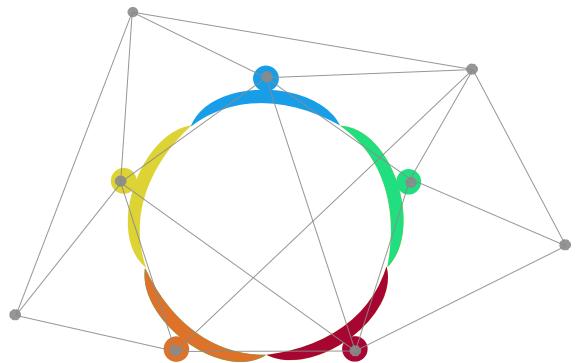


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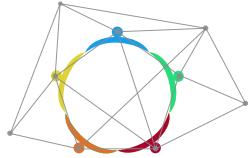


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open INnovation Ecosystems
for Do It Together process

D6.4 3D Printing of recycled plastic demonstrator

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1 Introduction

This deliverable deals with the description and implementation test of the 3D printing of recycled plastic demonstrator. The ambition of this use case is to test the feasibility of the distributed recycling via additive manufacturing (DRAM) ([Cruz Sanchez et al., 2020](#)) concept with the purpose to integrate in the Do-It-Together approach. There are two main goals:

Evaluate the technical and logistical feasibility of the distributed recycling approach for the furniture sector, highlighting the advantages and barriers found in the implementation process.

Provide a explain the a methodology in order

The document is structured in three main parts:

A baseline introduction is made regarding the plastic recycling issues in order to

2 Plastic Issues for the European Union

Since 1950', our society have gained enormous advantages in terms of quality of life thanks to the technical development of the development of plastic and polymer materials. Plastic is a material that is widely used in our daily lives and plays a fundamental role in industry and economic development. The plastic material are found in almost all our products: food packaging, cars, technological tools, clothing, among others. The main reason is that plastic materials offer a variety of chemical and mechanical properties to be useful for a wide array of applications. Plastics are extremely useful, but their mismanagement has affected the environment and our health. The over-consumption and especially bad practices (single use, difficulty of reuse, etc.), make plastics one of the major societal challenges of an ecological transition that has become imperative. The main problem is the end-of-life treatment which traditionally uses a centralized system where plastic waste often has to travel thousands of kilometers... to be incinerated or landfilled. In addition to the energy and environmental impact of their production, there is also the impact of the end of life.

Unfortunately, the plastic waste pollution poses a major threat because of the issue of non-degradability affecting the ecological environments ([Hopewell et al., 2009](#); [Ryberg et al., 2019](#); [Thompson et al., 2009](#)). Indeed, recycling rates remain small (approx. 14%) in the plastic packaging field on a global scale ([Hahladakis and Iacovidou, 2018](#)). Even in Europe, which tends to lead on environmental stewardship, the recycling rate is about 32.5 wt% ([Plastics, 2019](#)). However, these values consider the amount of plastic waste collected, rather than the total amount in circulation ([Kranzinger et al., 2018](#)). Rethinking the development and use of plastics is central to the circular economy paradigm, to provide less harmful options for the environment. Thus, more types of plastic packaging are available, but each reflects diverse circular economy strategies

To tackle this accumulation waste problem, the European strategy for plastics in the circular economy (CE) is gaining attention in the policy and business debate surrounding sustainable development of industrial production ([European Commission, 2018](#); [Geissdoerfer et al., 2017](#)). CE tackles a central societal issue concerning the current principle "take, make, dispose" (linear economy) and its negative effects caused by the depletion of natural resources, waste generation, biodiversity loss, pollution (water, air, soil) and non-sustainable economics ([van Buren et al., 2016](#)). The validation (technical, economic, legislative) of waste plastic as a secondary raw material in industrial processes is considered now a core target to integrate CE into the plastic value chain ([Simon, 2019](#)). Strategies of open and closed-loop recycling as well as upcycling and downcycling functionality approaches can offer paths to validate the secondary raw materials ([Zhuo and Levendis, 2014](#)). The promotion of cross-sectorial valorization of plastic wastes through Industrial symbiosis approaches seems to be a relevant strategy for the circular economy strategies of the EU ([Karayilan et al., 2021](#))

Based on this context, it is presented the demostration of the INEDIT project called '3D Printing of Recycling Plastic' that was developed and implemented. In the

3 Context of the 3D Printing of Recycled Plastic Demostrator

3.1 Presentation of the scale of the demostrator: Rives de Meurthe district (Nancy, France)

The demonstrator is placed at the City of Nancy - France. Nancy is a city located in northeastern France, in the region of Lorraine. It is the capital of the Meurthe-et-Moselle department and has a population of approximately 105,000 inhabitants.

