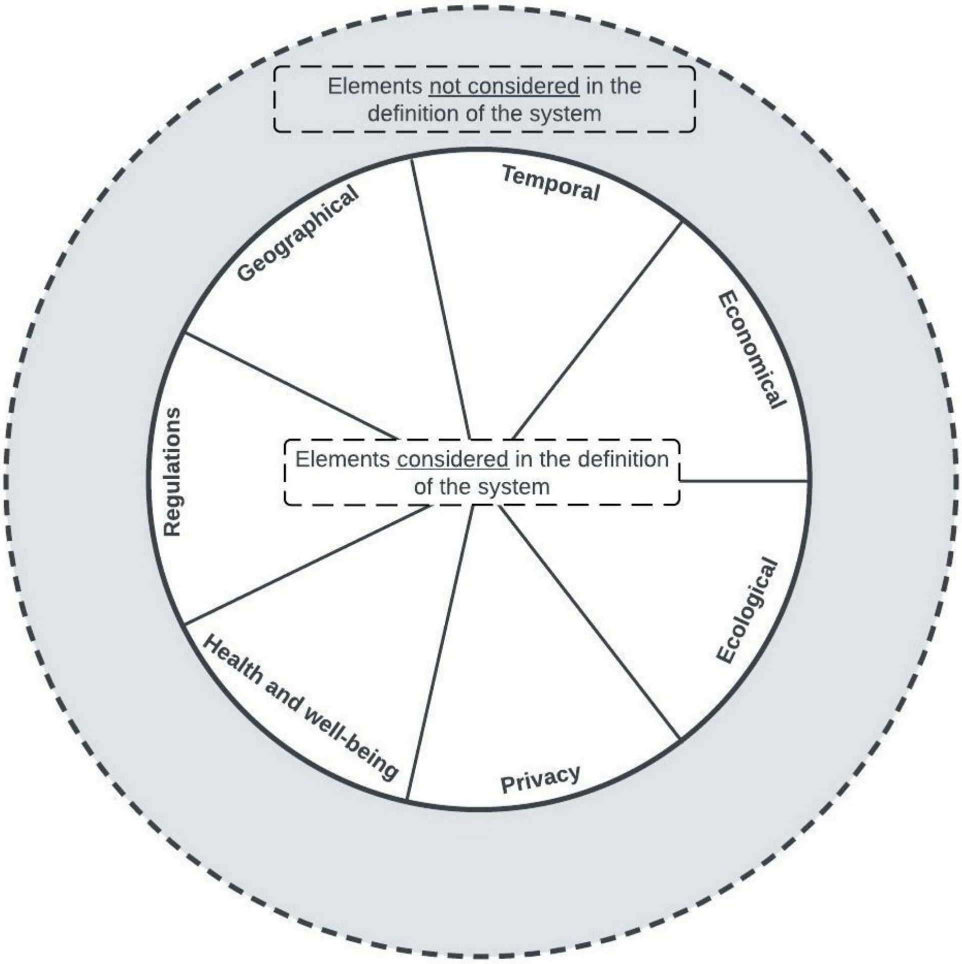


Figure 17 *Wheel scheme of direct factors for the sustainability assessment in the system definition*

There is also a group of circumstances in which the decision-maker has the possibility to decide whether to follow a particular route or not, but it is likely that he won't. In this work, these circumstances are categorized under the so-called *indirect factors*.

Indirect factors are all those limitations that are merely based on the willingness and choices of the single company. These are limitations that are almost never considered actual barriers to a decision-making process because most of the time is taken for granted, but it should not be the case. First of all, there are many ethical reasons why a company might decide not to follow a specific pathway. Just to provide an example, a company will arduously establish relationships with other stakeholders with whom it doesn't share the same values. Of course, it can be done, but it is likely that it will choose not to. This will also benefit the company itself as it would show integrity in other people’s eyes.

Throughout the years, many works pointed out the relationship between social justice and especially spirituality with environmental destruction. In their work, Dylan and Coates, from St. Thomas University (Fredericton, New Brunswick, Canada), argue that social injustices linked with environmental destruction usually remain at the margins of work practices (Dylan & Coates, 2012). They explained the relationship between social and environmental justice, and how globalization-induced social issues are rarely considered in new practices. Child labor, discrimination of any kind, and inequalities in the workplace can all have repercussions on the environment. Many reports reported how for example climate change in the form of drought, heavy rain, and other extreme weather is destroying farmland in many developing countries. This forces families to migrate and send their children to work in hazardous conditions to support the household and sabotages children’s education by interrupting their schooling and making them prioritize employment instead (Terre des Hommes, 2017).

Moreover, Dylan and Coates reported many frameworks and models developed in the years that are aimed at promoting meaningful collaboration toward environmental and social sustainability. They examined justice issues in the context of contemporary environmental challenges, giving emphasis to spirituality. They argued that this factor is in general situated at the periphery in the formulation of modern innovation and practices. As Dylan and Coates discuss in their ”The Spirituality of Justice: Bringing Together the Eco and the Social”: ”spirituality can play a vital role in drawing social and environmental injustices together enabling a truly transformative and radical practice” (pg.128) and likewise ”spirituality has an important role to play at the juncture of the environmental and the social, through acting as a vital arm in the facilitation of change, an organizing matrix, and a lubricant for social mores, and catalyst for long-term thinking” (pg.137) (Dylan & Coates, 2012).

In the same route as ethical reasons and moral principles (spirituality, equality, justice among others) another factor to take into account for companies that want to implement recycling pathways in their processes is competition. Considering that this is not a substantial limitation, and therefore each company can freely decide with whom to stipulate agreements, it is generally safer not to undertake dealings or develop processes involving companies that themselves have relationships with competitors. Especially for recycling pathways, these may involve the movement of materials and machinery from one company to another, therefore, it is important to be aware of other companies’ relationships, to prevent any unwanted misplacement.

4.2.5 Step 5: Design potential recycling pathways

The next phase is to design alternative recycling pathways that can potentially be a solution for the issue detected at the beginning of the process. Such recycling pathways should also comply with the system boundaries and factors. This is the step in which concrete ideas are explored and developed to come up with a succession of steps that can constitute the recycling pathways.

The framework presented in this work consists of the decision-making process of evaluating the most sustainable recycling solution among a set of alternatives. It is important to notice at this point that the identification of the drivers and limits of the process prior to the definition of potential recycling solutions gives a clearer idea of what can be considered and what not, in order to speed up the procedure. Defining beforehand many different possibilities can help to have a clearer idea of how the variables are dependent on each other. The identification of what must be modified, and the subsequent effects of such modification, in this way, can be better understood, in a quicker and more effective way.

Potential elements to identify in this phase can be:

- Materials: type of material, adoption of compounds and/or mixtures
- Type of recycling method
- Location facilities
- Type of technologies: current and alternatives technologies and possible improvements
- Stakeholders involved
- Mandatory, optional, and unnecessary processing steps
- End-use of the recycling material: adopting it for the same application or repurposing it for new ones
- Potential outcomes of implementation: an initial assessment based on qualitative and conceptual definitions.

An important concept to always keep in mind during the definition of potential pathways is that they should be easy to manage, clear, and straightforward. A complicated solution is almost never sustainable especially when it involves several passages as well as stakeholders. It would be necessary to take too many elements into account and the risk is always losing track of something, which is exactly what this methodology wants to help to avoid. Moreover, a recycling pathway must be implementable in the long term. Therefore all the steps must be consistent. Completing the recycling process once doesn't guarantee to be able to reproduce it continuously.

This phase of the framework can be compared to the *synthesis phase* proposed by Joore and Brezet in their Multilevel Design Model (MDM) for the development of products and product-service systems. As they discuss in their work "during this step, new creative directions are being explored, resulting in a description of a new possible solution. This phase is often considered the 'real' design phase, as new concepts and solutions are being generated, created, described, and visualized. In product design, this is often done by means of drawing and sketching. In product-service design, various other tools are available like the creation of solution maps, future scenarios, and storyboards" (Joore & Brezet, 2015). The creation of alternative recycling pathways can be done in the same way.

A first approach for the design of recycling pathways is by *analogy*. A useful step is to look for similar problems and understand how they have already been solved. Look for similar materials, and understand how they've been recycled. The analysis and exploration of what is already available in literature can save time and effort, for a more efficient decision-making process. Such research can constitute a starting point for the evaluation and achievement of different alternatives on an already developed frame. In this regard, interviews and exchanges with experts in the field can be very useful. What is stressed throughout the whole framework is that a recycling pathway to be sustainable should be compatible with all the four dimensions (4DS: technical, environmental, economic, and social) already presented. These dimensions cover a very broad spectrum of expertise and competence, therefore bringing together different specialists from different fields of expertise might be the appropriate solution to avoid overlooking some dimensions and with them some indicators. Developing pathways by analogy means looking for similar procedures where to change something (step, machinery, partners) each time, but maintaining the core structure constant.

A second approach is designing pathways for *opposition*. This work supports the idea that it is always more efficient to start from a basic set of steps, which can potentially constitute the basis where to start the definition of the other solutions, by adding steps and/or changing them. Adopting different technologies, mixtures, and stakeholders, for instance, is a way to deal with this step. This procedure is particularly useful when there are a lot of constraints that therefore limit extensively the decisions. On the other hand, it is possible to look also for solutions very different from each other, or even opposite in some cases. This will definitely be possible when there is a broader range of action, but it might be a longer and more complicated procedure, with fewer constants and more variables.

At the end of this design phase the expected outcome is a set of alternative recycling pathways that can be potentially adopted. All the needed steps to follow to obtain such recycling pathways should have been identified and described. Here is where the comparison between them can begin, to understand which one is the most sustainable pathway, according to the 4DS (technical, environmental, economic, and social).

4.2.6 Step 6: Screening of relevant indicators according to their applicability and system's objectives

The relevance of an indicator generally can be evaluated according to **alignment with the objectives**, **data availability**, **differences between the pathways**, and **end-use of the material**. Selecting indicators that align with the objectives is necessary to obtain a suitable and sustainable recycling pathway to reach the goal. The number of indicators selected per dimension can be multiple but in this phase, at least five indicators per dimension must be chosen. This is to make sure to have a sufficient amount of indicators to perform a preliminary qualitative evaluation.

Moreover, since indicators are variables, these must be calculated, therefore, data availability is fundamental to be able to reach a result. It is more efficient to check this factor in this early step, to avoid missing data in successive moments.

On the other hand, the various indicators for evaluating the best among all the potential pathways can be easily selected on the differences between them. If there are some constants within the processes it would be inefficient to base the considerations on them, since they, indeed, do not change. According to how the potential solutions have been found (analogy or opposition) it can be more or less easy to recognize what they differ. If the pathways have been selected by addition or subtraction of steps and variables to be considered, this stage will for sure be smoother. Variations can involve relationships with different stakeholders, different locations for the process chain, as well as technologies, types of machinery, and others. For example, it would be inefficient to adopt as a social indicator *the number of international partnerships* if all the recycling processes considered involve stakeholders based in the same country, as this calculation will not be significant for the final choice. At the same time, for two or more pathways that involve shipments of goods among countries, it would make sense to calculate *the number of kilometers traveled per pathway*, as this will have consequences in many aspects of the sustainability of the different pathways.

Another element to consider when selecting proper indicators is the final potential outcome of the material/process. Understanding the end-use allows, as already mentioned before, to define some requirements that the recycling pathway should fulfill, and this can be achieved through the selection of the indicators.

Figure 18 describes the process of screening the indicators. The idea behind this step is to take each indicator previously selected, and decide whether to keep it or discard it according to its applicability and the system's objectives. In the end, a list of indicators after the screening should result, that will provide the input for the next step (Step 7: qualitative assessment 4.2.7).

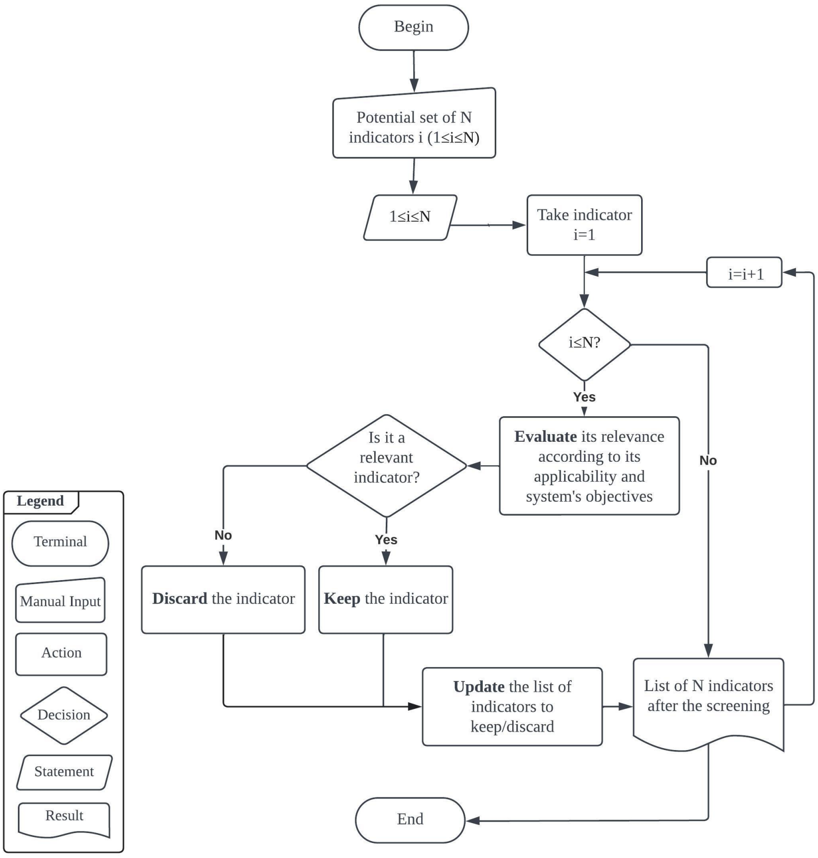


Figure 18 *Flowchart for the screening of the indicators*

4.2.7 Step 7: Qualitative assessment

Prior to the actual calculation of the indicators per pathway, it is necessary to make sure that the chosen indicators will lead to a significant result. The method presented in this work consists in calculating each indicator for each potential recycling pathway and then selecting the pathway that presents the indicator that best meets the objectives, with respect to the other alternative pathways. However, it is possible that this method leads to certain situations in which the results are not substantial. For example, it might happen that one indicator results to have the same value for all the pathways, or after having selected a particular indicator it is realized that there is not enough information or data available to calculate it. These are situations that might lead to slowing down the process of defining the most sustainable recycling practice. As already mentioned, prior to the calculation with actual numbers and data for each pathway and each indicator, it makes sense to perform a qualitative assessment of the different pathways to determine whether the chosen set of indicators allows for obtaining meaningful results. The process to conduct this qualitative assessment is represented in Figure 19.

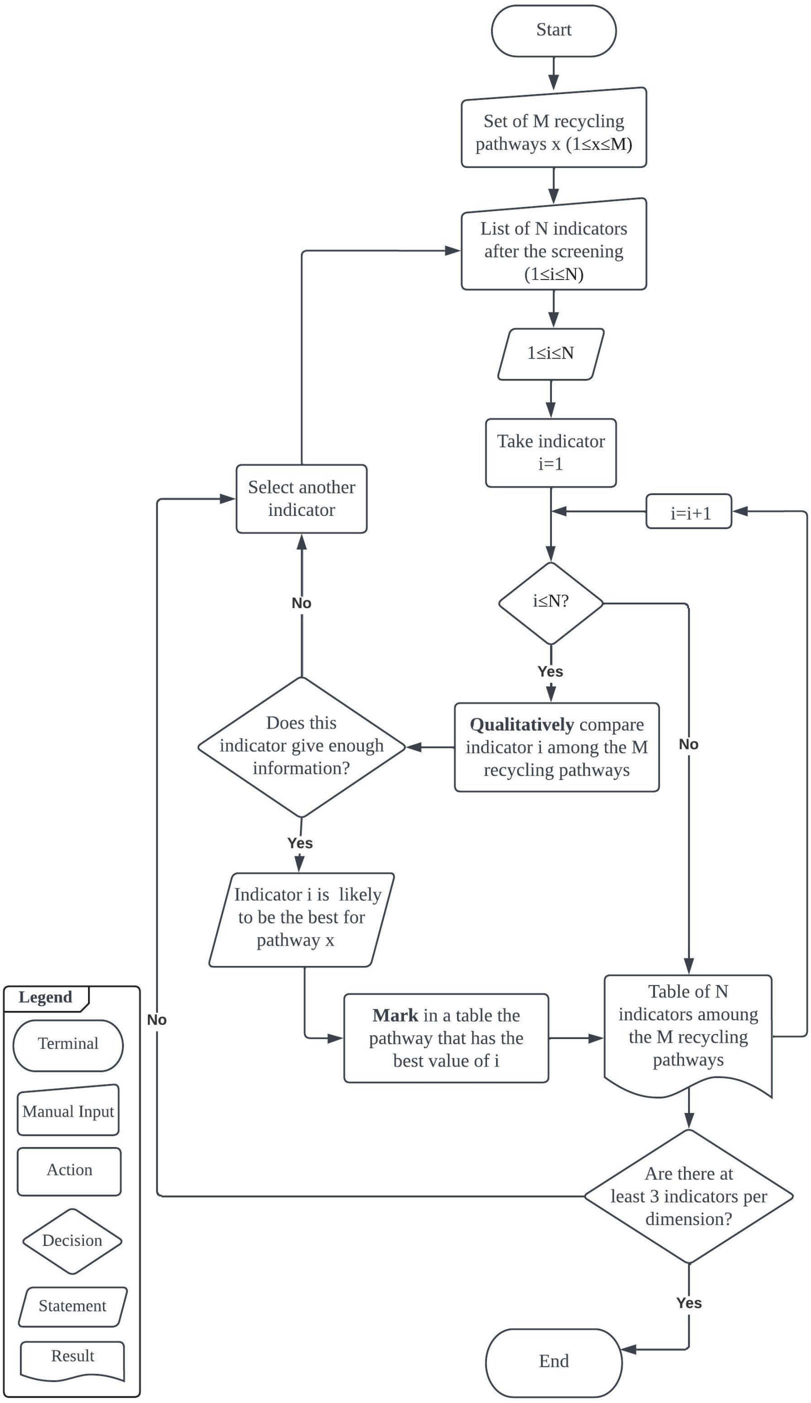


Figure 19 *Flowchart for the Qualitative Assessment*

Once a potential set of N indicators has been defined from Step 6 (Section 4.2.6), it is possible to evaluate each one within a set of M recycling pathways (defined in Step 5, Section 4.2.5). The method consists in starting with the first indicator (i=1) and qualitatively comparing it among all the different M pathways. If this qualitative approach gives meaningful results, and if enough data is available for the calculations, then it can be kept, otherwise discarded. Then, the next step consists in documenting (in a table such as Table 1) the recycling pathway against the indicators and marking with an X the pathway that presents the indicator ”i” that is most likely to meet the objectives.

	Pathway A	**Pathway B**	**Pathway C**	**Pathway D**	**Pathway E**
Indicator 1	X				
Indicator 2		X			
Indicator 3				X	
Indicator 4			X		
Indicator 5			X		
Indicator 6				X	
Indicator 7				X	
Indicator 8		X			
Indicator 9			X		
Indicator 10	X				
Indicator 11				X	
Indicator 12			X		

Table 1 *Substantial set of indicators: there are some pathways (C, D) with a higher number of indicators, and one pathway (E) can be discarded since it has no indicators*

In the following section, a practical example is given to clarify the procedure.

Practical example for the qualitative assessment

Objective: Minimize carbon footprint.
Indicator i: Total vehicle distance traveled (km).

- Scenario A: all the steps of the recycling pathway are within *Bayern*.
- Scenario B: all the steps of the recycling pathway are within *Germany*.
- Scenario C: all the steps of the recycling pathway are within *Europe*.

Result: Indicator i is likely to have the best value for scenario A. Shorter distance traveled means less carbon dioxide (CO_2) equivalents emitted per person to travel one kilometer. This value of course changes according to the mean of transport adopted, however, the evaluation in this step should be qualitative, more a forecast than a precise calculation.

The same procedure should be applied to each indicator (i=1,...,N). All the indicators that don't give any meaningful result or for which there is not enough information available must be discarded. It is important at this point to point out that for the scope of the framework presented in this work, at least three indicators per dimension should be included at the end of this qualitative assessment, therefore, after having discarded some indicators, if needed, others should be selected. In the end, a table (matrix) of N indicators (at least three per dimension) and M recycling pathways should be the result of this qualitative comparison.

According to how the N indicators are distributed in the table among the M scenarios it should be easily possible to understand if the results of this step are meaningful. For example, one or more scenarios should present a higher number of indicators with respect to the others, as shown in the example in Table 1. Indeed, in this example, it is possible to suppose that the recycling pathways C and D, with the highest number of indicators, are likely to be also the most sustainable ones. On the other hand, the recycling pathway E, with zero indicators, can potentially be discarded. However, these results come from a qualitative assessment, where no indicators have been calculated with real data, it is therefore suggested (especially when the distribution of the indicators among the recycling pathways is almost even), to keep considering all the different alternatives.

This step allows also to perform a first screening of the different recycling pathways selected. The aim is to understand if it is possible to narrow down the list of recycling alternatives and to perform fewer calculations afterward.

4.2.8 Step 8: Quantitative assessment

Once a set of indicators, that can potentially give substantial results, has been found on the basis of the previous qualitative analysis, it is possible to start with the quantitative assessment.

During this stage of the framework (Step 8 in Figure 16) each indicator should be calculated per each recycling pathway on the basis of real data.

The expected result is a matrix containing all the values of the indicators associated with each pathway considered. For each indicator, it would therefore be possible to select the value of the indicator that best meets the objectives among the different recycling pathways.

At the end of this step, a table similar to Table 1 from the previous step, but based on real data, should be obtained, where the indicators that best meet the objectives have been chosen for each recycling pathway considered. Even in this case, it would be possible to narrow down, even more, the set of potential alternative recycling pathways, in order to select the ones that, at the end of this stage, look more reasonable.

4.2.9 Step 9: Weighting dimensions and indicators: Best-Worst Method

Once the recycling pathways to compare and the indicators on which to base the comparison have been chosen, the process for the selection of the most sustainable alternative pathway can begin.

This work supports the idea that to perform an evaluation of sustainability, both the four dimensions and the indicators within them should have different weights (importance) on the decision-making process, according to companies' needs, interests and objectives. In fact, even if it is essential to consider all the dimensions, for a particular company one of them might be more important than another one.

The reason why each dimension should have at least a minimum weight is to avoid any extreme towards one dimension or another. All the dimensions should be considered in a balanced way. In fact, for a small company with little capital that has yet to grow in the market, it is possible that the only two dimensions that matter are, for example, economic and technical. On the other hand, for a large company with plenty of capital, the economic dimension might then not be so relevant. However, for a sustainable recycling path, all dimensions should be considered, albeit to varying degrees, without extreme situations.

The weighting method proposed in this work both for the indicators within each dimension, and for the four dimensions between each other, is the Best-Worst Method (BWM) developed by Jafar Rezaei, from the Delft University of Technology, in 2014 (Rezaei, 2015). This method has been developed to solve multi-criteria decision-making (MCDM) discrete problems, where a number of alternatives (in this case the recycling pathways) are evaluated with respect to a number of criteria (the indicators) in order to select the best alternative. For the scope of the present work, the BWM will be applied between the dimensions and inside each dimension between the indicators to assign a weight to each of them.

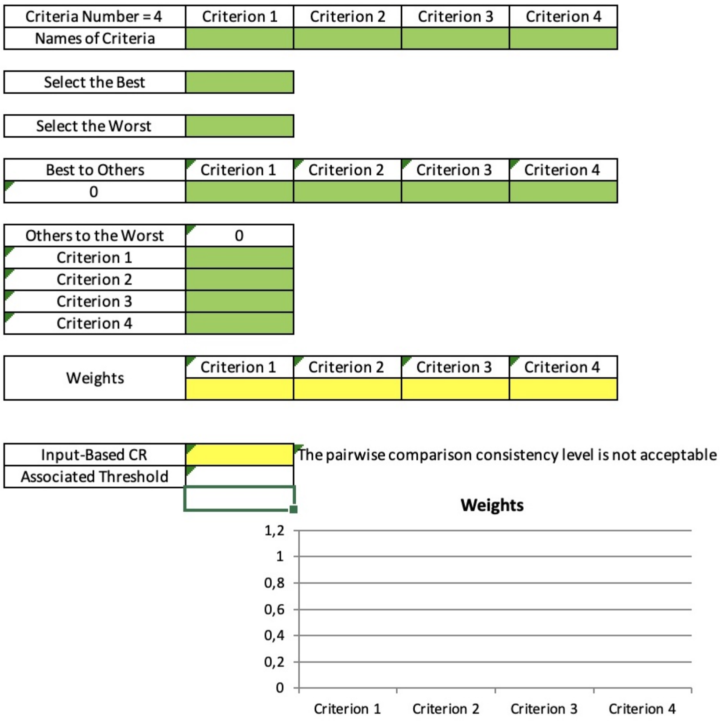
According to the BWM, the best criterion and the worst criterion within a set of criteria to weight are identified first by the decision-maker. Subsequently, pairwise comparisons are conducted between these two criteria (best and worst) and the other criteria (Rezaei, 2015).