It is the capital of the Meurthe-et-Moselle department, on the Meurthe River in Lorraine. Nancy was the capital of the steel industry until its collapse. In 1977, it created France's third largest technology park, Nancy-Brabois, which is very accessible thanks to the highway network.

Located in the east of the city, the Rives de Meurthe district extends from the banks of the Meurthe in the east to the boulevard Lobau and the boulevard of the 26th infantry regiment in the west. To the south, it is bounded by the rue de Tomblaine and to the north by the rue du Crosne. It is separated from the rest of the city of Nancy by the canal from the Marne to the Rhine. It thus gives the impression of being an independent city, adjacent to Nancy.

3.2 Third place Octroi Nancy

The third place Octroi Nancy is a part of the neighborhood of the Rives de Meurthe. This project transforms the former slaughterhouses of the city of Nancy into “*cultural, creative and citizen*” third place with $4600 m^2$ of renovated buildings (Pallot et al., 2021). Four large buildings (Figure 1) were adequated to provide a friendly and multidisciplinary meeting place between culture and innovation; open to experimentation and intended to operate as a creative laboratory for the city. This place is intended to be an open space allowing the connection of future occupants, such as artists and creatives, with the inhabitants of the city and companies.



(a) Description of the OK3 site

(b) Photo of OK3

Figure 1: The OK3 Site

At the 2023, this third place is an open ecosystem that will bring together artists, researchers and creative people with the public, the city's inhabitants and businesses.

3.3 Lorraine Fab Living Lab®

The Lorraine Smart Cities Living Lab (LSCLL) is a trans-disciplinary resource center of the Université de Lorraine, to support and link the different societal challenges of the Lorraine territory with the local resources. It enables the integration of different users, implementing collaborative and agile approaches in the service of *Research, Development of Innovations, Training and a Citizen Culture*. It experiments in terms of projects, governance and support platform since 2008, involving several laboratories and other public and private partners as detailed in the Figure 2a. Since 2010, this project is member of the European Network of Living Labs (ENoLL)¹, seeking to develop public-private-population Partnerships (PPPs) to disseminate innovation and related practices.