For more information regarding the BWM it is suggested to check Rezaei's paper "Best-worst multi-criteria decision-making method" (Rezaei, 2015). However, to make the explanation of the framework clearer, a short description of the method is presented in Appendix B.

For the scope of the framework proposed in the present work, the BWM must be applied on five sets of criteria:

1. the four dimensions of sustainability 4DS.
2. the indicators within the *technical* dimension.
3. the indicators within the *environmental* dimension.
4. the indicators within the *economical* dimension.
5. the indicators within the *social* dimension.

To simplify the procedure, an Excel Solver provided by the author of the method has been used to assign a weight to dimensions and indicators within the dimensions. Such Excel Solver has been defined according to the number of criteria to weight. Figure 20 for instance, shows the solver for a set of four criteria.



Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria				

Select the Best	

Select the Worst	

Best to Others	Criterion 1	Criterion 2	Criterion 3	Criterion 4
0				

Others to the Worst	0
Criterion 1	
Criterion 2	
Criterion 3	
Criterion 4	

Weights	Criterion 1	Criterion 2	Criterion 3	Criterion 4

Input-Based CR	
Associated Threshold	

The pairwise comparison consistency level is not acceptable

Figure 20 *Excel solver for the Best-Worst Method*

The table must be filled with the names of the criteria, the best and the worst criteria, and the preferences from 1 to 9 following the steps proposed for the BWM and by clicking on the solver this gives the weights of the criteria selected and the consistency level. For the aim of the work, just the weights that show an acceptable consistency level must be used.

However, as the weights the indicators are valued with can change according to the user, it is recommended when performing the weighting to organize the consensus within the company in order to obtain repeatable calculations. How the consensus should be assessed within the company is a very broad topic which is out of the scope of the current research. Moreover, despite being aware of the complexity of such theme, the idea behind the framework is to provide easy assessment procedures that can be conducted in short timeframes, and by everyone.

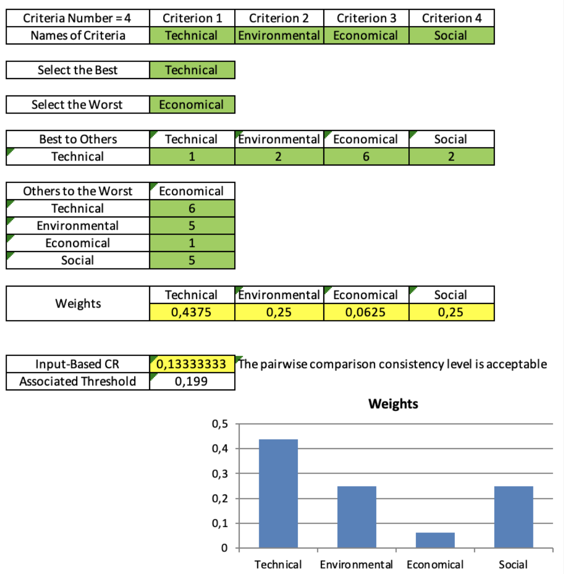
Example 1: weighting using the BWM Excel Solver

Let's suppose for simplicity of the explanation to have twelve indicators (from 1 to 12).

The indicators are distributed within the dimensions as follows:

- Indicators 1,2,3 - TECHNICAL dimension
- Indicators 4,5,6 - ENVIRONMENTAL dimension
- Indicators 7,8,9 - ECONOMIC dimension
- Indicators 10,11,12 - SOCIAL dimension

After the calculations with the BWM (Figures 21 and 22), the weights of the dimensions and the indicators are summarized in Table 2.



Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Technical	Environmental	Economical	Social

Select the Best	Technical

Select the Worst	Economical

Best to Others	Technical	Environmental	Economical	Social
Technical	1	2	6	2

Others to the Worst	Economical
Technical	6
Environmental	5
Economical	1
Social	5

Weights	Technical	Environmental	Economical	Social
	0,4375	0,25	0,0625	0,25

Input-Based CR	0,13333333	The pairwise comparison consistency level is acceptable
Associated Threshold	0,199	

Figure 21 *BWM for the 4DS*

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Indicator 1	Indicator 2	Indicator 3

Select the Best	Indicator 1

Select the Worst	Indicator 2

Best to Others	Indicator 1	Indicator 2	Indicator 3
Indicator 1	1	7	2

Others to the Worst	Indicator 2
Indicator 1	7
Indicator 2	1
Indicator 3	5

Weights	Indicator 1	Indicator 2	Indicator 3
	0,596153846	0,076923077	0,326923077

Input-Based CR	0,071428571	The pairwise comparison consistency level is acceptable
Associated Threshold	0,1294	

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Indicator 4	Indicator 5	Indicator 6

Select the Best	Indicator 6

Select the Worst	Indicator 5

Best to Others	Indicator 4	Indicator 5	Indicator 6
Indicator 6	2	8	1

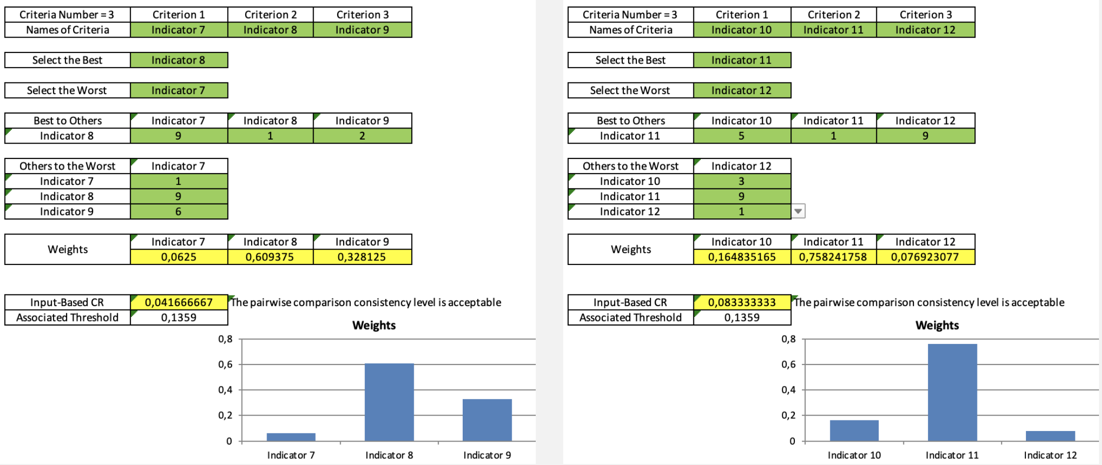
Others to the Worst	Indicator 5
Indicator 4	5
Indicator 5	1
Indicator 6	8

Weights	Indicator 4	Indicator 5	Indicator 6
	0,321428571	0,071428571	0,607142857

Input-Based CR	0,035714286	The pairwise comparison consistency level is acceptable
Associated Threshold	0,1309	

(a) *Technical indicators*

(b) *Environmental indicators*



Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Indicator 7	Indicator 8	Indicator 9

Select the Best	Indicator 8

Select the Worst	Indicator 7

Best to Others	Indicator 7	Indicator 8	Indicator 9
Indicator 8	9	1	2

Others to the Worst	Indicator 7
Indicator 7	1
Indicator 8	9
Indicator 9	6

Weights	Indicator 7	Indicator 8	Indicator 9
	0,0625	0,609375	0,328125

Input-Based CR	0,041666667	The pairwise comparison consistency level is acceptable
Associated Threshold	0,1359	

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Indicator 10	Indicator 11	Indicator 12

Select the Best	Indicator 11

Select the Worst	Indicator 12

Best to Others	Indicator 10	Indicator 11	Indicator 12
Indicator 11	5	1	9

Others to the Worst	Indicator 12
Indicator 10	3
Indicator 11	9
Indicator 12	1

Weights	Indicator 10	Indicator 11	Indicator 12
	0,164835165	0,758241758	0,076923077

Input-Based CR	0,083333333	The pairwise comparison consistency level is acceptable
Associated Threshold	0,1359	

(c) *Economic indicators*

(d) *Social indicators*

Figure 22 *BWM for the indicators within the four sustainable dimensions*

	Weight		Weight
Technical dimension	0.4375	**Indicator 1**	0.596
		Indicator 2	0.077
		Indicator 3	0.327
Environmental dimension	0.25	**Indicator 4**	0.321
		Indicator 5	0.072
		Indicator 6	0.607
Economic dimension	0.0625	**Indicator 7**	0.063
		Indicator 8	0.609
		Indicator 9	0.328
Social dimension	0.25	**Indicator 10**	0.165
		Indicator 11	0.758
		Indicator 12	0.077

Table 2 *Example 1: weights of each indicator within each dimension with the BWM*

At this point it is important to check in Table 2 that the sum of the scores of the indicator within each dimension is equal to 1.

4.2.10 Step 10: Selection of the sustainable recycling pathway

After the weighting procedure based on the BWM solver, both for indicators and dimensions, the final scores of each recycling pathway are then calculated by multiplying the weight of each indicator and the weight of the dimension where it belongs and then aggregating the scores of the indicators per each recycling pathway.

Example 2: evaluating the most sustainable recycling pathway

Following the data from Example 1 in Section 4.2.9, it is possible to perform the rest of the calculations to select the most sustainable recycling pathway.

Step 1
As shown in Table 3, the first step is to multiply the weight of each indicator by the weight of its dimension.

	Weight		Weight	Calculation	Score
Technical dimension	0.4375	**Indicator 1**	0.596	0.4375*0.596	0.261
		Indicator 2	0.077	0.4375*0.077	0.034
		Indicator 3	0.327	0.4375*0.327	0.143
Environmental dimension	0.25	**Indicator 4**	0.321	0.25*0.321	0.080
		Indicator 5	0.072	0.25*0.072	0.018
		Indicator 6	0.607	0.25*0.607	0.152
Economic dimension	0.0625	**Indicator 7**	0.063	0.0625*0.063	0.004
		Indicator 8	0.609	0.0625*0.609	0.038
		Indicator 9	0.328	0.0625*0.328	0.021
Social dimension	0.25	**Indicator 10**	0.165	0.25*0.165	0.041
		Indicator 11	0.758	0.25*0.758	0.190
		Indicator 12	0.077	0.25*0.077	0.019

Table 3 *Example 2: Step 1 - Calculation of the weight of each indicator within each dimension*

Step 2

The second step consists in assigning the weight of the indicator to the recycling pathway that presents the value of that indicator that meets its objective. Let's suppose for simplicity to have two recycling pathways to compare (A and B). After the calculation of each indicator per each pathway, thus after the quantitative comparison (Step 8 of the framework, Section 4.2.8), the table looks like the following Table 4.

	Pathway A	Pathway B
Indicator 1	X	
Indicator 2		X
Indicator 3		X
Indicator 4	X	
Indicator 5	X	
Indicator 6		X
Indicator 7	X	
Indicator 8		X
Indicator 9		X
Indicator 10	X	
Indicator 11		X
Indicator 12	X	

Table 4 *Example 2: arrangement of indicators within the recycling pathways*

At this point all the data are available to select the most sustainable recycling pathway between A and B. It will only be necessary to assign the score of each indicator to the recycling pathway where its value is closest to the objectives, according to Table 4.
As shown in Table 5, the score of the recycling pathway is therefore obtained by aggregation of all the scores that belong to it.

	Pathway A	**Pathway B**	**Score indicator**	**Score pathway A**	**Score pathway B**
Indicator 1	X		0.261	0.261	
Indicator 2		X	0.034		0.034
Indicator 3		X	0.143		0.143
Indicator 4	X		0.080	0.080	
Indicator 5	X		0.018	0.018	
Indicator 6		X	0.152		0.152
Indicator 7	X		0.004	0.004	
Indicator 8		X	0.038		0.038
Indicator 9		X	0.021		0.021
Indicator 10	X		0.041	0.041	
Indicator 11		X	0.190		0.190
Indicator 12	X		0.019	0.019	
Sum				0.423	0.577

Table 5 *Example 2: Step 2 - assigning the score to the recycling pathways*

Therefore the most sustainable recycling pathway to choose according to this method is **pathway B**, since it presents the highest overall score.

Once the comparison has been performed, one of the alternative recycling pathways should stand out over the others. If this is the case, then the most sustainable recycling pathway has been found, and the only missing step is to compare it with the base case scenario (the current scenario without considering any recycling pathway). The methods for comparing the sustainability of the recycling pathway and the base case scenario can be the same as those shown in the previous steps. If the new recycling pathway after the results of the calculation is more sustainable than the base case scenario, then the process is completed. Otherwise, the procedure should be repeated.

A suggestion after the implementation of the standard recycling pathway, is to recheck and in case redefine the direct and indirect factors that may influence the decisions expressed in Section 4.2.4, on a semi-annual basis. This way it will always be sure to have the most sustainable recycling solution that at the same time is up-to-date with the times. Indeed, within the automotive industry, everything changes very quickly. What is sustainable today, may not be sustainable anymore tomorrow.

This chapter provided an overview and explanation step by step of the framework for defining and selecting sustainable recycling pathways. According to what has been discussed so far, the next chapter will show the application of the framework to a real-world situation. The application in question is the case study of the work: recycling Polyamide 12 automotive prototyping wastes for other automotive applications.

Chapter 5

Application of the framework to the case study

The focus of this chapter is to adopt the framework defined in Chapter 4 to a case study and to evaluate its applicability. The selected case study is the recycling of Polyamide 12 manufacturing waste from the automotive industry. The overall procedure of definition and application of the framework has been carried out at the BMW Additive Manufacturing Campus (AMC) based in Munich, Germany.

For the selection of the most sustainable recycling pathway for PA12 the ten steps of the framework in Figure 16 will be applied in a systematic and consistent way. The current section will serve as a verification of the applicability of the proposed framework. Therefore, all the choices made to reach the results will be explained and all the equipment (material, processes, tools) will be described in detail. All the findings provided in this chapter are the result of months of field experience, interviews, and workshops with industry experts, partners, and workers in BMW's various departments.

Disclaimers: All images in this chapter, except when otherwise specified, were taken on the field during the various experiments. All images were pre-approved by the company (BMW), which allowed the tests to be carried out at the Additive Manufacturing Campus. In the case of the graphs, they have been created ad hoc during the writing of the report.
Moreover, it was decided to omit the names of the companies with which arrangements were made to establish recycling pathways. All companies involved will be here cited as polymers' processing companies, external companies, or polymers suppliers.

5.1 Step 1: Problem definition

The issue that caused the need for recycling PA12 prototyping waste has already been presented in the first chapter of this work. It is possible to divide the problem into many different levels, from the general to the specific: the whole society, the automotive industry, and the singular BMW case.

As already mentioned, plastic pollution is one of the most urgent issues that modern society has to deal with. As demonstrated in the literature review, the manufacture and use of plastics keep growing exponentially, and with that, their disposal. Therefore, the need for environmentally friendly ways to reduce the amount of plastic discarded every day is becoming always more urgent.

Moreover, the automotive industry is one of the most plastic-consuming overall. In 2015, from the prototyping to the actual series production of the vehicles, almost 7% of the overall production of plastic was destined for the automotive industry (Geyer et al., 2017). Plastic is one of the key materials in the production of vehicles, being lightweight, easy to manage, and fairly inexpensive. On the other hand, one of the main applications of plastics within the automotive industry is vehicle prototyping. As discussed in Chapter 2, prototyping is one of the key processes of the entire automotive engineering chain. In this regard, one of the most relevant techniques for prototyping production in the automotive industry is rapid prototyping (see Section 2.1.3). Rapid prototyping allows obtaining physical design in a fast way, without much material expenditure with respect to other manufacturing techniques. Rapid prototyping involves many different technologies, that work with several materials. In this work, the focus is on PA12 polymeric parts out of the SLS process.

The BMW AMC is where most of the SLS prototypes in PA12 are produced for BMW's vehicles prototyping in Germany, in particular in Munich. All the various departments of BMW that are involved in vehicles' prototyping simply order the parts to the AM production based at the AMC. The parts are then printed, sent out, and once delivered to the different facilities, tested out in a series of prototyping steps. As already discussed in the previous chapters, such SLS PA12 parts have a limited lifetime. In a variable time frame that can range from a few months to a few years, such parts end up being thrown away because no longer useful. On the other hand, together with the PA12 waste as parts, another issue that the BMW Additive Manufacturing section faces on a daily basis involves the PA12 powder management. Indeed, as already mentioned, the SLS process, generates huge amounts of old powder as a byproduct that can't be fully reused for the same process. Approximately 11 tons of powder waste are being currently produced at the AMC just out of two SLS printers. On the other hand, in 2021 the AMC production, produced and sent, just internally, a total of 46.041 white PA12 parts, for a total of 679.677.961 mm^3, all destined to be discarded and end up as waste after some (not so long) time. A method for managing the significant PA12 waste at BMW's sites is therefore needed. This can be the recycling of such material to reduce its waste.

5.2 Step 2: Determine the relevant aspects of the Business As Usual

Current PA12 management

Figure 23 shows the pathway that the PA12 material (in the form of powder, then filament and parts) follows without the implementation of any recycling pathway. As shown, the current procedure for PA12 use starts with the purchase of new PA12 powder from a company specializing in polymers. The powder is purchased by the AMC for its adoption in SLS printers (this in general happens once per year, except for special cases).

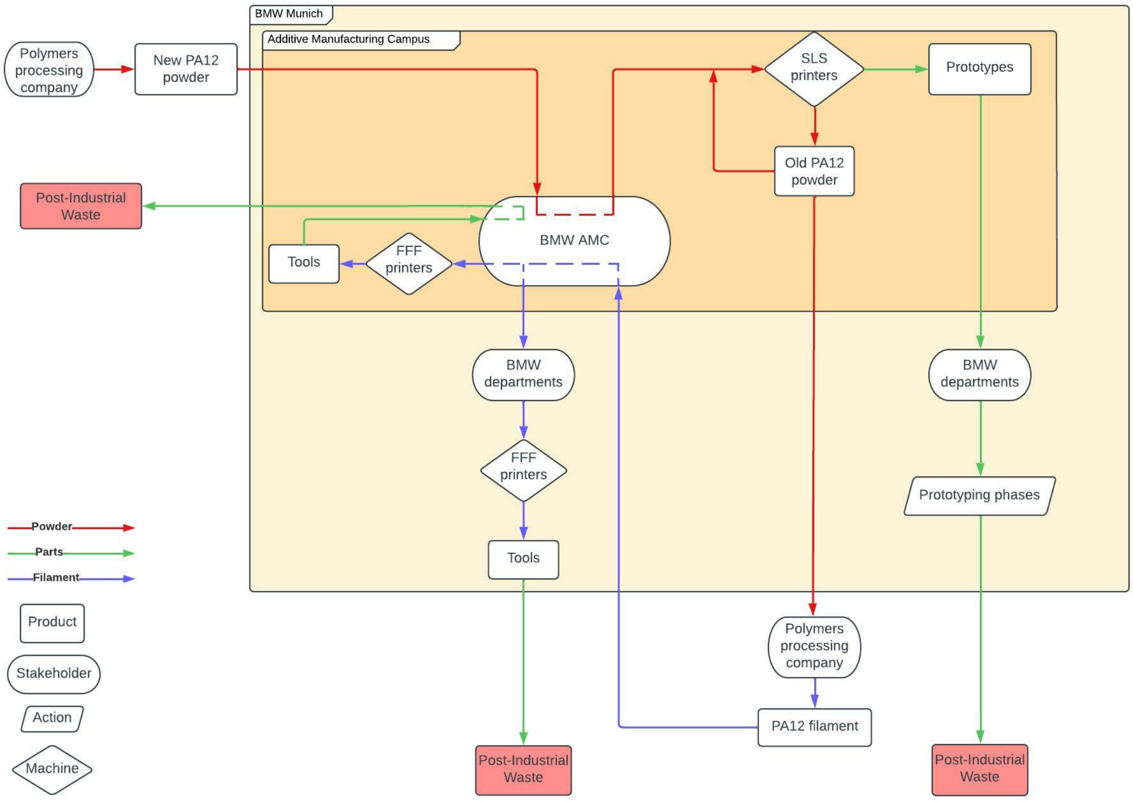


Figure 23 *Current BMW's PA12 management*

The production works every day, five days per week. In general two days of the week are dedicated to the print jobs within the SLS printers while the others are for the post-process of the parts. After each print job, there is always leftover powder from the printers. Due to exposure to high temperatures for long times, the powder during the SLS process changes its properties in a way that doesn't allow for full reuse for the same procedure. Part of it goes back into the SLS mixture and is used to print new prototypes, but the rest is either packed and delivered to another processing company that agreed to turn the old PA12 powder into filament, or thrown away. The filament spools are then delivered back to the AMC. Some of them are tested in-house in FFF printers for the creation of useful tools for the workers in the AMC production line. Moreover, part of the spools is then sent to other BMW departments that adopt them for the production of other parts (mainly jigs and fixtures) in their own FFF printers. In the end, even these parts are then discarded as Post-Industrial Waste (PIW), and can potentially be reused, as this work will attempt to do.

Being the topic of the work the recycling of PA12 is it important to understand how the wastes are currently managed within the BMW production plants. For common-use materials, waste is in general separated directly in the production area and disposed of already sorted out. This applies to wood, plastics, paper, and metals. Despite the most used types of plastics being separated from each other, some others such as PA12 are disposed of together with the other Mixed Plastic Waste (MPW) as PIW and destined for incineration with energy recovery (Waste To Energy (WTE)). It is therefore important to remember in this regard that landfilling in Germany is forbidden because of the space scarcity to store the waste. Being most of the parts confidential, a common practice before their disposal is to make them unsuitable with the adoption of shredders. This is to avoid information leakage to benefit competitors on the one hand, but also illegal sales of parts or any kind of black market sale.

Data collection

- **What** type of data are adopted? - Most of the information regarding various topics (energy consumption and purchases, emission factors, costs) is often organized in folders, Excel files, and/or dashboards.
- **Who** is in charge of organizing the data? - The data are organized by the employees/department that works with them. Some employees are allowed to edit the files and the folders, while others are only granted permission to consult them, depending on their function.
- **Where** are the data stored? - All the potentially useful data are organized in different databases, specific to each department. It is possible to access them just with special permission or by asking those in charge of their control.
- **How** to retrieve the data? - The safest way to retrieve data is by planning meet-

ings and interviews with BMW employees. In fact, it is generally needed to require them to the singular employee or to ask for access through the BMW server.

- **How often** are the data updated? - All the data are updated every time a new purchase/order is made.

Stakeholders analysis

The BMW Group is organized into departments, each of which has a specific focus. Sustainability has many facets, and therefore, in order to make an assessment of this, different departments must be approached for information. To sustainably recycle PA12 waste from AM prototyping, there are many aspects to consider within the four dimensions defined above, and with them the internal stakeholders involved. Below is a list of the departments involved in the research through interviews and meetings. The departments were divided according to two of those four dimensions of the framework, the technical and the environmental. In fact, the economic and social aspects are involved in each of them.

TECHNICAL

- Additive Manufacturing
    - Projects, Qualification
    - Pre-development, Planning
    - Production
- Painted Body
- System Integration, Painted Body, Exterior, Interior
- Test Center, Vehicle and Prototype Workshop
- Hardware Test Parts, Planning, Purchasing, Quality
- BMW Motorrad
- Production Control, Systems Engineering, Maintenance, Production Improvement
    - Central Maintenance Body-in-White

ENVIRONMENTAL

- Product Sustainability

  - Life Cycle Analysis
  - Circular Economy
- Location Development, Energy, Environmental Protection
- Regional Steering
- Quality
  - Recycling
- Distribution System, Sustainability
- Sustainability Supply Chain
- Sustainability Production

Considering the number of departments that are part of BMW, despite existing a sustainability board for the overall company, the decisions on a lower level such as pilot projects are taken by the singular project leader that must obtain approval from the department head who is basically the representative to do the interests of the company as a whole.

For the scope of the research, a stakeholders analysis has been conducted within the context of PA12 adoption in BMW, whose results are presented in Figures 24 and 25. All the actors evaluated in this analysis are currently part of the system, and they will remain potentially even after the implementation of a recycling pathway. Albeit to varying degrees, all of them have a role and can be influenced (both positively and negatively) by the implementation of a recycling pathway for PA12.

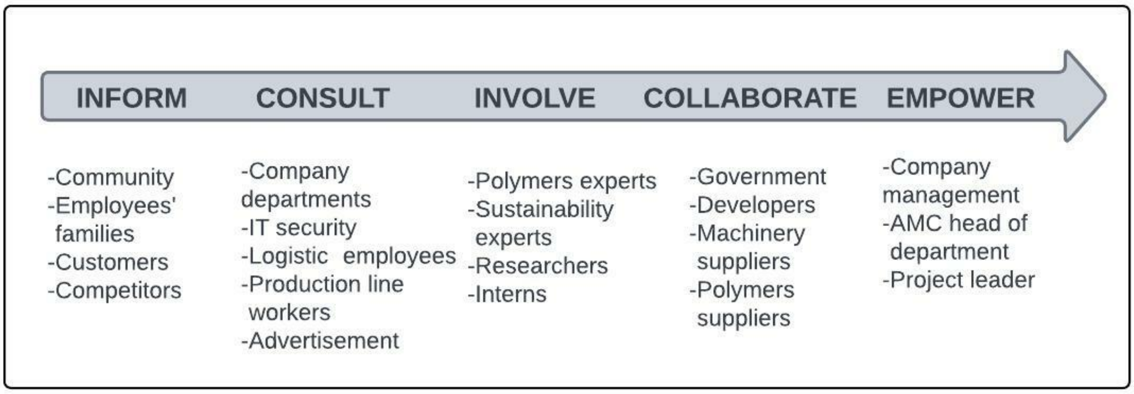


Figure 24 *Stakeholders analysis: varying degrees of engagement*

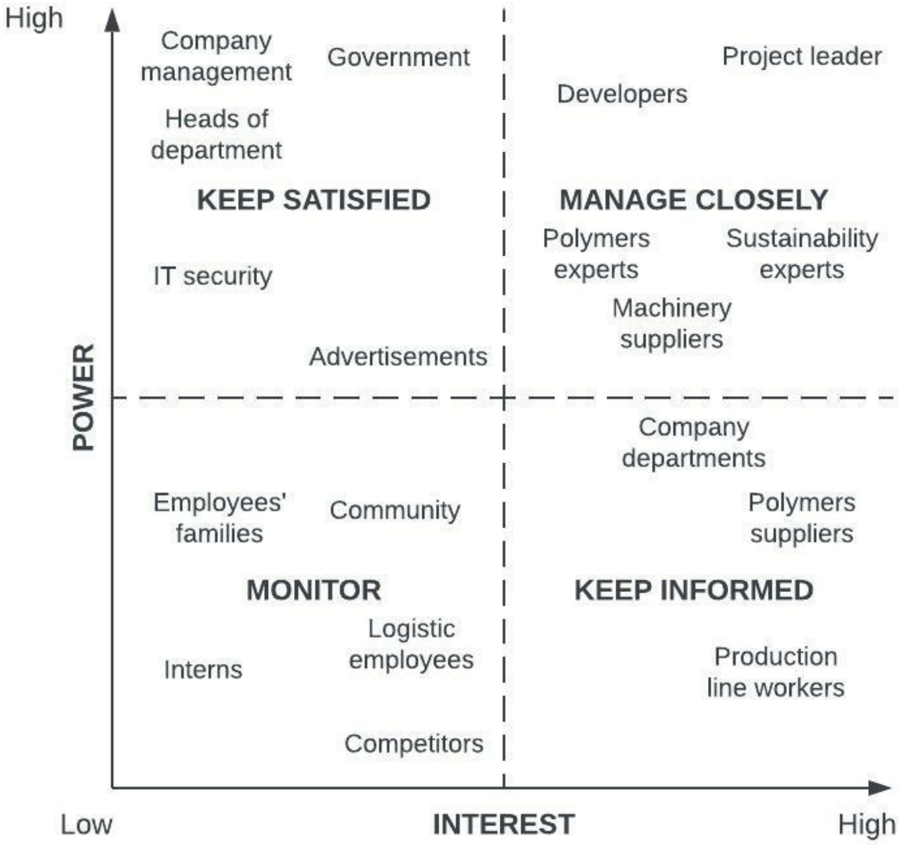


Figure 25 *Stakeholders analysis: Power VS Interest*

5.3 Step 3: Set objectives and indicators within 4DS

The third step of the framework is the definition of SMART objectives and indicators within the dimensions. Within the case study focus of this work, the objectives can be divided into two main levels: the objectives of the company (BMW) and the objectives of the singular facility/department (AMC).

BMW Group's objectives as a company

Over the past decades, BMW has repeatedly set itself ambitious sustainability goals for the future. The aim is to continue in this direction, demonstrating that the company not only supports changes towards sustainability, but it also aims to shape this change (BMW Group, 2022). As the company claims: "The fight against climate change and the way we use resources will determine the future of our society and that of our company, too" (BMW Group, 2022). The vision and strategy of BMW for the future are to establish a link between product excellence and sustainability, where the economy, ecology, and society are in harmony with each other. One of BMW's focuses right now is circularity. According to the company, the proportion of secondary materials will

increase significantly, with a particular focus on minimizing the necessary reduction in resources.
BMW divides its sustainability goals into three dimensions, which are summarized immediately after (BMW Group, 2022).

- **ECOLOGICAL**: commitment to the Paris Climate Agreement, resource efficiency, circularity, environmental standards in the supply chain.
    - Reduction of the carbon footprint along the entire value chain of a vehicle.
    - Reduce the CO_2 footprint within the supply chain by 20% by 2030.
    - Reduce the carbon footprint in production by over 80% by 2030.
    - Optimizing energy efficiency. By 2021, all of BMW's sites are carbon neutral and the use of renewable energy sources is quickly being adopted. In Germany, and in particular, in Munich, the main source of green electricity is hydro-power.
    - Increase to 50% the share of secondary materials on average per vehicle by 2030.
- **SOCIAL**: long-term jobs and staff development, diversity and employee health, social standards in the supply chain. Social sustainability is also very important for BMW, and in the company's vision, this is divided into three levels: the employees, the partners, and the society.
    - Implement environmental and social standards
    - Be more committed to society with cultural and social engagement.
    - Grant a healthy environment for all the employees.
    - Give value to diversity and individuality.
    - Ensure safe workplaces where jobs are protected and guaranteed.
- **ECONOMIC**: economic impact, compliance, sustainable corporate governance, future-oriented risk management.

To conclude this overview of BMW's objectives as a company, it is important also to mention its commitment to achieving the 1.5°C target set by the Paris Climate Agreement. Since 2021, the BMW Group is the first German carmaker to join the "Business Ambition for 1.5°C". This includes its commitment to achieving climate neutrality along the value chain by 2050. It also makes automatically BMW a member of the UN's Race to Zero program.

BMW AMC's objectives

The next level to evaluate the objectives is the Additive Manufacturing Campus as a singular facility/department of BMW. The main objectives, in this case, are multiple. First of all, as part of the BMW Group, it is clear that the main goal is to work towards achieving the objectives and targets set by the company as a whole. On the other hand, even the department itself has its own objectives to meet.

The first objective to point out, in this case, comes from the definition of the problem from Step 1 of the framework. Reducing the amount of waste in the facility (especially plastic, both in terms of raw materials and parts) is what in the first place suggested the creation of a recycling pathway for PA12. Moreover, being Additive Manufacturing still a niche, with a lot of potential in terms of sustainability, working towards advancing its R&D is what AMC's employees do on a daily basis. To continue, it is also important to mention the role of the campus in the overall energy consumption of the company. The AMC is a facility aimed at being a central hub for production, research, and training in 3D printing. It operates roundabout 50 industrial systems (3D printers) for processing metal and plastics, each one with its own consumption of energy. Being able to reduce the impact (in terms of both energy consumption and carbon footprint) of such a big facility is a step towards the overall sustainability of the company.

Another common thread for most of the projects that take place at the AMC is process automation. Several projects have been conducted throughout the years aimed at reducing workers' manual tasks in the production line. Achieving this objective will benefit the employees both in terms of daily effort but also safety in the workplace. It will also allow having a more efficient production line by unlocking the possibility of printing overnight and during weekends and holidays when the workers are not there. Moreover, processing materials often requires the adoption of machinery, procedures, and practices that can be potentially dangerous. Cutting metal parts, moving heavy loads, and working with high temperatures, for instance, expose workers to dangers that can potentially be avoided by a higher degree of automation.

Presented below is a list of objectives as a summary of what has been said so far. They have been divided into the four different sustainability dimensions.

Overall objectives to achieve sustainability

- **TECHNICAL (T)**
  - T1. Advance R&D in Additive Manufacturing.
  - T2. Increase by 50% the share of secondary materials on average per vehicle.
  - T3. Reduce the amount of PA12 parts waste from SLS at the AMC.

T4. Reduce the amount of PA12 powder waste at the AMC.
T5. Reduce the energy consumption of the AMC.
T6. Increasing overall resource efficiency at the AMC.

- **ENVIRONMENTAL (EN)**

EN1. Reduce by 40% the CO_2 footprint per vehicle over the entire value chain by 2030.
EN2. Reduce by 80% the CO_2 footprint per vehicle over the production line by 2030.
EN3. Achieve climate neutrality at the latest by 2050.
EN4. Fully commit to the Paris Agreement's targets.
EN5. Reduce PA12 footprint.

- **ECONOMIC (EC)**

EC1. Reduce the cost of production.
EC2. Reduce the costs associated with energy consumption.
EC3. Reduce costs associated with waste disposal.

- **SOCIAL (S)**

S1. Improving social and environmental standards.
S2. Achieve complete process automation overall.
S3. Implement practices that are socially and creatively rewarding for all working people.

Selection of indicators within the dimensions

For the purpose of the case study, a preliminary list of indicators, and their link to the company's objectives are presented:

- Technical indicators
  - Amount of recycled material (flakes) [kg] - T2, T3, T6, EN2, EN5, EC1, EC3.
  - Amount of recycled material (powder) [kg] - T2, T4, T6, EN2, EN5, EC1, EC3.
  - Standard deviation tensile strength [%] - T1, T2, EC1, S3.
  - Standard deviation elongation at break [%] - T1, T2, EC1, S3.
  - Rate of printability of the material [%] - T1, T2, EC1, S3.

  - Total vehicle distance traveled [km] - T5, T6, EN1, EN3, EN4, EC2.
  - Energy used for transportation [kWh] - T5, T6, EN1, EN3, EN4, EC2.
  - Amount of space adopted for recycling pathway [m^2] - T3, T4, EC1, S3.
  - Time required for completion [days] - T6, S1, S2.
  - Amount of hours invested (lead time) [h] - T6, EC1, S1, S2, S3.
- Environmental indicators
  - CO_2 emissions transportation [CO_2eq.] - EN1, EN2, EN3, EN4, EN5, S1.
  - CO_2 emissions recycling equipment [CO_2eq./spool] - EN1, EN2, EN3, EN4, EN5, S1.
  - Percentage of fumes control devices [%] - EN1, EN2, EN3, S1, S3.
  - Amount of chemicals used [kg] - EN1, EN2, EN3, S1, S3.
  - Noise pollution duration [min] - S1, S3.
- Economic indicators
  - Costs associated with transportation [€] - EC1, EC2.
  - Energy costs for transportation [€] - EC1, EC2.
  - Amount invested per pathway [€] - EC1, EC2, EC3.
  - Waste disposal costs [€] - EC3.
  - Operating labor costs [€] - EC1, S1, S3.
  - Potential revenue [€] - EC1, S1.
  - Amount saved per pathway (reuse of material) [€] - EC1, EC3, S3.
- Social indicators
  - Workers' preference (recycling pathway) [%] - S1, S2, S3.
  - Customers' preference (end-use filament) [%] - T1, S1, S3.
  - Ease of management [%] - S1, S2, S3.
  - Number of manual steps performed by employees [N] - S1, S2, S3.
  - Number of injuries [N] - S1, S2, S3.
  - Amount of hours training needed per pathway [h] - EC1, S1, S2, S3.
  - HR diversity [%] - S1, S3.

Once all the potential indicators have been defined, the final list at the end of this step is composed of 10 technical indicators, 5 environmental indicators, 7 economical indicators, and 7 social indicators. Therefore, it is possible to move further with the next step, as it is sure to have at least 5 indicators per dimension as specified in Chapter 4 of the framework definition.

5.4 Step 4: Define system's boundaries

The fourth step of the framework is the definition of boundaries and factors. For the scope of the case study and the application of the framework, all the indicators and factors involved in the system will be considered just in the context of the AMC. In Figure 26, a graphical representation of the system boundaries is presented. The grey area represents all the elements of the recycling pathway that are involved in the calculations. All the recycling steps that take place at the AMC (yellow boxes), carried out by BMW's employees, are part of the system. Together with it, all the transportation steps (light blue boxes) that allow the material to reach/leave the AMC are taken into consideration as well.

For the technical, environmental, economic, and social assessment, the recycling steps carried out by external companies are excluded, as well as the conversion of the material into end-use parts since the recycling pathway is considered concluded when the recycled material in the form of filament reaches again the AMC.

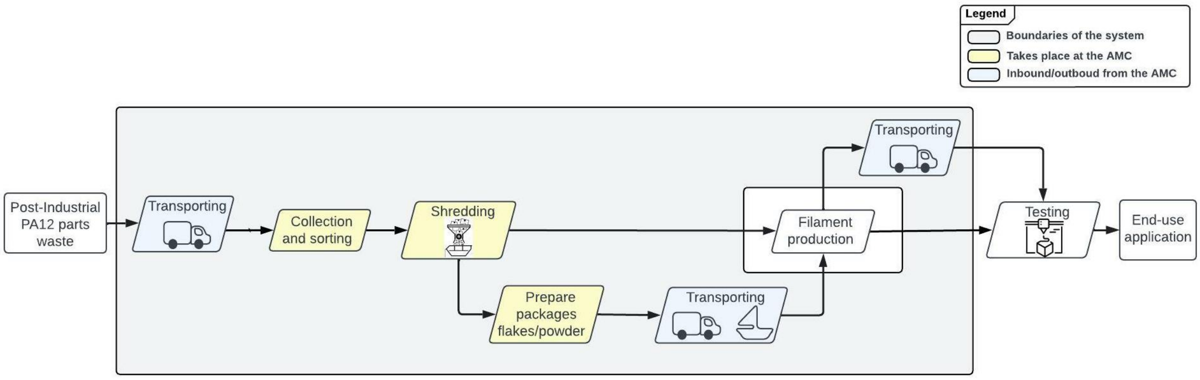


Figure 26 *Boundaries of the system*

As presented in Chapter 4, the *direct factors* for the sustainability assessment are organized according to the seven categories previously defined (temporal, economical, ecological, privacy, health and well-being, regulations, geographical). In Figure 27, all the direct factors considered for the system definition, have been divided into such categories, to show which elements are part of the system, and which are outside of the scope (grey area of the wheel scheme).

Regarding the factors for the sustainability assessment for the case study, for example, it is possible to notice how *IT protection* must be considered as part of the system. It involves the prevention of unauthorized access to the company's resources such as computers, networks, and data. Automotive prototyping in this case, for example, involves the production and utilization of parts whose design is often confidential because it is company-owned. These parts can be potentially adopted in the future series production of new vehicle models, therefore this is one of those sensitive data that must be particularly protected from competitors. Pictures of parts, files containing the designs, and dimensions of the parts are all data that must be previously authorized to be accessed. Moreover, other elements considered in the definition of the system are, for example, *use of safety equipment*, as recycling solid materials most of the time involves the adoption of potentially dangerous machinery such as granulators. Therefore, appropriate equipment is fundamental for the success of the recycling pathway. As for the ecological factors, *the delivery of material by boat or truck* can be adopted for the design of the recycling pathways, whilst the delivery with aircraft is not considered in the definition of the system (it has been placed in the gray area of the wheel) being the plane more polluting than other means of transport. Together with these factors, many more have been evaluated (see Figure 27) that are meant to simplify the design of the potential recycling pathways in the next step of the framework.

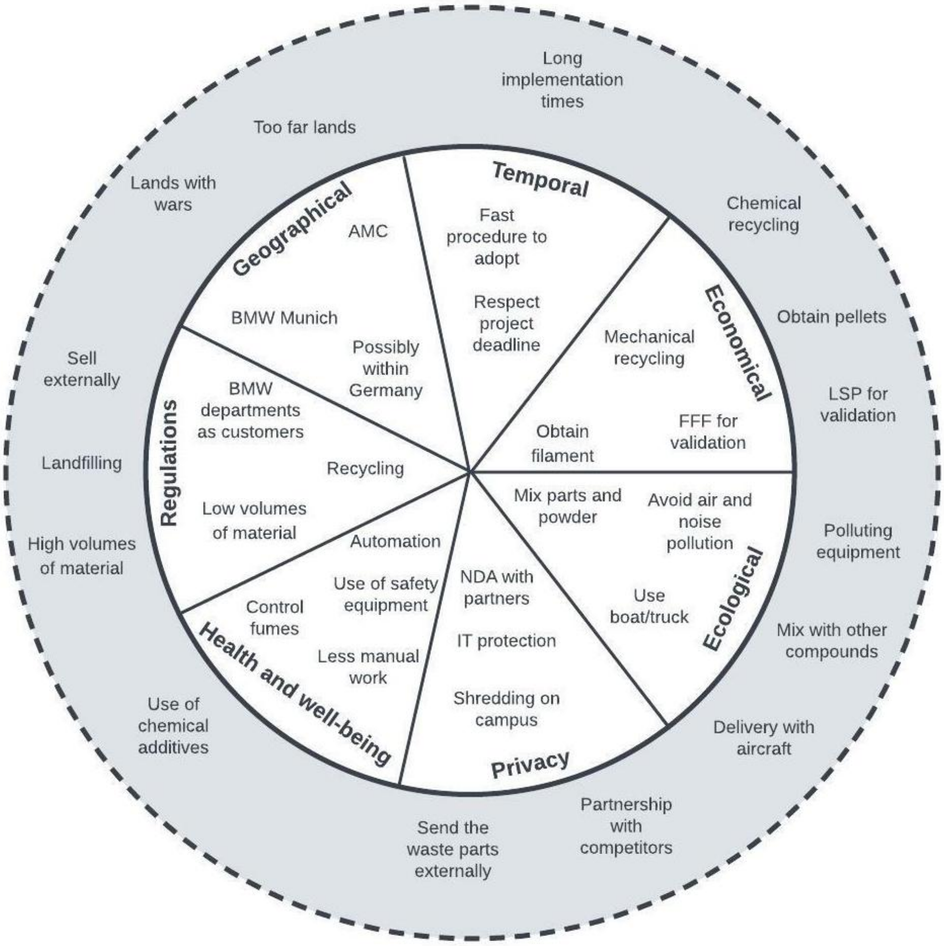


Figure 27 *Wheel scheme of the direct factors involved in the definition of the system for the sustainability assessment - Recycling PA12 parts waste from BMW Munich*

5.5 Step 5: Design potential recycling pathways

In this step of the framework, as suggested in Chapter 4, the potential recycling pathways are designed. The following section will therefore show which steps are involved for each different alternative pathway for the recycling of PA12. For this reason, this section will employ diagrams and graphs to make it clearer how the different pathways are composed.
A research has been conducted for the scope of the work to understand what type of recycling (mechanical or chemical) was most suitable and most sustainable for PA12 prototypes, according to this type of waste's main characteristics. The results of the research are presented below.

Preliminary evaluation

Being plastic waste (in this case PA12) sources more difficult to recycle than other materials such as metal or glass, the environmental impact of such practice needs to be a basic criterion for the definition of the different processing steps. The main challenges come from the fact that recycling plastics does not ensure obtaining a recycled material comparable to the virgin one and also might lead to not sustainable procedures. First of all, most of the time manufacturing wastes are made up of mixed plastics, which makes it more difficult to sort them and it might require the addition of further steps which means more time, as well as more energy use. Secondly, if the recycled plastics are contaminated or are constituted by a mixture of plastics, the end-material might present lower quality with respect to the virgin one (Rudolph et al., 2017).

There are three common methods for plastics recycling: mechanical recycling (primary and secondary recycling) and chemical recycling (tertiary recycling). Mechanical recycling consists in recovering the material through a series of mechanical steps (grinding, washing, separating, drying, re-granulating and compounding), as shown in Figure 28. Steps may occur in a different order, multiple times, or not at all, depending on the type of the waste (Ragaert et al., 2017). It is defined as primary recycling (closed-loop) when after the conversion a product that serves a similar function is obtained. On the other hand, secondary recycling allows for obtaining a different product made of the same material. Chemical recycling, in contrast, requires breaking materials down chemically to obtain a different secondary raw material.

For the definition of the most suitable recycling pathway for PA12, research has been conducted to evaluate which of these recycling methods should be chosen.

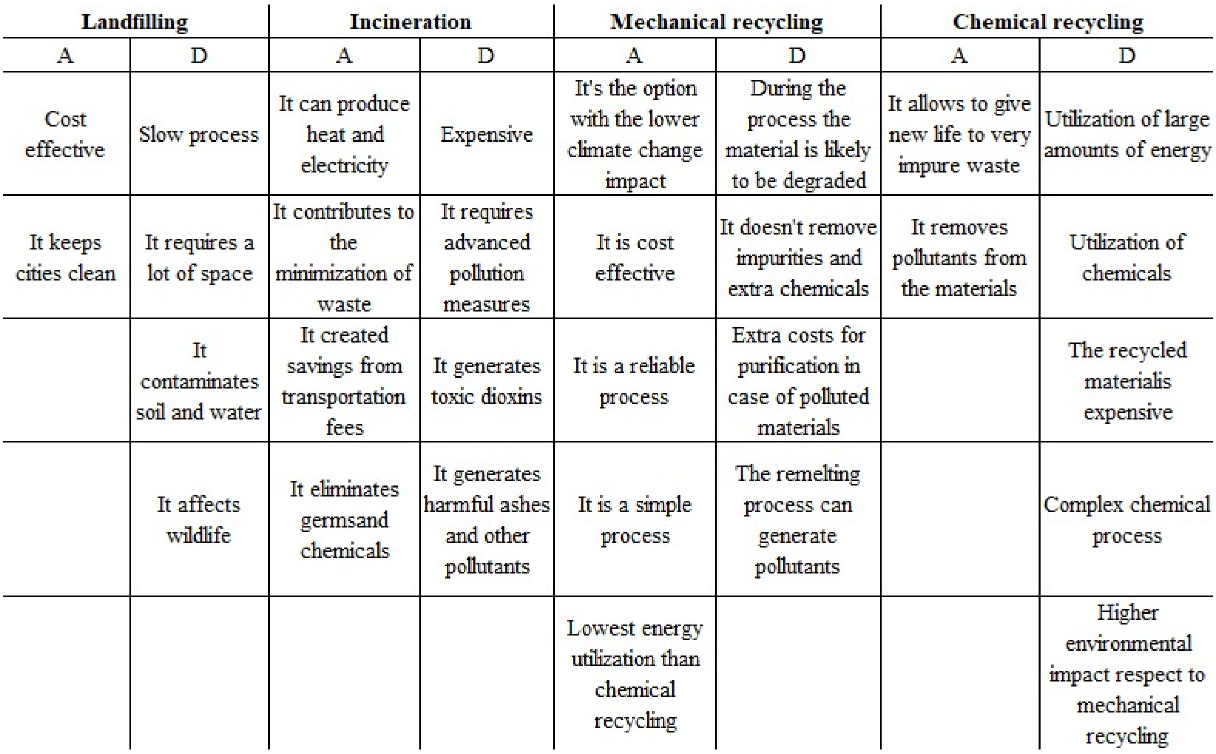
First of all, depending on the degree of contamination of the plastics with organic or

Figure 28 *Mechanical recycling process (Chengshi Mesh and Filter, 2020)*

inorganic substances, one of these three recycling methods is recommended (Rudolph et al., 2017). In general, chemical recycling is preferred when the material is highly contaminated. For example, processes such as coating and painting can highly contaminate the material. Due to the presence of chemicals, this type of recycling removes pollutants from the cycle that with mechanical recycling cannot be removed.