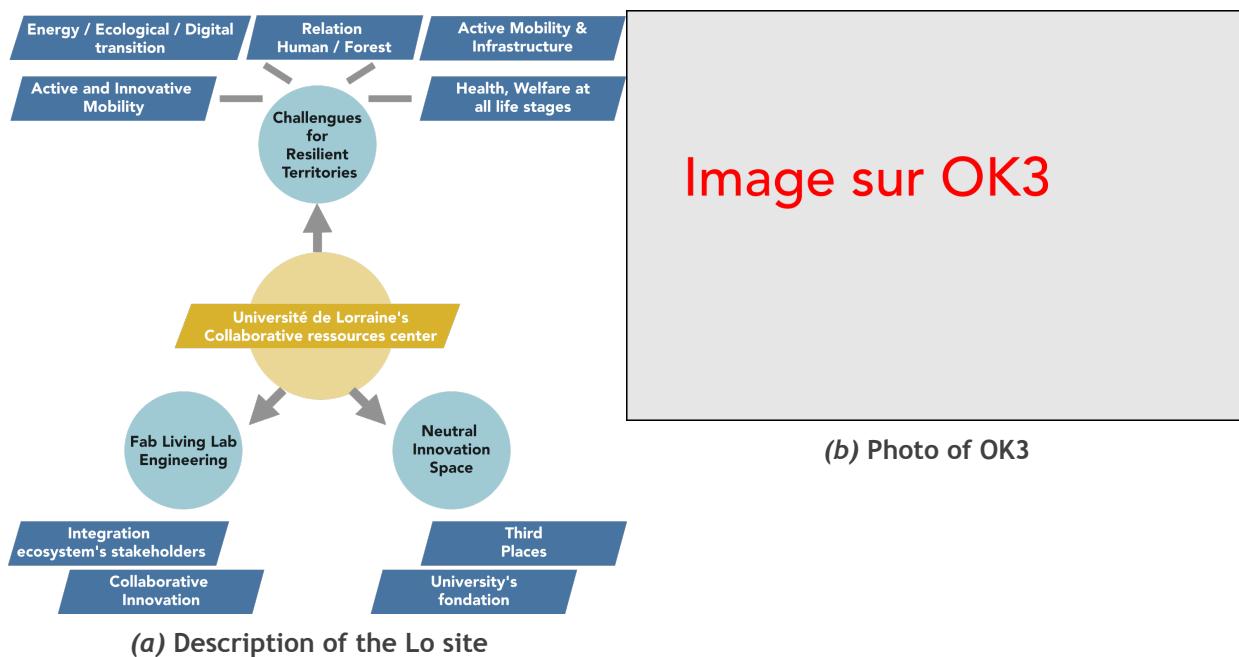


Figure 2: The OK3 Site

Since 2014, the LSCLL formalizes its strategic intention with the the Lorraine Fab Living Lab®(LF2L®) research platform for prospective assessment of innovative usages ([Dupont et al., 2016](#)).

The LF2L physical environment is constituted by a collaborative and a fabLab space. The collaborative space allows users to foster co-operation in engineering design with different stakeholders in order to new create concepts/designs. On the other hand, FabLab space allows users to materialize the concepts/designs in an easy and quick way in order to have an prospective evaluation ([Boujut and Blanco, 2003](#); [Dupont et al., 2015, 2014](#)). The synergy of these two spaces enables the project development in a living lab approach taking into account the User Centered Design principles.

The conceptual framework is composed of three main elements as illustrated in Figure 3:

¹4th wave of labelisation)

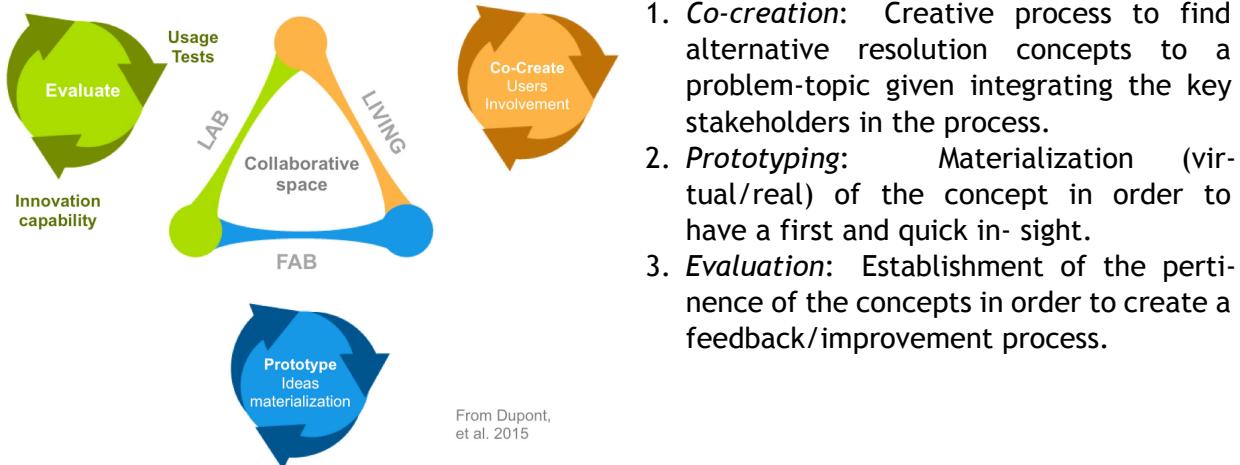


Figure 3: The Lorraine Fab Living Lab methodology.

The conceptual innovation framework of LF2L takes into consideration the 2D (concept), 3D (object), 4D (over time) approaches involving different type of stakeholders (e.g. researches, companies, networks,) in order to have a foresight usage evaluation of a new concept, technology or project. The stages and 2D/3D/4D resources allowing prospective assessment of innovative usages in order to support this conceptual framework inside this “innovation space” as indicated in figure 2.3 ([Dupont et al., 2016, 2015](#)): This approach is useful to accelerate the deployment of industrial and/or urban demonstrators.