PA12 waste from BMW's production, can be considered as PIW. PIW meaning by-products from an industrial process, with a well-known composition that are separated from the waste stream in the manufacturing process, and therefore most of the times are in a pre-contamination state. Being PA12 parts not contaminated with other materials or chemicals, therefore relatively clean, their sorting can be easily obtainable via mechanical procedures. In fact, already by simply removing any clips and other small glued parts, the material to be recycled does not need any other process to be ready. For this reason, mechanical recycling appears to be the most appropriate solution.

However, in order to be sure to find the most sustainable solution for PA12 recycling, the advantages, and disadvantages of the various waste disposal methods have been analyzed, whose results are presented right below, in Table 6. In here, also landfilling and incineration as waste disposal methods have been analyzed for completeness, which however won't be considered ex-ante for PA12 reprocessing.



Landfilling		Incineration		Mechanical recycling		Chemical recycling	
A	D	A	D	A	D	A	D
Cost effective	Slow process	It can produce heat and electricity	Expensive	It's the option with the lower climate change impact	During the process the material is likely to be degraded	It allows to give new life to very impure waste	Utilization of large amounts of energy
It keeps cities clean	It requires a lot of space	It contributes to the minimization of waste	It requires advanced pollution measures	It is cost effective	It doesn't remove impurities and extra chemicals	It removes pollutants from the materials	Utilization of chemicals
	It contaminates soil and water	It created savings from transportation fees	It generates toxic dioxins	It is a reliable process	Extra costs for purification in case of polluted materials		The recycled materialis expensive
	It affects wildlife	It eliminates germsand chemicals	It generates harmful ashes and other pollutants	It is a simple process	The remelting process can generate pollutants		Complex chemical process
				Lowest energy utilization than chemical recycling			Higher environmental impact respect to mechanical recycling

Table 6 *Overview of advantages (A) and disadvantages (D) based on the sustainability of waste disposal methods*

Such findings confirmed that overall, mechanical recycling is the most suitable, due to its low cost and reliability, as well as simplicity, with respect to chemical recycling, where the polymers are subjected to complex chemical procedures (Hamad et al., 2013). Moreover, in a study published in 2020 by the German Environmental Agency, it is stated that mechanical recycling, involving simpler recovery processes, has more advantages with respect to chemical recycling, both ecologically and economically. Indeed, it has been demonstrated that it requires fewer additives and less energy utilization.

On the other hand, one of the main disadvantages that come with mechanical recycling consists in the downgrading of properties of the material after the conversion. During the process, indeed, the polymer is exposed to different conditions that might lead to degradation, such as heat, oxidation, light, ionic radiation, hydrolysis, and mechanical shear (Ravve, 2000). While comparing different studies on the mechanical properties of virgin/recycled plastics, Rudolph et al. found out that it is common practice to mix virgin material with recycled one to refresh its mechanical properties (Rudolph et al., 2017). Therefore, another step that will be evaluated for the recycling of PA12 is to mix the flakes out of old prototype parts, with aged powder from SLS processes, in different shares.

Potential recycling pathways

The different alternatives are enumerated alphabetically, from A to E. The main differences between the pathways consist of the processing locations and the recycling mixtures adopted. In particular, pathways A and B take place entirely within the AMC. On the other hand, Pathways C and D take place in different parts of the World, while Pathways E and F are entirely set up within Germany.
According to the recycling mixtures, the idea behind the recycling of PA12 is to mix flakes from end-of-life parts with PA12 old powder (a byproduct from SLS printers). These mixtures have been distinguished in the different scenarios within pathways B, D, and F.

Pathway A: no mixing and within BMW

The first pathway that has been considered consists of a series of steps that all take place at the AMC in Oberschleißheim (Germany).

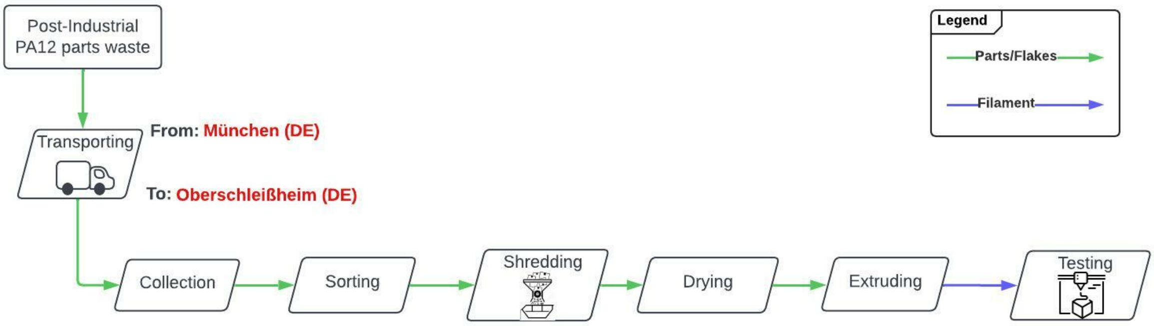


Figure 29 *Pathway A*

In Figure 29 the process that the material undergoes to become filament is presented. The end-of-life parts are transported by truck from the BMW head-quarter, where the prototypes are tested, to the AMC. Afterward, the parts are collected and sorted out in order to select just the ones out of PA12. Being it waste, it is indeed possible, that such parts are mixed with other prototypes with different materials for example PA11, Polyamide 6 (PA6), and other thermoplastics. Sorting them manually is therefore needed to make sure that the PA12 content of the future recycled filament will be as close as possible to 100%. Likewise, in this step, any additional elements applied to the parts, such as adhesives and metal clips, are removed manually. Following this, once all the parts to recycle are selected, the shredding process takes place. For the purpose of the case study, part of the budget destined for the project has been allocated to the purchase of a shredder (or granulator). However, due to longer delivery times, the first attempts for testing have been conducted by renting the shredder from the firm for one full working day.

The machine purchased for this purpose has the following technical characteristics (Table 7):

Characteristic	Value
Type	D30.50
Motor power	7,5 kW
Voltage supply	400 V / 50 Hz
Rotor speed	450 rpm
Stator knives	2
Rotor knives	6
Cutting chamber opening	395 mm x 500 mm
Sieve size	5 - 15 mm
Throughput	>250 kg/h
Weight	600 kg
Noise emission value	<85 dB

Table 7 *Main technical characteristics of the shredder purchased for recycling (Wanner Technik GmbH, 2022)*

Figure 30 *Polymers parts shredder*

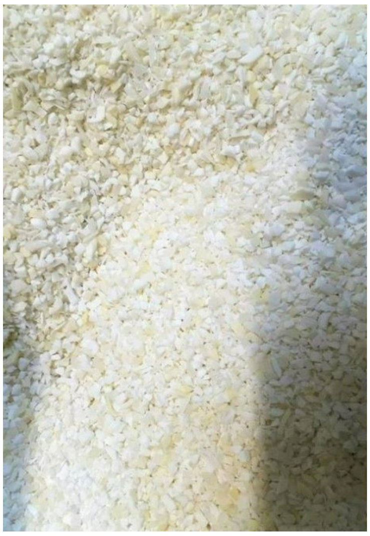


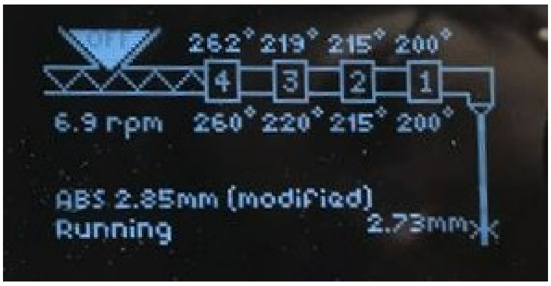
Figure 31 *PA12 material after shredding process (6mm flakes)*

The shredder in Figure 30 is the one that has been used on-site to turn the PA12 waste

prototypes into flakes (size 6 mm), as shown in Figure 31.
After the shredding procedure, the PA12 flakes are then dried in an oven at 80°C for a minimum of 3 hours in order to be ready to be extruded and turned into filament.

Being this a pilot project, the first attempt to turn PA12 parts into filament has been conducted by adopting a desktop filament maker (already present on site), whose depiction can be found in Figure 32.

Figure 32 *Filament Maker (3devo B.V., 2022)*



ABS 2.85mm (modified)
Running
2.73mm

Figure 33 *Extrusion process parameters*

The extruder has four different heaters, that can be controlled according to the type of material in order to obtain the best quality achievable. Extrusion speed and filament diameters can be also selected accordingly. However, because of defects due to prolonged use of the machine over the years, the material that was obtained in such a way showed imperfections (material composition and filament diameter inconstancy) that made it challenging to use it on FFF printers for its validation. In order to obtain a sufficient quantity of filament at a constant diameter of 2.85 mm, the extruder runs for about 4 hours. The temperatures of the different heaters and other extruding parameters adopted for the process are shown in Figure 33.

Pathway B: mixing and within the AMC

For pathway B exactly the same machinery and steps as pathway A have been adopted. The only difference, in this case, is the addition of a mixing step after the shredding procedure.
The two mixtures adopted for this purpose are:

- Scenario **1B**: 90% flakes/10% powder
- Scenario **2B**: 70% flakes/30% powder

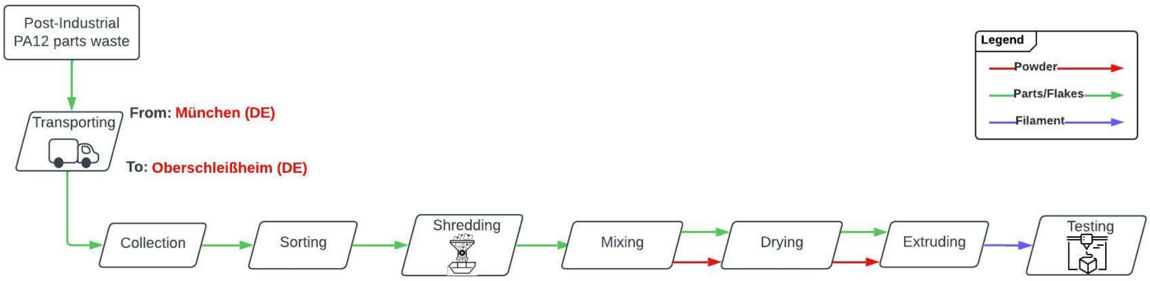


Figure 34 *Pathway B*

Pathway C: no mixing and worldwide

Pathway C, includes the involvement of other polymers' processing companies for the production of the filament. In this case, it is necessary to make a premise.

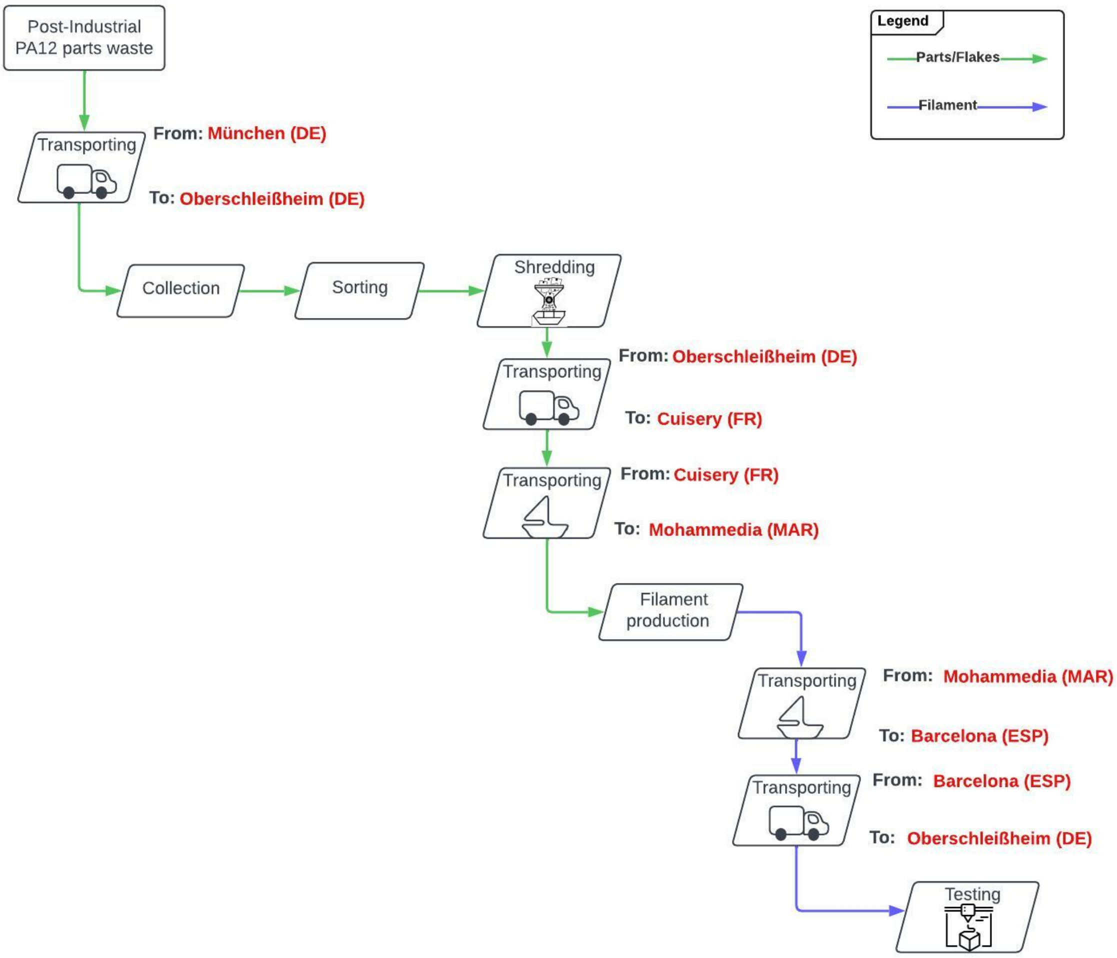


Figure 35 *Pathway C*

As the potential recycling pathway is expected to be implemented in a short time frame, the first possible company for the production of filament that has been considered is the same one that currently produces the filament for the AMC out of old PA12 powder (as explained in Section 5.4). In fact, having already had contact with this company, knowing its rules and values, and having already had the opportunity to test the quality of its products made it straightforward to involve it in the project. However, due to internal reasons, the company is based in Spain, has a storage facility in France, and currently has a production facility in Morocco. Therefore, pathway C, with the involvement of the external company, looks like the one shown in Figure 35.

The material is collected in the AMC from the other BMW facilities in Munich. Then it gets manually sorted out the same way as the previous pathways in order to be properly shredded. In this case, the purchase of a shredder does not have just a functional purpose of processing the material, but also a regulation one. Indeed, the parts that are produced via SLS from BMW, being prototypes adopted for testing purposes, are likely to be confidential designs. As explained in Section 2.1.3, such parts are adopted for many different testing purposes, which mainly involve the creation of new designs that can potentially be used in future vehicles' series production. Such designs must be protected and therefore it is not allowed to deliver the parts to other companies without making them unsuitable. Therefore, the shredding procedure is one of those steps that must be pursued in-house. Moreover, shredding the parts in-house allows also reducing the volume occupied by the parts. In this way, it is possible to deliver to the potential processing companies more material in weight, in a reduced amount of space.

After being shredded the PA12 flakes are sent to the storing facility in France by truck, where they get shipped by boat to Morocco for their post-processing to be turned into filament. In this case, the company adopts professional machinery for the extrusion. Once the material is turned into filament, it gets shipped by boat to Spain, where it is checked for potential issues and then it goes back to the AMC by truck.

Pathway D: mixing and worldwide

Pathway D involves the same steps, companies, and machinery as Pathway C, with the addition of a mixing step for the production of four different mixtures of flakes and powder.

- Scenario **1D**: mixing 90% flakes and 10% powder
- Scenario **2D**: mixing 80% flakes and 20% powder
- Scenario **3D**: mixing 70% flakes and 30% powder

- Scenario **4D**: mixing 50% flakes and 50% powder

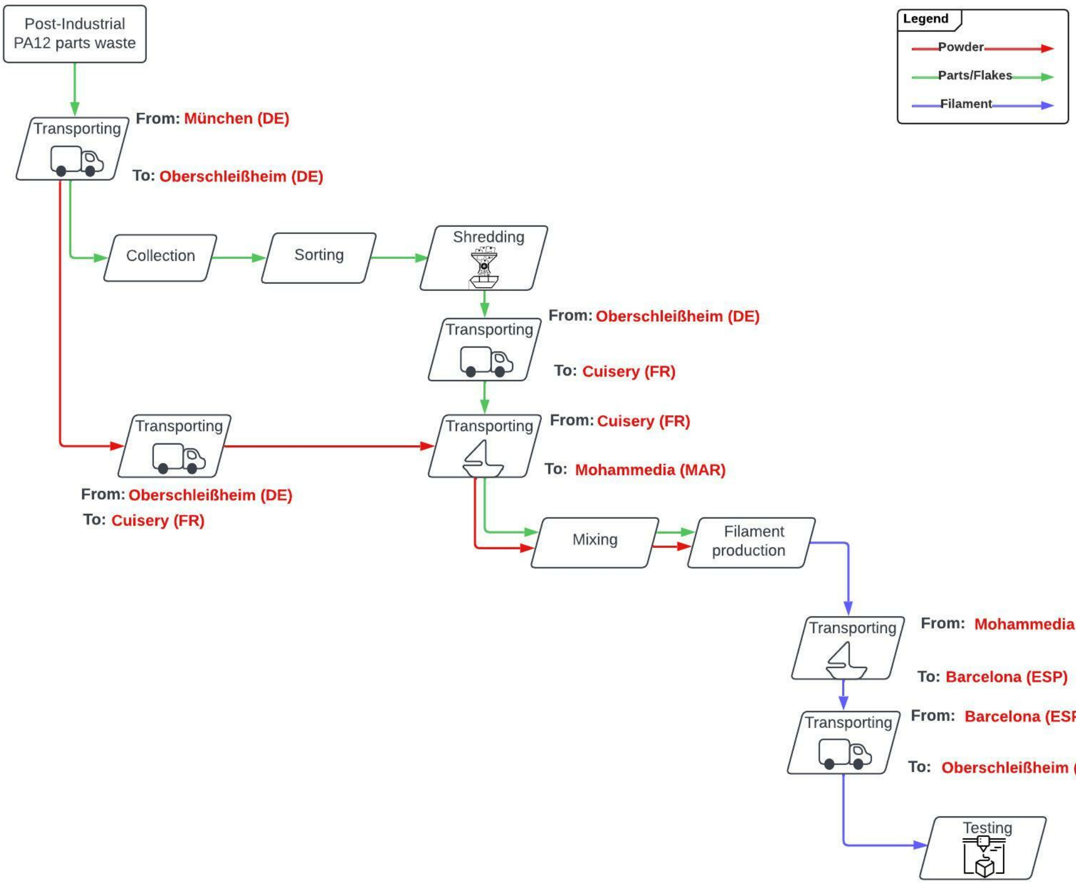


Figure 36 *Pathway D*

In this case, it made even more sense to collaborate with the same company that produces the filament out of just powder for the AMC. In fact, the delivery procedure for the powder, with all the necessary documents needed, was already set up, which made it possible to speed up the production procedure.

Pathway E: no mixing and within Germany

Another potential pathway considered, involves the collaboration of the same company as before, but in this case, it is planned to take place all within Germany.
The machinery is also the same. What changes are mainly the transportation process of the material, both in terms of means of transport and distance. The reason why this pathway has been considered comes directly from the partner company that is in charge of producing the filament. Being most of their customers based in Germany, as they are also working in become more environmentally friendly and reduce their emissions for the overall production line, from various interviews with the company's

employees it turned out that for them it made sense to look for a formula within Germany, without any international shipment.

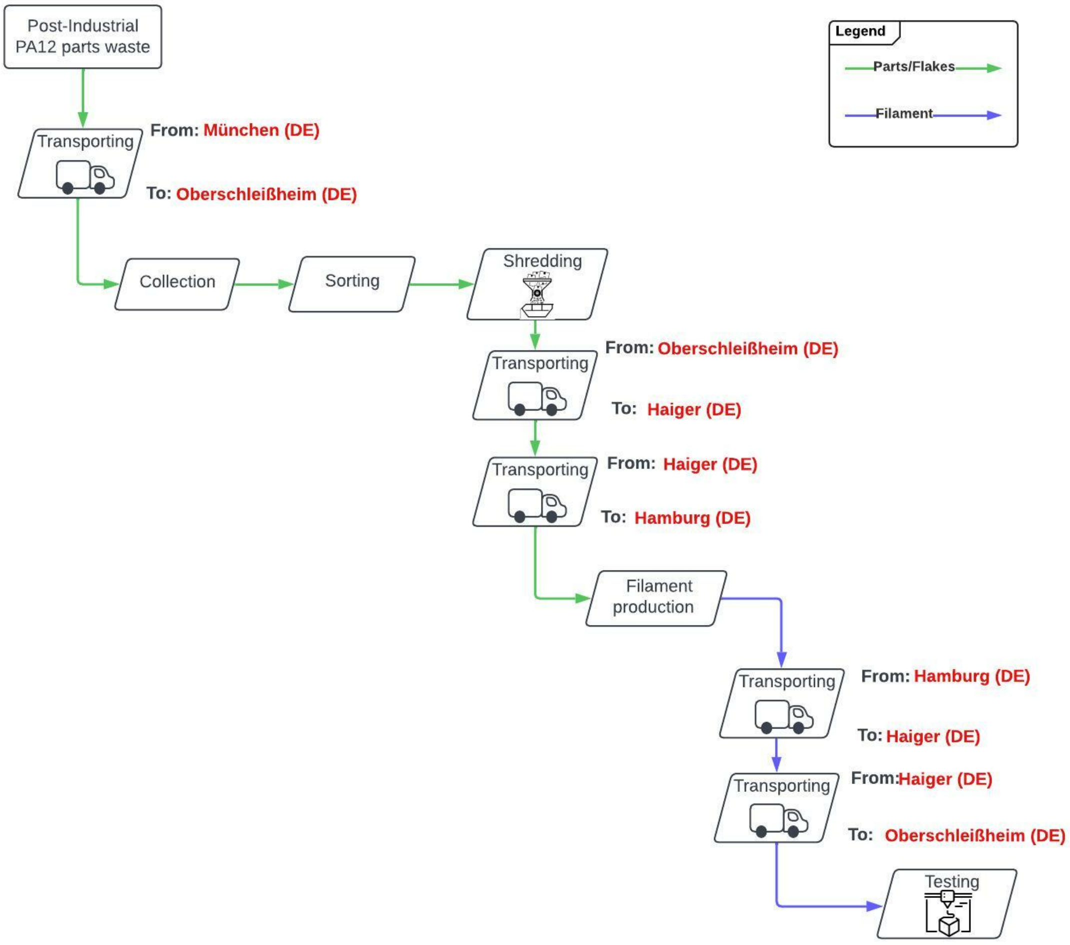


Figure 37 *Pathway E*

That being said, it was further proof that this company shares the same values as the BMW Group. Working towards sustainability, in all its aspects, and trying to constantly improve in this direction, is one of the main requirements that have been considered for potential partnerships with material processing companies.

Pathway F: mixing and within Germany

The last pathway considered is exactly like Pathway E (within Germany) but with the addition of the mixing step.
Indeed, even in this case, four potential scenarios have been considered consisting of four different mixtures of flakes and powder.

- Scenario **1F**: mixing 90% flakes and 10% powder

- Scenario **2F**: mixing 80% flakes and 20% powder
- Scenario **3F**: mixing 70% flakes and 30% powder
- Scenario **4F**: mixing 50% flakes and 50% powder

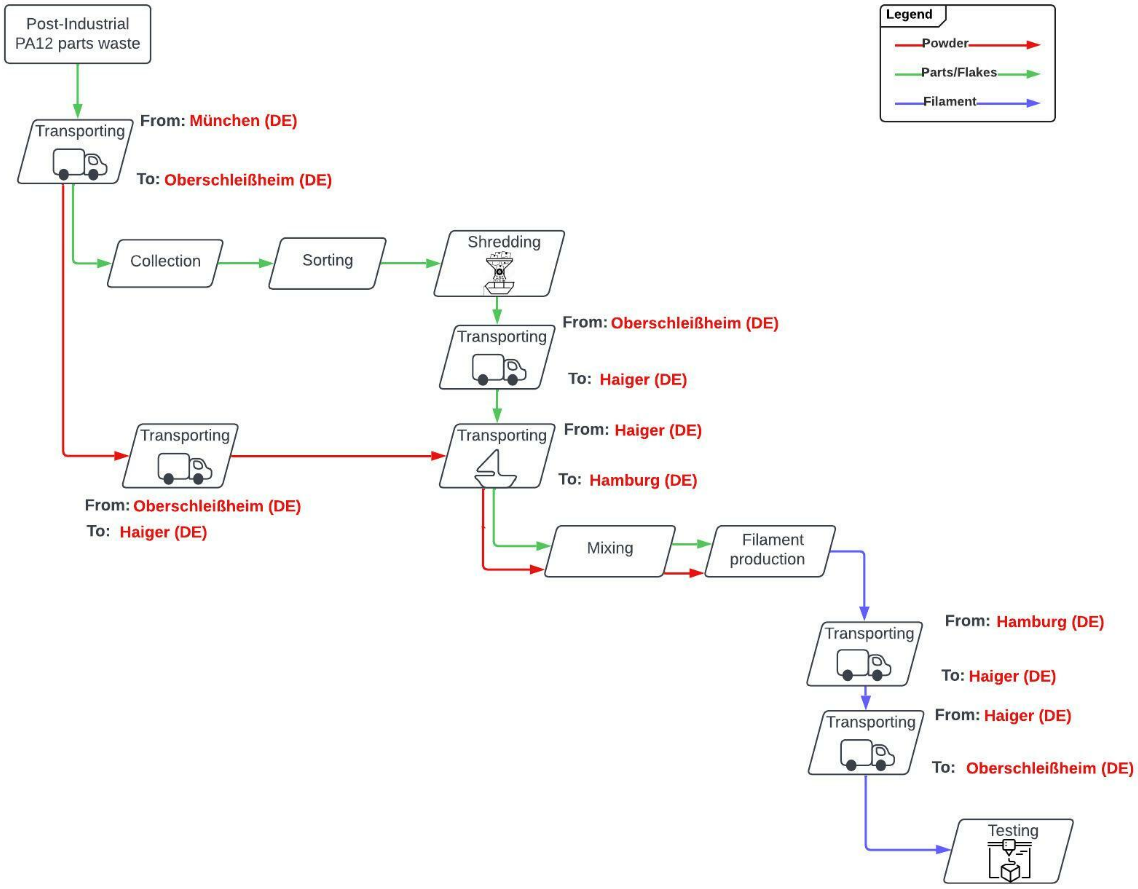


Figure 38 *Pathway F*

5.6 Step 6: Screening of relevant indicators according to their applicability and system's objectives

Following the steps in the framework presented in Chapter 4, the next step is to refine the list of indicators from the different dimensions, that align with the company's (in this case BMW) objectives, and with the case study requirements, defined in Step 3 of the framework. The indicators for the present case study have been selected in particular according to data availability, differences among the pathways, and alignment with the objectives.

For all the potential pathways considered, the idea is always to turn the material into filament for FFF 3D printing technologies. The potential application evaluated for the recycled filament is the production of jigs, fixtures, and tools for BMW workers in the production line.
Many different requirements and characteristics can be considered when evaluating the quality of a material. For the particular context of the case study, the material must be easy to print and reliable. BMW workers would adopt it as an additional help for their work. Whenever they need a part (e.g. to facilitate the movements of a robot for the assembly, to facilitate taking measurements, etc...) it is very useful to print it with an FFF printer in an easy and fast way. Therefore, for the material to be recycled, this characteristic is fundamental, as these potential customers do not have enough time during their working hours for trials and errors. Moreover, most of the parts that can be potentially printed with the recycled PA12 do not need to be particularly refined or aesthetically pleasing. Appearance, smoothness, and surface quality are for sure way less important in this case than functionality. Such supplement parts for the facilitation of the assembly almost never have to support heavy loads.

In the following Table 8, it is possible to find all the indicators selected in the previous steps. Here, it has been evaluated whether to keep them for the subsequent calculations or discard them. The motivation behind the removal is also specified.

Most of the indicators selected in the previous step were chosen in relation to recycling pathways A and B which were carried out completely in-house. Obtaining filament from these two pathways drawn at the beginning was definitely a way to demonstrate that it is possible to obtain new material from old pieces of PA12. However, it was decided not to consider these two pathways in subsequent calculations are they are too unpredictable, too labor intensive, and too time-consuming. A comparison with other potential recycling pathways, in this case, was not needed to understand that they were too inefficient to be implemented. Therefore, some of the following indicators proved to be of no use since pathways A and B were removed. For instance, the amount of space adopted in the recycling pathway, fumes control devices, operating labor costs, and amount of hours of training needed, make sense only in the case where most of the recycling pathway is set up in-house. Calculating them outside the AMC would be outside of the scope of the research and the boundaries defined in Section 5.4.

Indicator	Keep/Discard	Motivation
Amount of recycled material (flakes)	K	
Amount of recycled material (powder)	K	
SD - tensile strength	D	Similar for all materials
SD - elongation at break	K	
Rate of printability	D	Similar for all materials
Total vehicle distance travelled	K	
Energy used for transportation	K	
Amount of space adopted	D	Same for all pathways
Time required for completion	K	
Amount of hours invested	D	Outside of the boundaries
CO2 emissions transportation	K	
CO2 emissions recycling equipment	K	
Fumes control devices	D	Outside of the boundaries
Amount of chemical used	D	No chemicals adopted
Noise pollution duration	K	
Costs associated with transportation	K	
Energy costs for transportation	K	
Amount invested per pathway	K	
Waste disposal costs	K	
Operating labor costs	D	Outside of the boundaries
Potential revenue	K	
Amount saved per pathway	D	Not enough information
Preference (recycling pathway)	K	
Preference (end-use filament)	K	
Ease of management	K	
Number of manual steps	K	
Number of injuries	D	Zero for all pathways
Amount of hours training needed	D	Outside of the boundaries
HR Diversity	K	

Table 8 *Screening of the indicators*

Indicators explanation

In this section all the indicators that have passed the screening (denoted by K in Table 8 above) will be presented one by one, defined, and for each one of them, the motivation behind the choice will be stated. Moreover, as the indicators have been also chosen according to the alignment with BMW's objectives, these will be also mentioned according to the list provided in Section 5.3. It is also important to remind the reader that for a proper selection of an indicator, a time frame must be chosen. For this reason, since no recycling practice has yet been implemented, the time frame considered is one year from the potential implementation of each recycling pathway, based on a set of assumptions that will be defined later. All the indicators will be defined following this approach.

Technical indicators

- **Amount of recycled material (flakes)** [kg/spool]
  Definition: It refers to the amount of PA12 flakes that can be converted into filament in one year to produce one recycled spool.
  Motivation: Understanding how much material in terms of parts it is possible to recycle to obtain filament is a useful indicator when comparing the different pathways as more material used means less waste in the facility, and a higher share of secondary material in the production line.
  Objective(s): T2, T3, T6, EN2, EN5, EC1, EC3.

- **Amount of recycled material (powder)** [kg/spool]
  Definition: It refers to the amount of PA12 old powder from the SLS process that can be converted into filament in one year to produce one recycled spool (depending on the mixing ratio).
  Motivation: Also powder waste, together with parts waste, is a problem that must be solved. However, as already mentioned, old PA12 powder can be also reused in the same process of SLS. It is therefore less urgent than disposing of parts, that will for sure end up for incineration otherwise.
  Objective(s): T2, T4, T6, EN2, EN5, EC1, EC3.

- **Standard deviation elongation at break** [%]
  Definition: It refers to how much the specimens of a batch differ in elongation at break from the mean value of the batch.
  Motivation: Predictability in mechanical properties is one of the most important features that the new material should present. Being able to print parts via FFF with consistent quality will allow for saving both time and material.
  Objective(s): T1, T2, EC1, S3.

- **Total vehicle distance travelled** [km]
  Definition: It refers to the distance between the different facilities to complete a recycling process.
  Motivation: Achieving a successful recycling pathway in which the different facilities involved are close to each other will benefit not only the environmental impact of the pathway itself, but it will allow also to minimize the time required for recycling as well as the costs for transportation. Ultimately, favoring neighboring businesses generates benefits for the entire community. Moreover, the extrusion location is one of the main differences between the pathways defined in Section 5.5.
  Objective(s): T5, T6, EN1, EN3, EN4, EC2.

- **Energy used for transportation** [kWh]
  Definition: It refers to the energy consumption of transportation steps involved in the recycling pathway. This depends on the mean of transport adopted, but also on the amount of material that it is possible to recycle in one year.
  Motivation: Increased use of energy for transportation involves the utilization of fossil fuels (coal, gas, and oil) and generates global warming and pollution. Therefore, it should be minimized. Of course, different means of transport correspond to different energy consumption levels.
  Objective(s): T5, T6, EN1, EN3, EN4, EC2.

- **Time required for completion** [days]
  Definition: It refers to the amount of time that the material (in any form: flakes, powder, filament) takes from the moment it leaves the AMC to the moment it comes back.
  Motivation: Minimizing the time required for recycling is essential to comply with company-defined deadlines for an efficient organization. The transportation steps are the most crucial in this case as they might take the longest amount of time.
  Objective(s): T6, S1, S2.

Environmental indicators

- CO_2 **emissions transportation** [kgCO_2eq.]
  Definition: It refers to the annual carbon emissions generated by the different means of transport for the recycling pathway. This is calculated considering the mean of transport adopted, but also the amount of material that it is possible to recycle in one year.
  Motivation: Transportation is the largest contributor of carbon emissions worldwide, therefore it should be one of the main elements to keep track of when defin-

ing a sustainable recycling pathway. Moreover, as already mentioned, transportation is one of the main differences between all the different recycling pathways. It would be valuable information to understand which one of the pathways generates the lowest amount of carbon emissions associated with transportation, as most of the other steps within the pathways remain constant.
Objective(s): EN1, EN2, EN3, EN4, EN5, S1.

- CO_2 **emissions recycling equipment** [kgCO_2eq./spool]
  Definition: It refers to the annual carbon emissions generated by the different recycling equipment. This is calculated considering the machinery adopted, but also the amount of material that it is possible to recycle in one year.
  Motivation: Global warming is one of the key environmental concerns of the modern era. Identifying all the major sources of global warming within each recycling pathway will allow for identifying the pathway with the lowest global warming potential.
  Objective(s): EN1, EN2, EN3, EN4, EN5, S1.

- **Noise pollution duration** [min/spool]
  Definition: Time when noise above 65 dB (World Health Organization (WHO) threshold to define noise pollution) is generated.
  Motivation: There are many sources of potential noise pollution within a recycling pathway. For instance, the shredding process consists of grinding plastic pieces by means of very noisy metal teeth. Moreover, PA12 out of the SLS process presents a shore hardness of 75D which is labeled as ”extra hard” in the durometer scale, in between the hardness of a wooden ruler (70D) and a bone (90D) (Aeromarine Products, Inc., 2020). Therefore, shredding such hard material is likely to generate very high noise that can potentially be harmful. According to the WHO noise becomes harmful above 75 dB and is painful above 120 dB (WHO, 2022).
  Objective(s): S1, S3.

Economic indicators

- **Costs associated with transportation**[€]
  Definition: It refers to all the costs generated for the different movements of the material per year. This includes also costs for delivery and costs generated by the different means of transport adopted.
  Motivation: As already mentioned, the transportation step is one of the main differences within the different pathways designed. Therefore, calculating the costs associated with this difference (leaving aside the elements held constant), can be an efficient way to quickly evaluate the economic impact of the different

pathways.
Objective(s): EC1, EC2.

- **Energy costs for transportation**[€]
  Definition: It refers to the amount of money associated with the energy for the different means of transport and distances adopted.
  Motivation: Transportation relies on the use of energy. Therefore, understanding which recycling pathway involves the lowest energy costs for its successful completion can be useful information when selecting the most sustainable one.
  Objective(s): EC1, EC2.

- **Amount invested per pathway** [€]
  Definition: It refers to all the costs involved in the successful completion of the recycling pathway per year.
  Motivation: The various recycling pathways designed involve different machinery, stakeholders, and mixtures of material. All these elements generate different costs that should be considered when evaluating the economic feasibility of a recycling route. Achieving a convenient recycling pathway can also ensure its feasibility and implementation in the long term.
  Objective(s): EC1, EC2, EC3.

- **Waste disposal costs** [€]
  Definition: It refers to the amount of money incurred for the disposal of waste materials left over from a manufacturing process.
  Motivation: In regions with higher disposal costs, implementing a recycling pathway for waste can generate savings, or even revenues, on the annual operating costs. Moreover, while PA12 parts must be disposed of (if not used), the powder is already reused (at least in part).
  Objective(s): EC3.

- **Potential revenue** [€]
  Definition: Costs associated with the potential value of the recycled filament in the market. PA12 filament as a raw material for FFF printing is very expensive, therefore, obtaining it from waste with sufficient quality will allow avoiding not only the purchase of new PA12 filament but also any other material for FFF that can be substituted by the recycled PA12 filament. This corresponds to some extent to a form of potential revenue.
  Motivation: Recycling materials can lead both to up-cycling and down-cycling. Understanding the value of the material after its reprocessing is useful in understanding whether it is worth it from an economic standpoint to recycle. Moreover, different mixtures can produce different amounts of filament.
  Objective(s): EC1, S1.

Social indicators

- **Workers' preference (recycling pathway)** [%]
  Definition: Preference of the customers with respect to some actions involved in the different recycling pathways. Preference is evaluated in terms of a sense of safety, satisfaction, gratification, and physical effort.
  Motivation: Mechanical recycling involves the addition of many steps of material post-processing which can be tiring and even dangerous for a worker. These include grinding, melting at high temperatures, and preparing powder packs and flakes for their shipment. Therefore, the different characteristics of the recycling pathways can lead to different degrees of workers' satisfaction and happiness in the workplace. In addition, a more satisfied worker will be more productive and willing to work more.
  Objective(s): S1, S2, S3.

- **Customers' preference (end-use filament)** [%]
  Definition: Percentage of BMW's employees who tested the material and showed preference.
  Motivation: The defined end-use application for the new material is the production of tools for the workers in the production line. This can be achieved by designing and printing parts in-house (AMC) or by sending the filament to the other BMW departments that can use them in their FFF printers. Being able first of all to obtain good quality parts but also to use the filament with ease are two of the reasons that can generate satisfaction in potential users of the material (referred to here as customers).
  Objective(s): T1, S1, S3.

- **Ease of management** [%]
  Definition: Percentage of BMW's employees who showed a preference for the management of the different recycling pathways.
  Motivation: The recycling pathway should be easy to achieve not only in terms of recycling steps for the processing of the material but also from an organizational standpoint. Obtaining a recycling pathway that is easy to set up can be very helpful to cut downtime and improve the mood and efficiency of management employees.
  Objective(s): S1, S2, S3.

- **Number of manual steps performed by employees** [N]
  Definition: Number of steps within the recycling pathway that involve the manual work for the employees.
  Motivation: Automating as much as possible a recycling pathway, can lead to

fewer workers' physical effort, together with less risk of injuries and diseases. Moreover, as already mentioned before, the steps involved in mechanical recycling are not always very high-quality jobs. If on the one hand recycling generates more jobs, on the other hand, low-quality jobs can lead to low morale and quality of life for the employees. In addition, obtaining a fully automated process can potentially generate more revenues allowing one to carry on the process even during the night, holidays, and weekends, when the employees are not in the workplace.
Objective(s): S1, S2, S3.

- **HR diversity** [%]
  Definition: Standard deviation of employees' features (age, race, gender, religion, language) considering all the employees involved in the recycling pathway.
  Motivation: This indicator is meant to evaluate the state of diversity, equity, and inclusion (and belonging) within a recycling pathway. A diverse workplace should be seen as a strength as it involves different perspectives and opinions that can benefit the business.
  Objective(s): S1, S3.

It is possible now to move further with the qualitative assessment, in order to analyze each of the indicators against the different recycling pathways.

5.7 Step 7: Qualitative assessment

After a preliminary selection of the indicators, the next step is to analyze each one of them against the various recycling pathways qualitatively to determine in the end the effectiveness of both indicators and pathways. All the indicators for which there are no sufficient data available or that don't give any significant insight will be discarded. The end goal for this step is to obtain a list of at least three significant indicators per dimension.

Considerations after the material validation procedure

In order to analyze the sustainability of all the different pathways, a necessary step was to attempt to complete each recycling route, right down to the use of the recycled material, to understand the positive and negative aspects of each of these practices also from a material outcome viewpoint. Further information regarding the material validation for AM that has been conducted for the case study, can be found in Appendix C.

The most evident outcome has been noticed at the very beginning of the implementation of the recycling pathways. The material out of **Pathway A** and **Pathway B** (in-house), turned out to be challenging both from a production and printing standpoint. Producing good quality material out of flakes from the machinery already present in the facility turned out to be arduous. The extrusion process required continuous monitoring in order to obtain consistency. Moreover, after being extruded, the filament appeared non-homogeneous and at intervals too thick to be used successfully in the FFF printer. Therefore, it was decided to discard the material in the first place, as the process was too unpredictable and time-consuming, in the end, not efficient.
On the other hand, the material extruded professionally by the external company, appeared to be more homogeneous and suitable for FFF printing. However, being this a pilot project, the material has been, for the time being, produced just for **Pathway C** and **Pathway D**, as these were the first potential pathways considered with the involvement of an external company.
The possibility to shift the entire process within Germany arose later on, after repeated dialogues and meetings with the external filament production company. Therefore, for **Pathway E** and **Pathway F** the filament has not yet been produced. It was in any case decided to keep these two recycling pathways (E and F) for the evaluation. The machinery used (and the materials of course) would be exactly the same as those used for pathways C and D, so the quality of the material is expected to be the same.

That being said, the materials for which mechanical properties could be tested are those obtained from pathways C and D. Indeed, five different types of filaments have been tested, corresponding to five different mixtures PA12 flakes/powder: 100% flakes, 90% flakes, 80% flakes, 70% flakes, and 50% flakes.

Figure 39 *Spools with different mixtures obtained via recycling pathways C and D*

In Figure 39, all the five different types of filament produced by the polymers' processing company are shown. From right to left these are respectively: 100% flakes (no mixing), 90% flakes, 80% flakes, 70% flakes, and 50% flakes.

Qualitative assessment

During the qualitative assessment, all the indicators that remained after the screening (Step 6) have been evaluated against the different recycling pathways. For each indicator, in Table 9 right below, the pathway that best aligns with the objectives was selected and marked with an X. In the rows where more than one pathway is marked for a specific indicator, the reason is that the qualitative value is the same.

The final result after the qualitative assessment shows that the pathways that are more likely to be the most sustainable are:

- Pathway C - 100% flakes and worldwide (Score: 5).
- Pathway 4D - mixing 50% flakes and 50% powder and worldwide (Score: 9).
- Pathway E - 100% flakes and within Germany (Score: 11).
- Pathway 4F - mixing 50% flakes and 50% powder and within Germany (Score: 12).

Indicators	**Pathways**[1]									
	C	**1D**	**2D**	**3D**	**4D**	**E**	**1F**	**2F**	**3F**	**4F**
Amount of recycled material (flakes)	X					X				
Amount of recycled material (powder)					X					X
SD elongation at break					X					X
Total vehicle distance travelled						X				
Energy used for transportation						X	X	X	X	X
Time required for completion						X				
CO2 emissions transportation						X				
CO2 emissions recycling equipment					X					X
Noise pollution duration					X					X
Costs associated with transportation						X				X
Energy costs for transportation						X				X
Amount invested	X	X	X	X	X					
Waste disposal costs	X					X				
Potential revenue					X					X
Preference (recycling pathway)					X					X
Preference (end-use filament)					X					X
Ease of management						X	X	X	X	X
Number of manual steps	X					X				
HR diversity	X	X	X	X	X	X	X	X	X	X
Score	5	2	2	2	9	11	3	3	3	12

Table 9 *Qualitative assessment indicators against alternative recycling pathways.*

Moreover, after the qualitative assessment shown in Table 9, it has been decided to conduct a further screening, and remove two indicators from the evaluation: **energy costs for transportation** and **HR diversity**. It has been realized that the indicator ”energy costs for transportation” does not add any new information to the evaluation. The previous indicator ”costs associated with transportation” provides indeed the same information. The indicator ”HR diversity”, on the other hand, has been realized that it

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[1] C (100% flakes, worldwide), 1D (90% flakes, worldwide), 2D (80% flakes, worldwide), 3D (70% flakes, worldwide), 4D (50% flakes, worldwide), E (100% flakes, Germany), 1F (90% flakes, Germany), 2F (80% flakes, Germany), 3F (70% flakes, Germany), 4F (50% flakes, Germany).

is the same for all the pathways, as the employees do not change between recycling procedures.

The table allows us to move further with the steps of the framework, as it is demonstrated that it contains at least three indicators per dimension, as required from Step 7 in Figure 16. This is the result of a qualitative comparison obtained with discussion and interviews with employees from various departments (Sustainability Supply Chain and Production, Quality and Recycling, Distribution System, Environmental Protection and Circular Economy). As already mentioned, the table obtained is not based on real numbers and data, therefore, in the next section, all the calculations for the various indicators will be carried out. In this way, it will be possible to both confirm and reverse the qualitative results presented so far.

5.8 Step 8: Quantitative assessment

After a qualitative comparison of all the selected indicators against the different recycling pathways, and following the framework developed, is required to perform a quantitative comparison between the pathways, in order to support the conceptual analysis with numerical data. Therefore, in this section, the indicators are calculated to provide all the different values associated with each recycling pathway, in order to understand which one best meets the objectives defined in Section 5.3.

Tables 10 and 11 present the final values of each indicator calculated according to each recycling pathway. As highlighted in red, the values closest to the objectives have been selected.

For the scope of the work, all the calculations that have been conducted are based on data collected on the field during the development of the project, through interviews, workshops and databases research. Together with a series of assumptions, it has been possible to obtain reliable results. Such assumptions and calculation procedures are presented per each indicator in Appendix D. The calculations have been conducted according to the system boundaries, as specified in Section 5.4.

Quantitative Assessment for Technical and Environmental indicators	**C**	**1D**	**2D**	**3D**	**4D**	**E**	**1F**	**2F**	**3F**	**4F**
Amount of recycled material (flakes) [kg/spool]	1.67	1.41	1.18	0.97	0.63	1.67	1.41	1.18	0.97	0.63
Amount of recycled material (powder) [kg/spool]	0	0.16	0.29	0.42	0.63	0	0.16	0.29	0.42	0.63
SD elongation at break [%]	36.03	35.30	19.94	24.69	12.92	36.03	35.30	19.94	24.69	12.92
Total vehicle distance travelled [km]	13814	14553	14553	14553	14553	3818	4292	4292	4292	4292
Energy used for transportation [kWh]	127.08	328.61	342.33	359.98	416.44	87.93	215.36	224.67	236.64	274.95
Time required for completion [days]	67	67	67	67	67	34	34	34	34	34
CO2 emissions transportation [kgCO2eq]	46.76	96.49	101.64	108.26	129.44	22.72	56.64	59.12	62.31	75.51
CO2 emissions recycling equipment [kgCO2eq/spool]	0.0114	0.0096	0.0080	0.0067	0.0043	0.0114	0.0096	0.0080	0.0067	0.0043
Noise pollution duration [min/spool]	0.4	0.34	0.28	0.23	0.15	0.4	0.34	0.28	0.23	0.15

Table 10 *Quantitative assessment with real data (for the technical and environmental dimensions).*

Quantitative Assessment for Economic and Social indicators	**C**	**1D**	**2D**	**3D**	**4D**	**E**	**1F**	**2F**	**3F**	**4F**
Costs associated with transportation [€]	2247	2368	2368	2368	2368	1662	1741	1741	1741	1741
Amount invested [€]	52547	52668	52668	52668	52668	53022	53101	53101	53101	53101
Waste disposal costs [€]	336	1986	1986	1986	1986	336	1986	1986	1986	1986
Potential revenue [€]	8640	10240	12240	14811	23040	8640	10240	12240	14811	23040
Preference (recycling pathway) [%]	84.62	15.38	15.38	15.38	15.38	84.62	15.38	15.38	15.38	15.38
Preference (end-use filament) [%]	67	0	0	0	33	67	0	0	0	33
Ease of management [%]	0	0	0	0	0	100	100	100	100	100
Number of manual steps [N]	3	5	5	5	5	3	5	5	5	5

Table 11 *Quantitative assessment with real data (for the economic and social dimensions).*

Once all the indicators are calculated for the recycling pathways (Tables 10 and 11) is it possible to move further with the assessment as shown in Step 8 of the framework (Section 4.2.8). In Table 12 below, it is required by the framework that each value closest to the objectives should be marked with an X. Subsequently, the number of Xs obtained by each pathway is summed up, to highlight which one is most likely to be the most sustainable according to the framework.

Indicators	**Pathways**[2]									
	C	**1D**	**2D**	**3D**	**4D**	**E**	**1F**	**2F**	**3F**	**4F**
Amount of recycled material (flakes)	X					X				
Amount of recycled material (powder)					X					X
SD elongation at break					X					X
Total vehicle distance travelled						X				
Energy used for transportation						X				
Time required for completion						X	X	X	X	X
CO2 emissions transportation						X				
CO2 emissions recycling equipment					X					X
Noise pollution duration					X					X
Costs associated with transportation						X				
Amount invested	X									
Waste disposal costs		X	X	X	X		X	X	X	X
Potential revenue					X					X
Preference (recycling pathway)	X					X				
Preference (end-use filament)	X					X				
Ease of management						X	X	X	X	X
Number of manual steps	X					X				
Score	5	1	1	1	6	10	3	3	3	8

Table 12 *Quantitative assessment indicators against alternative recycling pathways.*

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[2] C (100% flakes, worldwide), 1D (90% flakes, worldwide), 2D (80% flakes, worldwide), 3D (70% flakes, worldwide), 4D (50% flakes, worldwide), E (100% flakes, Germany), 1F (90% flakes, Germany), 2F (80% flakes, Germany), 3F (70% flakes, Germany), 4F (50% flakes, Germany).

Once the quantitative assessment has been conducted, the pathways with the highest marks are selected. For the case study, these are C, 4D, E, and 4F. The results already differ from the qualitative assessment, where just a conceptual analysis was performed. This difference is due to the removal of the useless indicators but also it depends on the person that performed the analysis (during the qualitative assessment). Such elements were thus corrected through actual data and calculations in this section. After this step, it is, therefore, possible to narrow down the potential recycling pathways, by discarding all of them that present the lowest number of values closest to the objectives.

It is possible to notice that there is a clear trend towards those pathways that involve raw material either flakes or an even mixture between flakes and old powder.

The pathway that presents the highest indicators' values, meaning that it meets the objectives defined, is pathway E (100% flakes and within Germany). Moreover, the difference in scores between the pathways after the quantitative assessment looks abysmal. However, results can still change after the adoption of the Best-Worst Method (BWM) for the weighting of not only of the indicators, but also of the sustainability dimensions (4DS). These weights will be calculated taking into account BMW's objectives and needs.

5.9 Step 9: Weighting dimensions and indicators: BWM

After the quantitative assessment of the indicators, it is required to implement the Best-Worst Method (BWM) by Jafar Rezaei to the four dimensions (within each other, Figure 40) and to the indicators in each dimension (Figure 41), to assign them weight according to BMW's needs, interest, and objectives.

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Technical	Environmental	Economical	Social

Select the Best	Economical

Select the Worst	Environmental

Best to Others	Technical	Environmental	Economical	Social
Economical	1	3	1	2

Others to the Worst	Environmental
Technical	2
Environmental	1
Economical	3
Social	2

Weights	Technical	Environmental	Economical	Social
	0.3125	0.125	0.375	0.1875

Input-Based CR	0.166666667	The pairwise comparison consistency level is acceptable
Associated Threshold	0.1667	

Figure 40 *BWM for the four dimensions - Case study*

Criteria Number = 6	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Criterion 6
Names of Criteria	Flakes	Powder	Eb	Distance	Energy trans.	Time

Select the Best	Flakes

Select the Worst	Distance

Best to Others	Flakes	Powder	Eb	Distance	Energy trans.	Time
Flakes	1	4	2	7	3	3

Others to the Worst	Distance
Flakes	7
Powder	4
Eb	6
Distance	1
Energy trans.	4
Time	4

Weights	Flakes	Powder	Eb	Distance	Energy trans.	Time
	0.3591549	0.1056338	0.2112676	0.042253521	0.14084507	0.1408451

Input-Based CR	0.2142857	The pairwise comparison consistency level is acceptable
Associated Threshold	0.3029	

Criteria Number = 3	Criterion 1	Criterion 2	Criterion 3
Names of Criteria	Emissions	Emissions	Noise

Select the Best	Noise

Select the Worst	Emissions

Best to Others	Emissions	Emissions	Noise
Noise	5	9	1

Others to the Worst	Emissions
Emissions trans.	3
Emissions equip.	1
Noise	9

Weights	Emissions	Emissions	Noise
	0.164835165	0.076923077	0.7582418

Input-Based CR	0.083333333	The pairwise comparison consistency level is acceptable
Associated Threshold	0.1359	

(a) *Technical indicators*

(b) *Environmental indicators*

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Transportation	Total invested	Waste	Pot. Revenue

Select the Best	Total invested

Select the Worst	Pot. Revenue

Best to Others	Transportation	Total invested	Waste	Pot. Revenue
Total invested	2	1	2	7

Others to the Worst	Pot. Revenue
Transportation	5
Total invested	7
Waste disposal	5
Pot. Revenue	1

Weights	Transportation	Total invested	Waste	Pot. Revenue
	0.246376812	0.449275362	0.246376812	0.057971014

Input-Based CR	0.071428571	The pairwise comparison consistency level is acceptable
Associated Threshold	0.2457	

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Recycling procedure	Filament	Ease of manag.	Manual steps

Select the Best	Filament

Select the Worst	Manual steps

Best to Others	Recycling procedure	Filament	Ease of manag.	Manual steps
Filament	4	1	3	8

Others to the Worst	Manual steps
Recycling procedure	5
Filament	8
Ease of manag.	7
Manual steps	1

Weights	Recycling procedure	Filament	Ease of manag.	Manual steps
	0.170984456	0.549222798	0.227979275	0.051813472

Input-Based CR	0.232142857	The pairwise comparison consistency level is acceptable
Associated Threshold	0.2521	

(c) *Economic indicators*

(d) *Social indicators*

Figure 41 *BWM for the indicators within the four sustainable dimensions - Case study*

It is worth mentioning that in order to obtain reliable and repeatable results, the preference indicated for each dimension and indicator is the result of meetings and workshops with the different stakeholders involved in the decision-making process. All the preferences used to conduct the BWM have been previously agreed upon, to obtain the weigths.

Once the BWM has been applied, the weight of each dimension is multiplied by the weight of each indicator within that dimension and a score is assigned to each indicator, as presented in Table 13. This will constitute the base for the selection of the most sustainable recycling pathway.

Dimension	**DW** [3]	**Indicator**	**IW** [4]	**Score**
Technical	0.313	Amount of recycled material (flakes)	0.359	0.112
	0.313	Amount of recycled material (powder)	0.106	0.033
	0.313	SD elongation at break	0.211	0.066
	0.313	Total vehicle distance travelled	0.042	0.013
	0.313	Energy used for transportation	0.141	0.044
	0.313	Time required for completion	0.141	0.044
Environmental	0.125	CO2 emissions transportation	0.165	0.021
	0.125	CO2 emissions recycling equipment	0.077	0.010
	0.125	Noise pollution duration	0.758	0.095
Economic	0.375	Costs associated with transportation	0.246	0.092
	0.375	Amount invested	0.449	0.168
	0.375	Waste disposal costs	0.246	0.092
	0.375	Potential revenue	0.058	0.022
Social	0.188	Preference (recycling pathway)	0.171	0.032
	0.188	Preference (end-use filament)	0.549	0.103
	0.188	Ease of management	0.228	0.043
	0.188	Number of manual steps	0.052	0.10

Table 13 *Calculation of the weight of each indicator within each dimension - Case study*

5.10 Step 10: Selection of the sustainable recycling pathway

Following the framework, the next step is to calculate the most sustainable recycling pathway, as explained in Section 4.2.10.

---

[3] Dimension Weight (DW)

[4] Indicator Weight (IW)

According to the position of the marks in the quantitative assessment table (Table 12), it is possible to assign the weight of each indicator to the recycling pathway that best meets the objectives. In Table 14, the scores calculated for each indicator (based on DW and IW) are reported and assigned to the pathways where is applicable. Finally, all the values assigned to each recycling pathway are summed up and the most sustainable recycling pathway is the one that presents the highest score. In this case, Pathway E.

Dimension	Indicator	Weight	C	4D	E	4F
Technical	Amount of rec. material (flakes)	0.112	0.112		0.112	
	Amount of rec. material (powder)	0.033		0.033		0.033
	SD elongation at break	0.066		0.066		0.066
	Total vehicle distance travelled	0.013			0.013	
	Energy used for transportation	0.044			0.044	
	Time required for completion	0.044			0.044	
Environ.	CO2 emissions transportation	0.021			0.021	
	CO2 emissions equipment	0.010		0.010		0.010
	Noise pollution duration	0.095		0.095		0.095
Economic	Costs associated with transport.	0.092			0.092	
	Amount invested	0.168	0.168			
	Waste disposal costs	0.092		0.092		0.092
	Potential revenue	0.022		0.022		0.022
Social	Preference (recycling pathway)	0.032	0.032		0.032	
	Preference (end-use filament)	0.103	0.103		0.103	
	Ease of management	0.043			0.043	0.043
	Number of manual steps	0.010	0.010		0.010	
Score			**0.425**	**0.318**	**0.514**	**0.360**

Table 14 *Assigning the score to the recycling pathways - Case study*

What it is observable in Table 14 is that the score difference between the pathways is leveled when applying the BWM. In the 8th step of the framework (quantitative assessment, Section 5.8), pathway E resulted to have double the score with respect to pathway C. Moreover, the second most sustainable pathway resulting at that moment is pathway 4F, followed by 4D, and finally C (see Table 12).

The adoption of the BWM for BMW's case study, highlighted the importance of the economic dimension for the company (Section 5.9), followed by the technical, social, and environmental objectives. Therefore, all the indicators considered in the economic dimension assumed globally higher scores with respect to most of the other indicators evaluated.

This implementation of the BWM resulted in lowering the score of pathway E with respect to the quantitative assessment, as three out of four indicators within the economic dimensions were best met by other pathways, specifically *amount invested* was met by pathway C, while *waste disposal costs* and *potential revenue* by pathways 4D and 4F (see Table 12).

The adoption of the BWM, still maintained as the most sustainable pathway E but decreased its importance with respect to the others. Moreover, the weighting procedure changed the order of importance previously defined by the quantitative assessment, as now the second most sustainable pathway is pathway C, followed by 4F and finally 4D (see Table 14). This is a very interesting discovery as it allows reflecting on the fact that pathway E is the most environmentally friendly overall with respect to the others (in particular due to the short distances for transportation and the lower amount of material processed per year). Also, pathway C despite being arranged worldwide (which does not make it particularly environmentally friendly), on the other hand, is the cheapest pathway as for the investment costs, which led it to be the second best pathway to implement after pathway E.

A final very noticeable difference between the pathways has been given by the indicators within the social dimension. Through the evaluation of the results has been found that the employees prefer managing flakes with respect to powder. This factor led to an overall preference for the pathways without the adoption of powder respect to the others. The main concerns are related to discomfort in handling powder, together with concerns for potential health issues, although employees never actually experienced them.

Chapter 6

Discussion and conclusion

6.1 Discussion

The adoption of the ten-step framework in a systematic way made it possible to select the most sustainable recycling pathway for PA12 in BMW according to a set of indicators from the four dimensions of sustainability (4DS), defined and calculated ad hoc for the specific case study. Overall, the pathway that achieved the highest score is pathway E, which consists of the recycling of PA12 parts, to obtain filament with 100% flakes content (without any addition of old PA12 powder), conducting all the recycling steps within Germany.

On the technical dimension, pathway E is the one that obtained the best results overall. It indeed allows to recycle of the highest amount of PA12 flakes, with respect to the other pathways, together with pathway C. Moreover, Pathway E represents also the one with the shortest transportation distance, making it the least time and energy-consuming, as not only is set up in Germany but also does not require powder shipping. The evaluation of the mechanical properties of the material, on the other hand, suggests that other mixtures obtained better results, such as the mixture of 50% flakes and 50% powder. This factor did not make a big difference in the final evaluation, as all these materials resulted to have mechanical properties suitable to potentially substitute most of the filaments for FFF printing available on the market.

As for the environmental dimension, Pathway E resulted in the pathway with the highest generation of noise pollution, as the adoption of just flakes means greater annual utilization of the shredder with respect to the other mixtures. But pathway E is also the pathway with the lowest amount of carbon emissions for transportation overall.

Pathway E met just one of the four indicators within the economic dimension, which is the costs associated with transportation, as it is the pathway with the shortest transportation distances. However, the other three indicators within the economic dimension were best fulfilled by different recycling pathways. Pathway E is one of the most expensive pathways considered. This is due to the fact that filament production in Germany is more expensive than in Morocco (represented by Pathways C and D). Another element to take into account is that the economic dimension is the one that, according to BMW's objectives, obtained the highest weight with respect to the others through the application of the BWM. However, all the others indicators scored by pathway E were enough to turn the evaluation, allowing it to emerge over the others. Observing even more closely, the calculations suggest that the economic difference with respect to the other pathways is almost negligible for a company such as BMW, this being in the range of hundreds.

For the social dimension, pathway E met all the indicators considered. First of all, according to the surveys' results, the utilization of the shredder is the step that brings the highest gratification to the employees with respect to other steps. In fact, steps such as powder shifting into containers and packages, generate health concerns among the employees and therefore are the least preferred to perform. Secondly, this pathway led to the most satisfactory material in terms of printability for the customers. Moreover, the adoption of just flakes and no powder brings fewer manual steps to be performed by the BMW's employees, ending up in fewer risks for their health. Lastly, having the whole pathway within Germany makes the overall process more flexible and easy to manage.

The application of the framework to the case study was successful as it showed on the basis of real data which recycling pathway should be implemented to reduce PA12 waste in BMW's facilities. It generated a different version of a trade-off analysis, where all the indicators had a different score, allowing to select the alternative that was most efficient to implement according to the case study. The main reason why the framework turned out to be considered a useful tool was that it took into account the company's needs and objectives. Indeed, the application of the BWM demonstrated how the addition of subjectivity to the evaluation can change the results, still maintaining all the sustainability features, but with a closer eye toward the company that should actually implement the recycling pathway. By doing so, a company can potentially be more willing to implement sustainable procedures such as recycling, because its interests are taken into account together with the environmental ones.

6.2 Conclusions

The motivation that led to the establishment of this work was to find a way to assess sustainability for recycling pathways for solid materials. From an in-depth literature review it was found that when assessing sustainability, just three dimensions of sustainability are mainly considered, being these environmental, economic, and social. However for a recycling pathway to be efficient, it is important also to evaluate the quality of the material and the level of conservation of resources as part of a technical dimension for the sustainability assessment. A tool for addressing also this dimension has not been found in literature, therefore, a new framework for assessing sustainability in recycling pathways has been proposed in this work. A ten-step framework was presented to assess sustainability for recycling pathways according to four dimensions of sustainability (4DS) that are technical, environmental, economic, and social.

Such framework was then adopted to a real case study that served as validation of the framework itself. The case study considered was the sustainable recycling of Polyamide 12 automotive waste generated in BMW's production facilities in Munich, Germany. Several recycling pathways were designed and compared according to the sustainable framework to evaluate which recycling pathway was the most sustainable according to BMW's needs and objectives. The end-use application for the recycled material has been selected in the context of Additive Manufacturing, in particular, the material has been turned into filament for FFF printing. The recycling pathways considered were designed in the BMW's AMC, with the cooperation of external material processing companies. Then, the pathways have been compared according to the steps established by the sustainable framework defined in this research.

The framework consists of ten steps to be performed consistently in order to obtain the most appropriate recycling pathway among a set of alternatives. Such a framework can be adopted to facilitate the decision-making process for the management of solid waste material. The high degree of subjectivity that the framework shows, still maintaining consistency, makes it suitable to be applied in many different processes. The focus of the work was the application of the framework to automotive prototyping, where many different materials are discarded every day. Through a series of research sub-questions, the work was meant to describe such a framework and its implementation within the automotive prototyping industry.

First of all, it was necessary to introduce the main factors that influence sustainability in recycling pathways (SB1.*What are the main factors that influence the sustainability of* *recycling?*). In Chapter 4, four dimensions of sustainability (4DS) have been defined: technical, environmental, economic, and social. The idea behind the framework is that for the sustainability assessment of recycling pathways in particular, an important factor is constituted by the quality of the material obtained after the recycling pathway. Obtaining sufficient quality material is essential to make the whole procedure worth the effort, the investment, and the time spent on its completion. Someone might argue that anyways, regardless of the end material, recycling benefits the environment, and this is enough to implement a recycling pathway. However, even in this case, the procedure of recycling, as shown in the literature research conducted in this work, adds more steps to the processing chain. This addition can potentially result in more resources consumed such as water, energy, and materials; but also more carbon footprint, and investment. Therefore, the sustainability assessment should be conducted in the broadest way possible. The technical dimension, in particular, concerns the material quality, but also its requirements for the end-use application. Within this dimension also overall efficiency of resources (material, energy, machinery) is evaluated. The environmental dimension concerns, on the other hand, all those elements that can generate emissions in the environment in any form. The economic dimension involves the economic performance of the recycling pathway, both in the short and long term, such as initial investment, and potential revenues. Any movement of capital should be considered in this dimension. Finally, the social dimension involves all those factors that can either benefit or be harmed by the effects of the recycling pathways such as employees, communities, and customers.

Being the spectrum of factors to consider in a sustainability assessment for recycling very broad, a way to maintain it organized and easy to use was needed. The development of the framework was born exactly with the idea of bringing coherence and structure to these many different elements involved. First of all, for a proper sustainability assessment, the framework recommends starting off with the definition of the problem (the reason why the recycling pathway is needed in the first place) and a deep understanding of the current system where the recycling pathway should take place. Drawing the boundaries of the system, understanding how the system works, but also priorities and needs, allows obtaining in the end a recycling pathway tailored according to the company's goals, potentials, and interests. Subsequently, designing alternative recycling pathways to be compared according to a set of indicators per each dimension follows in the framework. The choice of indicators to calculate is essential for the selection of the most sustainable recycling pathway. The indicators are meant to be chosen for the single case study, according to a series of criteria explained in Section 4.2.6. This aspect of the framework, explained in detail in Chapter 4, is meant to answer the second research sub-question of the work (SB2. *How can sustainability in* *recycling be assessed?*). The selection of the indicators increases therefore the degree of subjectivity of the assessment.

As already mentioned before, the framework gives a lot of freedom to the user, in particular for the choice of indicators. Although it is essential that they are selected for each of the four dimensions of sustainability (4DS) and also based on the objectives of the company, it is important to give consistency to such elements, in order to ensure meaningful results, which leads to the next sub-question: SB3. *How to compare in a standard and consistent way different recycling pathways?*. To assess this question, a series of assessments have been considered within the framework, to give standardization. First of all, a qualitative assessment must be conducted to determine whether the chosen set of indicators allows for obtaining meaningful results, and in case, adjust them. Secondly, a quantitative assessment must be performed in which the indicators are calculated according to real data, and the pathways that best meet the objectives previously defined are chosen.
What really added consistency and standardization is the implementation of the Best-Worst Method (Rezaei, 2015). This work supports the idea that to perform an evaluation of sustainability, both the four dimensions and the indicators within them should have different weights (importance) on the decision-making process, according to companies' needs, interests and objectives. However, the weighting procedure must be to some extent guided, to avoid any kind of extreme situations that might verify themselves. Such weighting method (BWM) is meant to be applied on five sets of elements: within the 4DS and within the indicators in each of the 4DS. In this way, it is possible to obtain scores for each indicator which should depict the interests and objectives of the user, in a consistent way. With all this information, it would be possible in the end to select the most appropriate recycling pathway.

Finally, the framework required a validation procedure, not to remain just theoretical. Its application to a real-world case study is presented in Chapter 5, and is meant to answer the last sub-question of the work: SB4. *How the implementation of the framework can help design the most sustainable recycling pathway for PA12 in automotive prototyping?*. The framework was adopted to make the reuse of PA12 prototyping waste more sustainable for the BMW's production. A pathway that consists of the mechanical recycling of PA12 parts, to obtain filament for FFF has been selected. It has been evaluated that the most sustainable alternative, according to BMW's objectives, is to adopt 100% flakes content for filament production and conduct all the steps of the recycling pathway within Germany.

All together these findings allowed to develop and explain in detail the framework throughout the thesis, in order to answer the main research question of the work: *How does a framework for sustainable recycling look like and how can it be implemented in the automotive industry?*. To address this question a ten-step framework was developed. Starting from the literary basis on which it was constructed, the framework represents a new way to conduct a sustainability assessment, which is meant to facilitate and make less onerous the implementation of sustainable procedures for the companies, taking also their interests into account. Many times it happens that despite good premises and tight environmental agreements, companies that are not directly concerned with sustainability are more reluctant to make their processes more sustainable. Adopting definite and accessible tools can help this conversion towards more environmentally friendly practices, which can ultimately provide many benefits to the company itself, as this work wanted to demonstrate.

6.3 Strength and limitations of the framework

One of the main strengths of the pathway is that it takes into account the company's interests. It is meant to allow companies to select not only the most sustainable pathway in terms of environmental effects but also convenience and flexibility.
The idea behind the development of this framework is to create a tool easy and fast to implement, and that can be used and understood by employees with many different backgrounds. Also, as companies evolve and change very quickly, the framework has been developed in a way that it can be changed accordingly and updated with new objectives, indicators, and results every time in short periods. In this way, an always up-to-date assessment will be in place.
The framework is meant to provide a comparison between different recycling pathways. Its easiness of use lies also in the fact that it is not necessary to calculate each element that takes generally part in a sustainability assessment. In fact, all the common features of the different alternatives designed, are not part of the system as they don't add any new information for the evaluation. This feature makes the framework easier to use, but also faster to adopt.
Moreover, particular attention has been given to the right balance between the different dimensions of sustainability (4DS). The framework doesn't allow any extremes in any of the directions, which is aimed to protect at the same time everyone's interests. It is designed to provide a different way of conducting a trade-off analysis between all the potential factors that can be involved in a recycling pathway.
Lastly, the free definition of the indicators to calculate, allows the framework to be adopted for many different processes and industries. In this case, it would just be necessary to define proper objectives and understand which are the most influential factors involved in that particular process.

On the other hand, there are also some limitations to this framework. First of all, it doesn't take into account how big the difference in value is, for the indicators among the different pathways. To facilitate the procedure, for each indicator it is selected the pathway that best meets the objectives in that context. It can happen that sometimes the difference is negligible and in that case, the framework provides different steps in which it is possible to assess this problem, for example, the screening of the indicators in which if one indicator doesn't provide enough information it can be discarded. On the other hand, when the difference between the pathways with respect to one indicator is very large, this might be a reason to choose one pathway with respect to the others. But the framework does not take into account how big is the difference between the values of the indicators. The framework is designed to find the most sustainable recycling pathway, based on the company's preference. If the others dimensions are preferred over the economic one, for instance, the framework will take less into account the economic aspects of the recycling pathway. If there are some companies that are willing to invest in a pathway even if it is more expensive, other companies might have a budget limitation and not be able to afford it.

In the end, it has been estimated, that most of the objectives previously defined in the context of the case study have been met during the implementation of the framework, but not all of them. Indeed, another limitation is that even if during the definition of the indicators it is sure that all the objectives are covered, by the end, with the screening of both indicators and pathways, this certainty may come to lack.

6.4 Recommendations for future work

Suggestions for the sustainable framework

The limitations previously defined indicate the main areas of focus for further development of the framework.

First of all, it is suggested to find a way to account for the value gaps that may occur for an indicator versus different pathways. In this way, the framework will provide more complete and concrete results. It will be a way to make sure that the pathway selected as the most sustainable is really implementable and a more complete trade-off analysis will provide this result.

Moreover, despite this framework having been developed for the comparison of different recycling pathways, in general, it has the potential to be implemented also to analyze how is best to implement a single recycling pathway (for instance according to the frequency in which it has to be carried on). The basis is always the comparison between one or more elements. For example, taking into account one single recycling pathway, results might change if it is assumed a different frequency in which it should be implemented, such as once/twice per year. Indeed, by implementing a recycling procedure once per year, the process might be more efficient in terms of emissions as the whole transportation step must be done just once, however, this means also longer times to obtain the final material, and more storage space needed to collect the waste for an entire year, respect to a six months basis. The framework can be adopted in this regard to evaluating the best setup to implement the recycling pathway. A study on the potential of the framework to evaluate different elements (such as processes, and materials) which are not recycling pathways is suggested. In fact, the framework can be used to assess sustainability in any process, and also assess the sustainability of circular systems.

Suggestions for PA12 recycling

Moving towards the case study and the recycling of Polyamide 12 in automotive prototyping, many are the topics that can be suggested to move further in the research.
Now that the recycling pathway resulting from the framework will be implemented, it would be very interesting to study its effects in the long term. Again, as already mentioned, a pathway is really sustainable when it brings advantages in the present (short-term), but doesn't harm the future (long-term). Therefore, a deep understanding of the effects of the adoption of the recycling pathway suggested by the sustainable framework will be a further way to validate the framework itself and show its potential.
Additive Manufacturing is still a niche market and a niche industry, therefore, more research is suggested when it comes to recycling for 3D printing technologies. The evaluation of recycling for other technologies with respect to FFF can bring some interesting results. And also, the adoption of compounds in the mixture specifically for PA12 and its changes in the mechanical properties can bring added value to the research in PA12 recycling. The use of compounds such as glass fibers and carbon fibers has been discarded in the first place for the adoption within this research because the material risked not being recyclable anymore, but PA12's potential to be recycled with the addition of compounds is a topic that should be assessed. Lastly, within the case study of this work, the PA12 parts have been recycled just one time to be turned into filament for tooling. With the procedure moving further, it will come a moment in which the new tools out of PA12 recycled filament reach their end of life. Many works assessed the level of recyclability of different types of plastics, however, research is still lacking in the assessment of the degree of recyclability of PA12 parts, when they are printed out of recycled PA12 as obtained in this study. This potential new study will provide new insights into recycling procedures and new perspectives.

Appendix A

List of papers for indicators selection

In this section, a list of reports for indicator selection proposed in the literature is presented. Through these works, it is possible to obtain insights to select indicators that are best suited to the specific case study.

- Veleva, V. & Ellenbecker, M. (2001). Indicators of sustainable production: framework and methodology. *Journal of Cleaner Production.* `https://doi.org/10.1016/S0959-6526(01)00010-5`

- Veleva, V., Hart, M., Greiner, T. & Crumbley, C. (2001). Indicators of sustainable production. *Journal of Cleaner Production.* `https://doi.org/10.1016/S0959-6526(01)00004-X`

- Niemeijer, D. & de Groot, R.S. (2006). A conceptual framework for selecting environmental indicator sets. *Ecological Indicators.* `https://doi.org/10.1016/j.ecolind.2006.11.012`

- Bianchini, A., Guarnieri, P. & Rossi, J. (2022). A Framework to Assess Social Indicators in a Circular Economy Perspective. *Sustainability.* `https://doi.org/10.3390/su14137970`

- Umweltbundesamt (2022).
  `https://www.umweltbundesamt.de/en/daten/umweltindikatoren/bericht`

- Dong, Y. & Hauschild, M.Z. (2017). Indicators for environmental sustainability. *The 24th CIRP Conference on Life Cycle Engineering.* `doi:10.1016/j.procir.2016.11.173`

- Popovic, T., Kraslawski, A., Barbosa-Póvoa, A., & Carvalho, A. (2017). Quantitative indicators for social sustainability assessment of society and product responsibility aspects in supply chains. *Journal of International Studies.* `doi:10.14254/2071-8330.2017/10-4/1`

- Popovic, T., Barbosa-Póvoa, A., Kraslawski, A. & Carvalho, A. (2017). Quantitative indicators for social sustainability assessment of supply chains. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2018.01.142
- Hale, J., Legun, K., Campbell, H. & Carolan, M. (2019). Social sustainability indicators as performance. *Geoforum*. https://doi.org/10.1016/j.geoforum.2019.03.008

Appendix B

Best-Worst Method

Nomenclature for the Best-Worst Method (in order of appearance)

c_j decision element j

c_B best element

c_W worst element

a_{Bj} preference of the best element over the others

A_B Best-to-Others vector

a_{jW} preference of all the element over the worst

A_W Others-to-Worst vector

w_j weight of the element j

w_B weight of the best element

w_W weight of the worst element

$d.o.f.$ degrees of freedom

$s.t.$ subject to

ξ consistency factor

Best-Worst Method in detail

The BWM has been developed by Jafar Rezaei from Delft University of Technology in 2015. This method has been developed to solve MCDM discrete problems, where a number of alternatives (in this case the recycling pathways) are evaluated with respect to a number of elements (the indicators) in order to select the best alternative. It consists in five steps that will be now presented and discussed.

Step 1: Determine a set of decision elements $\{c_1, c_2, ..., c_n\}$.
The number "n" of elements within the set can vary from 3 to 9. For more than 9 elements, it is recommended by Rezaei to first cluster the elements into a number of groups.

Step 2: Determine the best ($c_B \in \{c_1, c_2, ..., c_n\}$) and the worst ($c_W \in \{c_1, c_2, ..., c_n\}$) element, where $c_B \neq c_W$.

Step 3: Determine the preference $a_{Bj} \in \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ of the best element c_B over all the other elements $c_j \in \{c_1, c_2, ..., c_n\}$ to obtain the Best-to-Others vector:

$$A_B = (a_{B1}, a_{B2}, ..., a_{Bn})$$

where a_{Bj} with $j \in \{1, ..., n\}$ indicates the preference of the best element c_B over element c_j.
It is clear that $a_{BB} = 1$ as it shows the preference of the best element over itself.

Step 4: Determine the preference $a_{jW} \in \{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ of all the elements over the worst element c_W, to obtain the Others-to-Worst vector:

$$A_W = (a_{1W}, a_{2W}, ..., a_{nW})$$

where a_{jW} with $j \in \{1, ..., n\}$ indicates the preference of the element c_j over the worst element c_W.
It is clear that $a_{WW} = 1$ as it shows the preference of the worst element over itself.

For Steps 3 and 4, the meaning of the numbers 1-9 is:

1: **Equally** important

2: Somewhat between Equal and Moderate

3: **Moderately** more important than

4: Somewhat between Moderate and Strong

5: **Strongly** more important than

6: Somewhat between Strong and Very Strong

7: **Very strongly** more important than

8: Somewhat between Very strong and Absolute

9: **Absolutely** more important than

Step 5: Find the optimal weights $(w_1, w_2, ..., w_n)$.

The optimal weight for the elements is the one where, for each pair of $\frac{w_B}{w_j}$ and $\frac{w_j}{w_W}$, it is found $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_W} = a_{jW}$. To satisfy these conditions for all j, the solution lies where the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized.
According to Rezaei, considering the non-negativity and sum condition for the weights, this translates into the following problem:

$$
\begin{aligned}
& minmax_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right| \right\} \\
& \text{d.o.f.} \\
& a_{Bj}, \text{for j} \in \{1, ..., n\} \\
& a_{jW}, \text{for j} \in \{1, ..., n\} \\
& \text{s.t.} \\
& \sum_j w_j = 1 \\
& w_j \geq 0, \text{for all j}
\end{aligned}
$$

Such problem can be transferred to the following problem:

$$
\begin{aligned}
&min\xi \\
&\text{d.o.f.} \\
&a_{Bj}, \text{for j} \in \{1, ..., n\} \\
&a_{jW}, \text{for j} \in \{1, ..., n\} \\
&\text{s.t.} \\
&\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi, \text{for all j} \\
&\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \xi, \text{for all j} \\
&\sum_j w_j = 1 \\
&w_j \geq 0, \text{for all j}
\end{aligned}
$$

According to Rezaei, solving this problem gives the optimal weights $(w_1, w_2, ..., w_n)$ of the elements considered and ξ, which refers as a consistency factor. The higher the ξ, the less reliable the comparison (Rezaei, 2015).

Appendix C

Material validation for AM

FFF as a validation technology

For the validation of the material, it was important to select a standard print job that would allow for the best possible quality. The selection procedure that was followed for proper printing parameters will now be explained and reasoned.

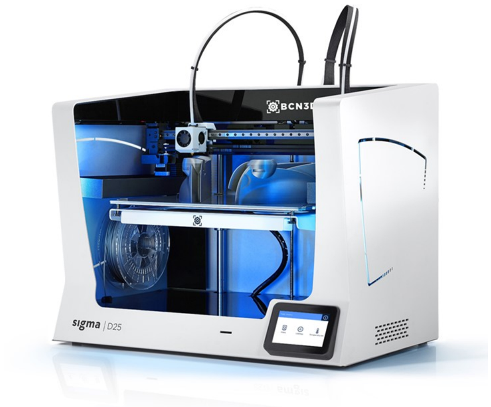

Figure 42 *BCN3D Sigma D25 (BCN3D, 2022b)*

First of all, the FFF printer that has been adopted for the validation of the quality of the material after the recycling procedure, is the BCN3D Sigma D25 (Figure 42). Further technical specifications on the machine can be found on the brand website. Some features of the FFF printer are presented in Table 15.

The Sigma D25 requires the design to be prepared in a particular slicing software called "BCN3D Stratos". The software is used to set up all the different printing parameters, together with the desired material to be used and the size of the hotend (the component of an FFF 3D printer that heats, melts, and extrudes the material layer by layer through a nozzle (BCN3D, 2022a)). What it is important to mention is that the

Characteristic	Value
3D printing technology	Fused Filament Fabrication (FFF)
Architecture	Independent Dual Extruder (IDEX)
Printing Volume	420mm x 300 mm x 200 mm
Number of extruders	2
Supported files	*.gcode
Nozzle diameter	0,4 mm — 0,6 mm — 0,8 mm
Filament diameter	2,85 ± 0,05 mm
Open filament system	Yes
File preparation software	BCN3D Stratos

Table 15 *Main technical characteristics of the Fused Filament Fabrication (FFF) printer BCN3D Sigma D25 (BCN3D, 2022b)*

Sigma D25 printer presents the so-called ”open-material system”. It allows in fact to use of many compatible materials and filaments, without the need for the brand of the material to be the same as the printer. That allowed therefore to test all the different materials that have been obtained with the recycling pathways.

Test specimen

The standard adopted in this work for mechanical behavior testing is DIN EN ISO 527-2. As a result of the unavailability of specific standards for material characterization of FFF parts (García Domínguez et al., 2019), ISO 527-2:2012 is adopted as it specifies the test conditions for determining the tensile properties of molding and extrusion plastics. The geometry of the specimen (Type 1A) according to such standard is shown in Figure 43. In Table 16, it is possible to find the dimensions of the standard test specimen.

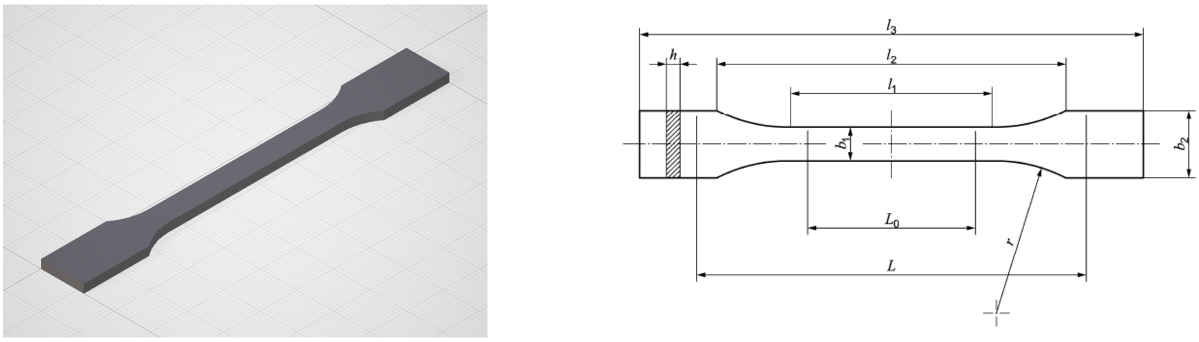

Figure 43 *Standard test specimen Type 1A in DIN EN ISO 527-2 (DIN, 2012) :* ***(a)*** *3D model (left) and* ***(b)*** *technical dimensions (right)*

Symbol	Characteristic	Value
l3	Total length	170 mm
l1	Length of the narrow parallel part	80 ± 2 mm
r	Radius	24 ± 1 mm
l2	Distance between the wide parallel sides	109,3 ± 3,2 mm
b2	Width at the ends	20,0 ± 0,2 mm
b1	Width of the narrow part	10,0 ± 0,2 mm
h	Preferred thickness	4,0 ± 0,2 mm
L0	Measuring length	75,0 ± 0,5 mm
L	Initial spacing of the terminals	115 ± 1 mm

Table 16 *Specimen Type 1A dimensions (ISO 527-2:2012) (DIN, 2012)*

Standard print-job selection

For the choice of the standard print job to be adopted, a preliminary selection process has been conducted. Four print jobs in the Sigma D25 have been carried out, with different printing parameters and the same material (PA12 filament obtained from old PA12 powder).

Firstly, for all the print jobs conducted the material has been dried at 80°C for a minimum of 3 hours to eliminate moisture. Moisture, indeed, can cause potential issues during the printing process having an impact on features such as mechanical parameters, printing quality, layer lamination, and porosity (Fang et al., 2020).

Afterwards, eleven tensile specimens per job have been printed (with a 0,6 mm hot end), all with a flat orientation on the printing surface. The parameters that have been changed in the four jobs were: infill density and infill pattern. The decision of changing these two parameters comes from the revision of various literature on the topic. As a result of this review, it was possible to assume that infill density and pattern are the factors that most influence the mechanical properties of specimens (Ćwikła et al., 2017). The following Table 17 shows the parameters adopted for each job. As it is possible to notice, just the infill density and pattern have been changed.

After printing and testing eleven tensile bars per each job, the tensile testing results reported the results showed in Figure 44. The tensile testing procedure adopted in this case uses the same standard, machinery, and parameters that will be adopted for the validation of the new material. Following, it is possible to find more information about the tensile testing machine adopted.

From tensile testing there are many material properties that can be derived. For the scope of this research, the whole validation of the material has been based on two

Job	N. of spec.	Orient.	Extruder Temp. (°C)	Bed Temp. (°C)	Print Speed (mm/s)	Layer Height (mm)	Infill Pattern	Infill Density (%)
Job 1	11	Flat	255	80	75	0,2	Lines (0°)	100
Job 2	11	Flat	255	80	75	0,2	Lines (90°)	100
Job 3	11	Flat	255	80	75	0,2	Lines (45°)	100
Job 4	11	Flat	255	80	75	0,2	Gyroid	60

Table 17 *Preliminary jobs conducted with filament from old PA12 powder for the selection of the standard print-job*

mechanical properties in particular: tensile strength and elongation at break. *Tensile strength* refers to "the maximum stress that a material can bear before breaking when it is allowed to be stretched or pulled" (Pal et al., 2022). While *elongation at break* is defined as "the ratio between changed length and initial length after breakage of the test specimen" (Djafari Petroudy, 2017), and it is a measure of material ductility.

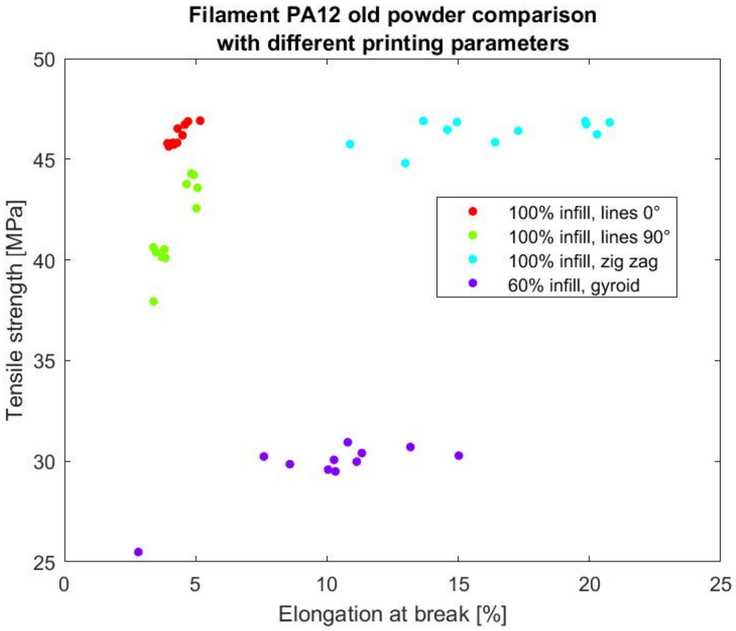

Figure 44 *Elongation at break VS Tensile strength for PA12 filament out of old powder with different infill characteristics*

As Figure 44 reports, the infill characteristics that generated the highest mechanical properties (tensile strength and elongation at break) was the combination of 100% infill density and lines (45°) as infill pattern (Job 3 in Table 17). Therefore, this has been accepted as the standard build-job for the validation of the PA12 filament out of the recycling process.

Validation results

For the purpose of the study, the validation of the material can be divided into two phases: the printing procedure and the tensile testing. Being the filament created out of old PA12 parts (a new material never created before), it was first of all necessary to find out whether it was suitable for the FFF technology and whether it could have been used for printing (from here the printing procedure phases), even before testing its quality and mechanical properties. As a result of the validation, all the different materials that were tested showed different characteristics both in terms of printability and mechanical properties, which will be reported in the following section.

Printing procedure

All the materials obtained from the different pathways have been used to print tensile specimens (with the same parameters as job 3 in Table 17). However, the number of tensile specimens printed per job was reduced from 11 (as in the previous tests) to 5 tensile bars. The reason for this choice is that it was noticed that the recycled material (especially from Pathways A and B) had large lumps and fluctuation in diameter. Such characteristics of the filament caused it to get stuck inside the 3D printer, resulting in under-extrusion. It was deemed more efficient to print fewer specimens per job to ensure that it would have been successfully completed.

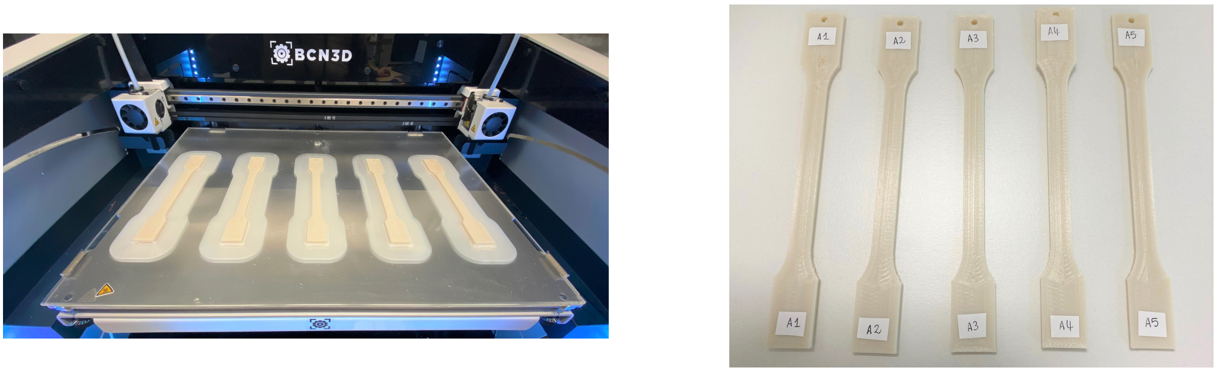

Figure 45 *Material validation procedure:* ***(a)*** *Standard print job (left) and* ***(b)*** *Test specimens labeled after the print job (right)*

Figures 45 (a) and (b) show the procedure that has been adopted. First, the material has been dried at 80°C for a minimum of 3 hours, then it has been printed and ultimately all the specimens have been labeled in preparation for testing.

For the purpose of the work, a total of 30 tensile specimens per type of material have been printed, corresponding to 6 jobs per mixture.

Material quality test

The tensile testing has been conducted on a tensile testing machine. The climatic conditions during the measurement were at the measuring room: 22°C and 50% humidity. Figure 46 shows the machine that is currently used at the AMC for tensile testing on plastic specimens.

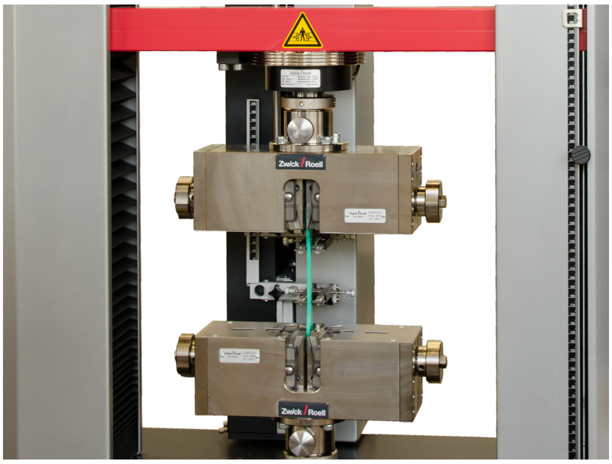

Figure 46 *Tensile testing machine adopted at the AMC (ZwickRoell GmbH & Co. KG, 2022)*

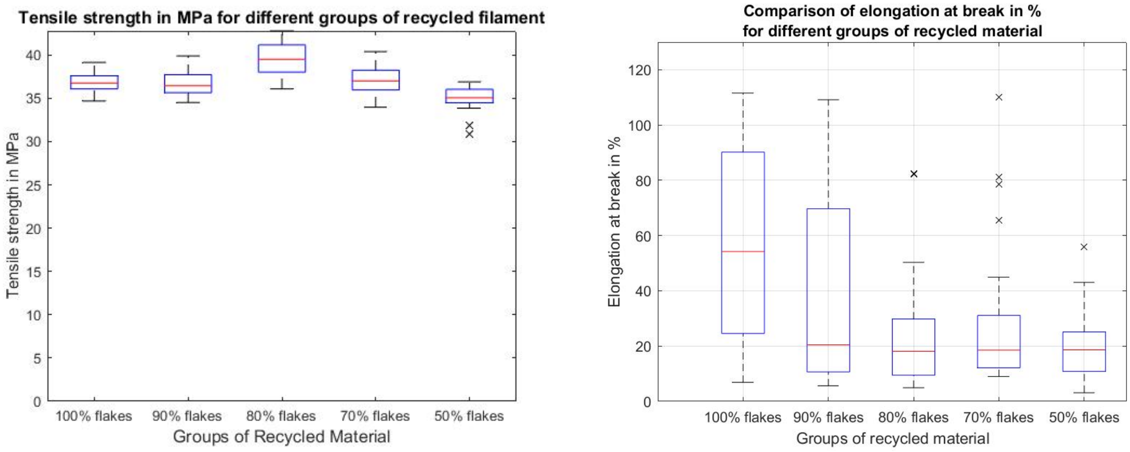

Figure 47 *Tensile testing comparison results on the different mixtures for Pathways C and D:* ***(a)*** *Tensile strength (left) and* ***(b)*** *Elongation at break (right)*

The tested materials, from the different recycling pathways, showed very interesting results both in terms of tensile strength and elongation at break, as the Figures 47 show. As it is possible to notice, especially for the elongation at break, the results show big differences in values among the various specimens even within the same mixture. Moreover, as it is possible to notice in Figure 47, the general trend appears to be that the elongation at break increases with an increasing share of flakes with respect to powder. However, the material with 80% flakes content deviates greatly from this average, being the one with the lowest elongation at break overall.

In Figures 48, 49, 50, 51, and 52, the before and after of the tensile testing for each material is shown. Even just visually there is no particular trend of elongation and breaking, also confirmed by the values obtained from the tensile tests. The reason for that is likely to be the fact that the filament is made out of very different quality parts, with very different levels of aging. No apparent consistency could be visualized for any of the materials in their breakage point. All the tensile bars elongated in different measures and broke at very different points.

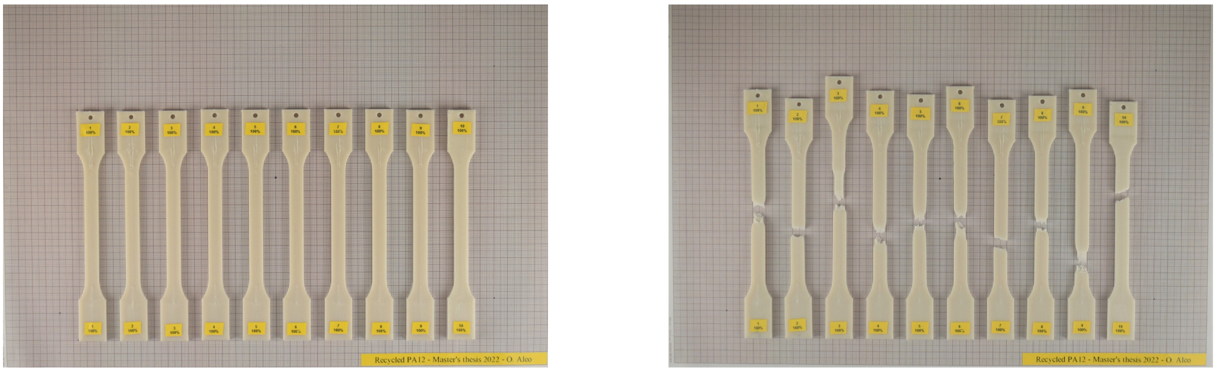

Figure 48 *Test specimens before/after tensile testing - Filament 100% flakes content: **(a)** before (left) and **(b)** after (right)*

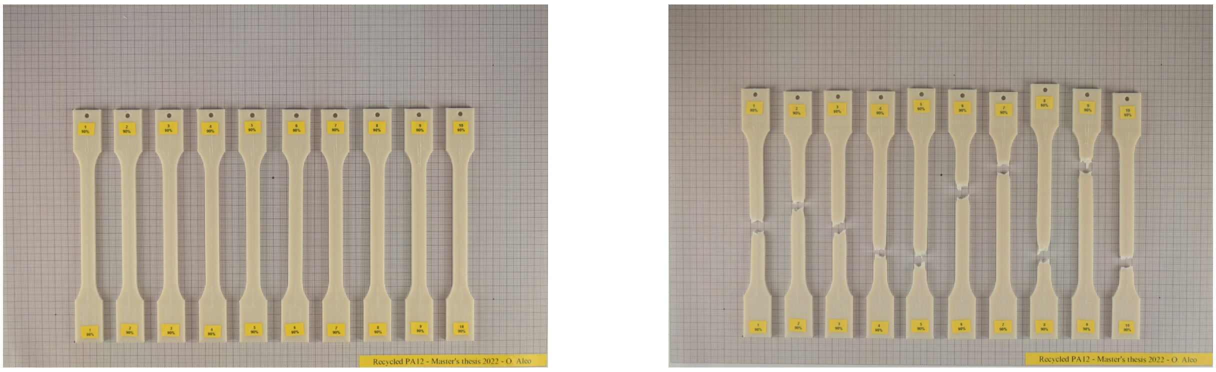

Figure 49 *Test specimens before/after tensile testing - Filament 90% flakes content: **(a)** before (left) and **(b)** after (right)*

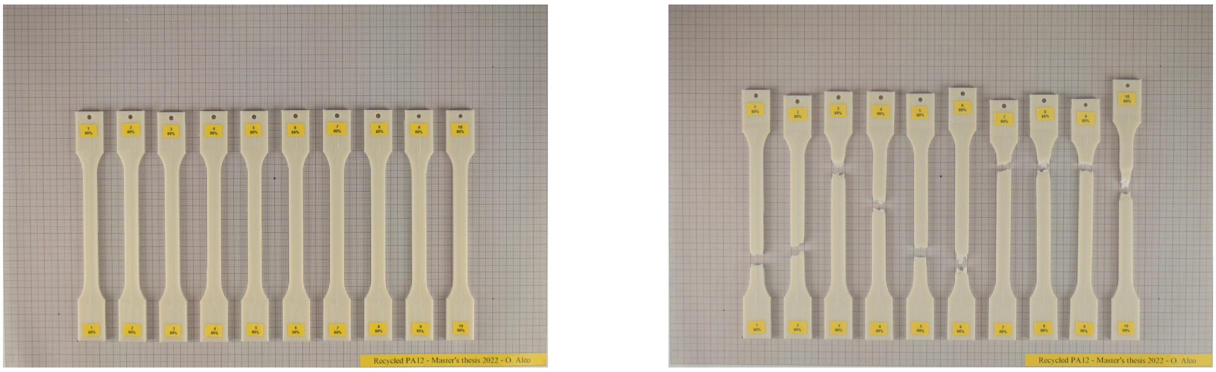

Figure 50 *Test specimens before/after tensile testing - Filament 80% flakes content:*
(a) *before (left) and* ***(b)*** *after (right)*

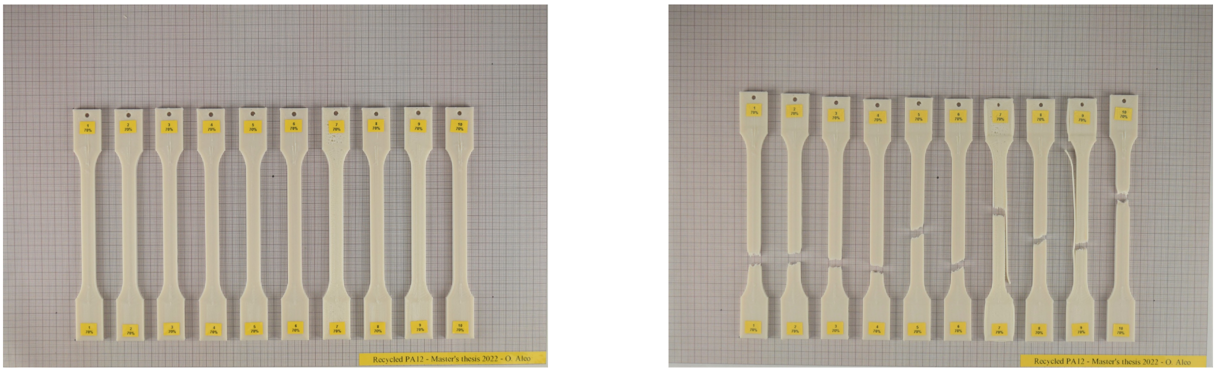

Figure 51 *Test specimens before/after tensile testing - Filament 70% flakes content:*
(a) *before (left) and* ***(b)*** *after (right)*

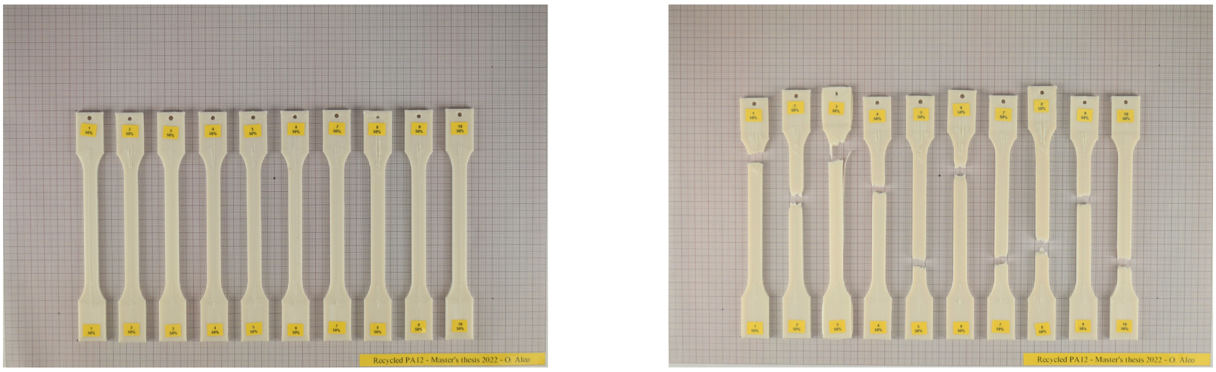

Figure 52 *Test specimens before/after tensile testing - Filament 50% flakes content:*
(a) *before (left) and* ***(b)*** *after (right)*

Appendix D

Assumptions and calculations for the indicators

For the calculation of the indicators presented in section 5.8, a series of assumptions have been made to make it possible to carry on the calculations. This section will provide information on all the different indicators and the procedure adopted to obtain the results.

The calculations are conducted considering a time frame of **12 months**. The recycling procedure is supposed to be carried out twice per year. The parts are collected for six months and then the recycling procedure can start.

Amount of recycled material (parts/powder) [kg/spool]

Data:

- Amount of parts collected in 6 months: 100 kg
- The production depends on the number of spools required: for 500 spools roundabout 540 kg of materials are enough; but for 50 spools, 90 kg of materials are required (BMW's AMC, 2022).

Calculation procedure:
By adding the powder to the mixture, the amount of raw material processable increases. Starting from 100 kg every half year (where no powder is added), by adding 10%, 20%, 30% and 50% of old powder more in weight in the mixture, the total amount of material processable is respectively: 111.11 kg, 125 kg, 142.85 kg, 200 kg.

From linear interpolation it is possible to find a relationship between the number of spools produced (x) and the amount of raw material required (y): x = y - 40. With this relationship, and with the amount of raw material available calculated before, it is possible to find how many spools can be produced every 6 months.

The **amount of flakes required per spool** is calculated by dividing the amount of raw material required and the number of spools associated with it, multiplied by the different percentages of flakes according to the mixture.

Equally, the **amount of powder required per spool** is calculated by dividing the amount of raw material required and the number of spools associated with it, multiplied by the different percentages of powder according to the mixture.

Standard deviation elongation at break [%]

Data: The elongation at break data come from the tensile testing conducted on 30 samples for each of the 5 mixtures at the AMC. The tensile testing provides 1 value of elongation at break per sample.

Calculation procedure: By the adoption of MATLAB, the mean value and the standard deviation of the elongation at break in % are retrieved. The results are shown in Figure 53.

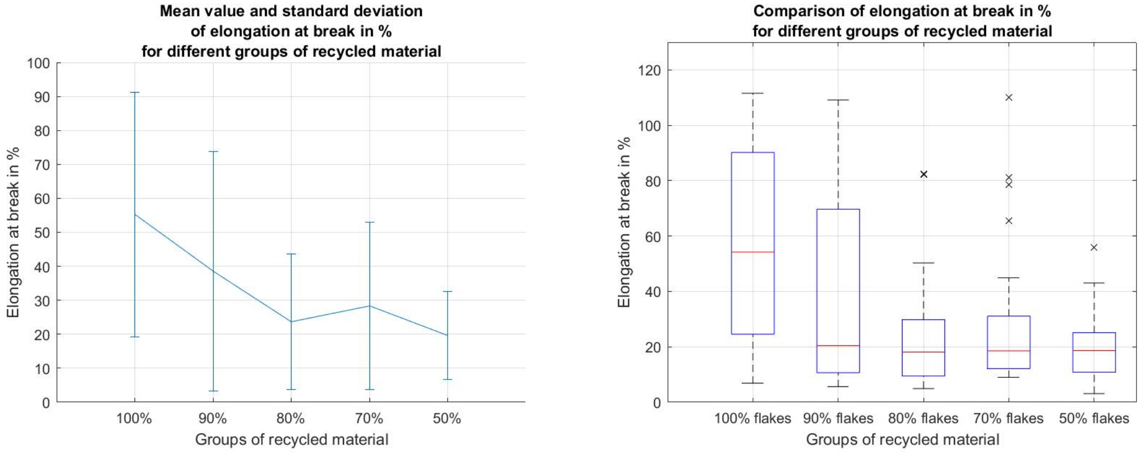

Figure 53 *Elongation at break comparison results on the different mixtures:* ***(a)*** *Standard deviation (left) and* ***(b)*** *Elongation at break Boxplot (right)*

Total vehicle distance traveled [km]

Data:

- For confidentiality reasons, the specific addresses of the different facilities that the material reaches during the recycling process are not mentioned. However, these are the main data used for the calculation.

- For the pathways that involve the adoption of powder in the mixture it is assumed that the powder is sent once per year (1 ton), in a different shipment than the flakes. In this case, the route is from the AMC to the storage facility.

Calculation: The total distance traveled by the material for the success of the recycling pathway has been calculated as the sum of the distance from each facility, according to the order that the material follows, from the delivery of the old prototype parts to the arrival of the recycled filament on site.

Note: For the ship rides the distances have been found in nautical miles from port to port. The results are converted in km to allow the sum, by adopting the conversion:
1 nautical mile = 1.8532 km.

Energy used for transportation [kWh]

Data:

- The distance (d) adopted for the calculation is the *total vehicle distance traveled* from the previous indicator.
- Amount of flakes produced in 6 months: 100 kg.
- The cargo weight depends on the mixture adopted for recycling. For each delivery step, a different amount of material (whether in the form of flakes, powder, or filament) is delivered.
- For the pathways that involve the adoption of powder in the mixture it is assumed that the powder is sent once per year (1 ton), in a different shipment than the flakes. In this case, the route is from the AMC to the storage facility. For the other steps, it is assumed that just the needed amount of powder is sent with the flakes.
- The overall calculation has been conducted considering a time frame of 1 year (2 recycling procedures).

The means of transport are assumed as follows:

- Minivan Renault Trafic Diesel
- Sprinter Panel Van Mercedes-Benz Diesel
- Triple E-class container ship engine

The data and assumptions specific for each mean of transport are shown in the following table:

Mean of transport	Speed	Efficiency	Engine power	Load capacity
[-]	v	c	P $engine$	M $load$
Minivan	40 km/h	60 %	145 hp	0.963 t
Sprinter	80 km/h	80 %	188 hp	5 t
Container ship	23 knots	80 %	60000 kW	165000 t

The Minivan speed is taken as an average speed between 50 km/h (for cars and motorbikes, the speed limit in towns and cities in Munich) and 30 km/h (the speed limit for smaller roads within urban areas in Munich).

Calculation procedure:
Calculate the energy consumption per route by the adopted mean of transport.

$$t\,[h] = \frac{d\,[km]}{v\left[\frac{km}{h}\right]}$$

$$E\,[kWh] = c * P_{engine}\,[kW] * t\,[h]$$

$$E_{mass}\left[\frac{kWh}{t}\right] = \frac{E\,[kWh]}{M_{load}\,[t]}$$

The results are then calculated in kWh according to the weight of the material transported per each delivery step. The overall energy consumption for transportation per pathway has been calculated as the sum of the energy consumption per route previously calculated.

Note on conversions:
1 hp = 0.7457 kW
1 knot = 1.85 km/h

Time required for completion [days]

Data:

- The recycling pathway starts the moment in which the flakes/powder are sent from the AMC to the external company, and it ends when the recycled filament reaches again the AMC.

- It is assumed that for the pathways within Germany, the time required for the completion of a recycling pathway is half the time required for the pathway worldwide.

Calculation:
The completion time has been calculated considering the date on which the material has been sent to the filament production company, and the date on which the recycled filament reached the AMC's logistics. For the scope of the calculation, all the weekdays have been considered, including holidays and weekends, as this would have not changed the end results.

CO2 emissions transportation [kgCO2e]

Data:

- Amount of flakes produced in 6 months: 100 kg.
- The cargo weight depends on the mixture adopted for recycling. For each delivery step, a different amount of material (whether in the form of flakes, powder, or filament) is delivered.
- Distance: the distance (d) adopted is the *total vehicle distance traveled [km]* per route per mean of transport.
- For the pathways that involve the adoption of powder in the mixture it is assumed that the powder is sent once per year (1 ton), in a different shipment than the flakes. In this case, the route is from the AMC to the storage facility. For the other steps, it is assumed that just the needed amount of powder is sent with the flakes.
- Greenhouse Gas Emission Factor (EF_{GHG} [kgCO2e/tkm] for each mean of transport. Data are retrieved from databases for Wheel to Wheel (WTW) mode (according to transport mode, vehicle type, and fuel type).
    - Minivan - EF_{GHG} = 0.065424 kgCO2e/tkm
    - Sprinter - EF_{GHG} = 0.074643 kgCO2e/tkm
    - Container ship - EF_{GHG} = 0.020711 kgCO2e/tkm

Calculation procedure:
Calculate the emissions for each route by the specific mean of transport.

$$GHG\ [kgCO_2e] = W_{cargo}\ [t] * d\ [km] * EF_{GHG} \left[\frac{kgCO_2e}{tkm}\right]$$

The overall emissions for transportation are calculated as the sum of each emission per route per mean of transport per recycling pathway.

CO2 emissions recycling equipment [kgCO2e/spool]

Data:

- The recycling pathway for PA12 in the most complex case includes packing raw material, sorting, shredding, mixing, drying, and extruding. The emissions associated with the equipment for mixing, drying, and extruding are outside of the boundaries of the study as these steps are carried out by an external company. The balance of the remaining steps showed that the process of **shredding** (when considered) contributes to the highest energy usage.
- For the shredding procedure it is assumed that the shredder runs just on electricity, without the adoption of any lubricant oil or the adoption of any fuel. The motor power of the shredder P_{engine} = 7.5 kW, and according to the databases for the district of Munich (DE) the emission factor for electricity $EF_{elec.}$ = 0.228 kgCO2e/kWh.
- The shredder can process 250 kg of material per hour ($C_{shredder}$= 250 kg/h).
- The amount of flakes required per spool is the same previously calculated for the indicator *amount of recycled material (parts)* (W_{flakes} [kg/spool]).

Calculation procedure:
Calculate the emissions generated from the shredder according to the different weights of flakes required per spool.

$$t \left[\frac{h}{spool}\right] = \frac{W_{flakes}\left[\frac{kg}{spool}\right]}{C_{shredder}\left[\frac{kg}{h}\right]}$$

$$E_{shredder}\left[\frac{kWh}{spool}\right] = P_{engine}\ [kW] * t \left[\frac{h}{spool}\right]$$

$$GHG_{shredder}\left[\frac{kgCO_2e}{spool}\right] = E_{shredder}\left[\frac{kWh}{spool}\right] * EF_{elec.}\left[\frac{kgCO_2e}{kWh}\right]$$

Noise pollution duration [min/spool]

Data:

- The only machine adopted in the recycling pathway (inside the system boundaries) is the shredder. The shredder generates an average of less than 85 dB, which is a very high value. However, for the recycling pathway at the AMC, an aluminum box has been built around the machinery to dampen noise.
- For the scope of the calculations the noise emitted from the shredder (inside the aluminum box) has been measured with a decibel meter. With this pattern, the shredder emits an average of $dB_{shredder}$ = 67.08 dB/min. This noise threshold is considered pollution.
- The shredder can process 250 kg of material per hour ($C_{shredder}$= 250 kg/h = 4.2 kg/min).

Calculation procedure:
The calculation has been conducted on the basis of the amount of material (flakes) needed to produce one spool. Indeed, this corresponds to the same amount of material to shred to produce one spool, considering the leaks due to spillage of materials from the shredder negligible. The amount of flakes required per spool is the same as previously calculated for the indicator *amount of recycled material (parts)* (W_{flakes} [kg/spool]).

$$t_{noise}\left[\frac{min}{spool}\right] = \frac{W_{flakes}\left[\frac{kg}{spool}\right]}{C_{shredder}\left[\frac{kg}{min}\right]}$$

Costs associated with transportation [€]

Data:

- The costs associated with transportation include the costs for the fuel spent by BMW to move the materials with the Van and the Sprinter from the different BMW facilities and the price for transportation charged from the recycled filament production company.
- Through interviews it turned out that the price for transportation charged from the filament production company is 25% less for the pathways within Germany (pathways E and F) with respect to the pathways worldwide (pathways C and

D). The price for delivery from the production company to the AMC is roundabout 1000 euros for every delivery (for delivery of an average of 15 spools (= 15 kg)). The transportation costs, in this case, include delivery, infrastructure, and workforce (BMW's AMC, 2022).

The other data assumed for the calculations are provided in the table below:

Pathways	**Mean of transport**	**Distance**	**Fuel consumption**	**Diesel price (10/2022)**
[-]	[-]	*d*	*C fuel*	*P diesel*
C and D	Minivan	9 km	0.079 l/km	2.02 €/l
	Sprinter	739 km	0.083 l/km	1.99 €/l
E and F	Minivan	9 km	0.079 l/km	2.02 €/l
	Sprinter	474 km	0.083 l/km	2.02 €/l

- The fuel price data are retrieved from `https://www.rhinocarhire.com/World-Fuel-Prices/Europe.aspx`. The fuel prices for the Minivan consider just the average price of the fuel in Germany for the month of October 2022, since the Minivan for that amount of kilometers moves just in Germany. On the other hand, the prices for the Sprinter (for pathways C and D) consider an average price for the month of October 2022 between Germany, Switzerland, and France, as the Sprinter crosses these three countries to reach the destination. The average price was taken as an assumption because it is likely that the driver does not always fill the fuel tank in the same country. For pathways E and F, the fuel prices are considered in Germany as the overall recycling pathway is within Germany.
- The overall calculation has been conducted considering a time frame of 1 year (2 recycling procedures).

Calculation procedure:
The total costs associated with transportation are the sum of the costs for the fuel for the BMW's vehicles and the charge for material delivery.
The amount spent on the fuel has been calculated with the formula:

$$P_{fuel}\,[euro] = d\,[km] * C_{fuel}\left[\frac{l}{km}\right] * P_{diesel}\left[\frac{euro}{l}\right]$$

The formula is applied for each route, by its mean of transport, for the specific recycling pathway.

Amount invested [€]

Data:

- The overall amount invested per pathway includes the production costs to manufacture the filament paid to the external company, the amount invested for transportation, and the amount invested for the purchase of the shredder.
- The amount invested for transportation is the same calculation for the indicator *costs associated with transportation* [€].
- The amount invested for the shredder is the same for all the pathways.
- Through interviews it turned out that the filament production in Germany (pathways E and F) is 20% more expensive than the production in Morocco (pathways C and D).
- The overall calculation has been conducted considering a time frame of 1 year (2 recycling procedures).

Waste disposal costs [€]

Data:

- The price for the disposal of plastic waste (MPW) is 42 €/gitterbox (it is considered just the cost for transportation) (BMW's AMC, 2022).
- The capacity of a gitterbox it is assumed to be around 25 kg (since generally the parts are big and take up a lot of volume).
- The price to disposing of Polyamide is 350 €/ton. To be added are the fixed costs for transportation which are roundabout 1300 € one way (BMW's AMC, 2022).
- It is assumed a baseline amount of PA12 powder, potentially available for recycling equal to 1 ton/year. This corresponds to the maximum amount of powder that it is possible to store by the external partner in their storage facility.
- It is assumed a maximum amount of flakes recyclable equals 200 kg/year.

Calculation procedure: The calculation has been conducted by considering the potential costs that the company faces in case the recycling pathway is not in place. This corresponds to the pathways with 100% flakes just to the disposal of MPW. For the pathways that involve the mixture of flakes/part, also the disposal of the powder has to be taken into account. By calculating the number of gitterboxes needed, it is possible to obtain the price to dispose of them, according to the data previously mentioned.

Potential revenue [€]

Data:

- The calculation has been conducted considering the amount of material that it is possible to convert into filament in 1 year (2 recycling procedures).
- Depending on the different share of mixtures flakes/powder, considering a baseline of 100 kg of flakes that are available every 6 months, the amount of material recyclable increases with the increase of the amount of powder in the mixture.
- Considering the amount of material recyclable every 6 months for the different mixtures, it is possible to produce a certain amount of spools according to the relationship between the number of spools produced (x) and the amount of raw material required (y): $x = y - 40$.
- The average market price for White Nylon PA12 filament (2.85 mm) has been found to be 72 €/kg.

Calculation procedure:
The calculation has been conducted by multiplying the market price for PA12 with the number of spools (1 kg of material) that it is possible to produce every 6 months, according to the different mixtures selected. Then, the potential revenue is calculated in one year, considering 2 recycling procedures per year.

Workers' satisfaction (recycling procedure) [%]

The workers' satisfaction has been calculated on the basis of a survey that was submitted to employees familiar with the recycling process. The main aim of the survey was to understand whether overall workers prefer handling flakes (shredding, packing) or old powder. The evaluation has been focused on four particular points, being a sense of safety in the workplace, a sense of gratification in carrying out particular tasks, a sense of discomfort and physical effort required to complete certain recycling steps (BMW's AMC, 2022).

Customers' satisfaction (end-use filament) [%]

The customers' satisfaction has been calculated on the basis of a survey that was submitted to customers and employees that tested out the material in its different mixtures. The main elements that have been evaluated in this case were printing feasibility, ease of print, material reliability, and printing quality (BMW's AMC, 2022).

Ease of management [%]

The ease of management has been calculated on the basis of a survey that was submitted to managers, project leaders, and employees on their preference regarding the recycling pathways. Ease of organization, flexibility, and management of problems and last-minute changes have been the most considered factors.

Number of manual steps performed by employees [N]

Data:

- The number of manual steps adopted changes for the different recycling pathways designed. In the pathways for 100% flakes content the step of packing the powder, as well as mixing, is not involved. The steps of drying the material, as well as extruding, are outside of the boundaries of the system, as they are carried out by an external company.

Calculation procedure: The amount of manual steps corresponds to the sum of all the steps required for each recycling pathway selected, performed by BMW's employees.

Technical and environmental calculations to accomplish Pathway E (100% flakes and within Germany)

Pathway E	**Werk 0 →**	**AMC →**	**Storage →**	**Prod.→**	**Storage → AMC**	**[unit / year]**
Mean of transport	Minivan	Sprinter	Sprinter	Sprinter	Sprinter	
Material [-]	Old parts	Flakes	Flakes	Filament	Filament	
W_mat. [t]	0.1	0.1	0.1	0.06	0.06	
Distance [km]	9	474	461	492	473	3818
Time [h]	0.23	5.93	5.76	6.15	5.91	
E_trans. [kWh/t]	15.2	132.9	129.3	137.9	132.6	
E_trans. [kWh]	1.52	13.29	12.93	8.28	7.96	87.93
Em_trans. [kgCO2e]	0.06	3.54	3.44	2.2	2.12	22.72

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