4 3D Printing of recycled plastic demonstrator: the “Green FabLab”

4.1 Rationale for the technological system of the 3D printing recycling demonstrator

Based on the context characteristics of the (LF2L®) and the Octroi local ecosystems, the 3D printed demonstrator, also called locally as the “*Green Fablab*” as illustrated in the Figure 4, it is an initial socio-technical demonstrator of the distributed recycling approach that combines a living lab approach inside a citizen third place ecosystem.



Figure 4: Initial overview of the Green Fablab at November 2021

The Green FabLab demonstrator aims to experiment the technical feasibility and evaluation of a distributed and local plastic recycling. The main purpose is to valorize plastic waste for 3D printing technology and manual injection moulding techniques in the context of an open innovation space such as the Octroi Nancy. The results of this experimentation can be a baseline for many archetypes of open communities such as fab labs, Hackerspaces or even industrial prototyping zones.

The main purpose of this demonstrator in the INEDIT project is to prove that plastic waste material can have several uses, and therefore several values, during its life cycle. The same material could be recycled and transformed into new raw material for different products. It is in this spirit that many associations, SMEs, local authorities and individuals are developing new local recycling practices that could allow us to aim for an economy that is more respectful of the environment, fairer for society and more engaging for local politicians.

Therefore, it is necessary to understand the key conditions under which to deploy a notion of circular economy with plastic waste to possibly establish a secondary raw material market for this asset. Likewise, it is required the study of technical parameters for the technological diversity to possibly use the waste material including the open source 3D printers and manual desktop injection. The outputs are, not only by minimizing use of the environment as a sink for

residuals but - perhaps more importantly - by minimizing the use of virgin materials. Hence, the environmental impact of this technology is significantly reduced.

Moreover, taking into account the exponential growth of these spaces (Fablab, Hakerspace, Makespace), they could help to increase the efficiency to the problem of polymer recycling through the development of a distributed recycling approach. In these geographically distributed spaces, the polymer recycling process of the surrounding areas (streets, neighbourhood, industrial zones) will be carried out at small lot sizes minimizing, energy consumptions, and carbon emissions compared to the tradition centralized systems, as some researches have already explored this path.

4.2 Distributed recycling via Additive Manufacturing DRAM

The Additive manufacturing (AM) -also known as 3D printing- is an important industrial vector in the and its direct (and distributed) manufacturing capabilities is becoming a key industrial process that could play a relevant role in the transition from a linear to circular economy ([De speisse et al., 2017](#)). AM technologies is expected to transform the production process ([Chen et al., 2017](#); [Jiang et al., 2017](#); [Rahman et al., 2018](#)) thanks to its ability to transform a numerical model into a deposition of material (points, lines or areas) to create a 3D part ([Boureil et al., 2017](#)). The expiration of the first patents has contributed to an increased interest, creating consumer value and potential for disruption ([Beltagui et al., 2021](#); [West and Kuk, 2016](#)). In economic terms, the global additive manufacturing market is expected to reach USD 23.33 billion by 2026 ([Data, 2019](#)). However, determining when and how to take advantage of the benefits is a challenge for traditional means of production. From a societal viewpoint, Jiang et al. ([2017](#)) reported that the product development could change from traditional stage-gate models to iterative, agile processes changing the scenario by 2030.

The technical development of INEDIT's demonstrator is based on the **distributed recycling via additive manufacturing (DRAM)** approach ([Cruz Sanchez et al., 2020](#)). This approach is a major scientific output from the INEDIT project as a proposition of the future industrial landscape.

DRAM is defined as the use of recycled materials by means of mechanical recycling process in the 3D printing process chain. In the literature, DRAM approach emphasizes the technical steps required to reuse plastic waste through the recycling chains for material-extrusion-based 3D printing ([Cruz Sanchez et al., 2020](#); [Little et al., 2020](#)). The use of recycled material, either in the form of raw material or blended with virgin material, is a method of special interest to contribute to sustainable manufacturing ([Zhao et al., 2018](#)).

Figure 6 illustrates the conceptual model of DRAM.

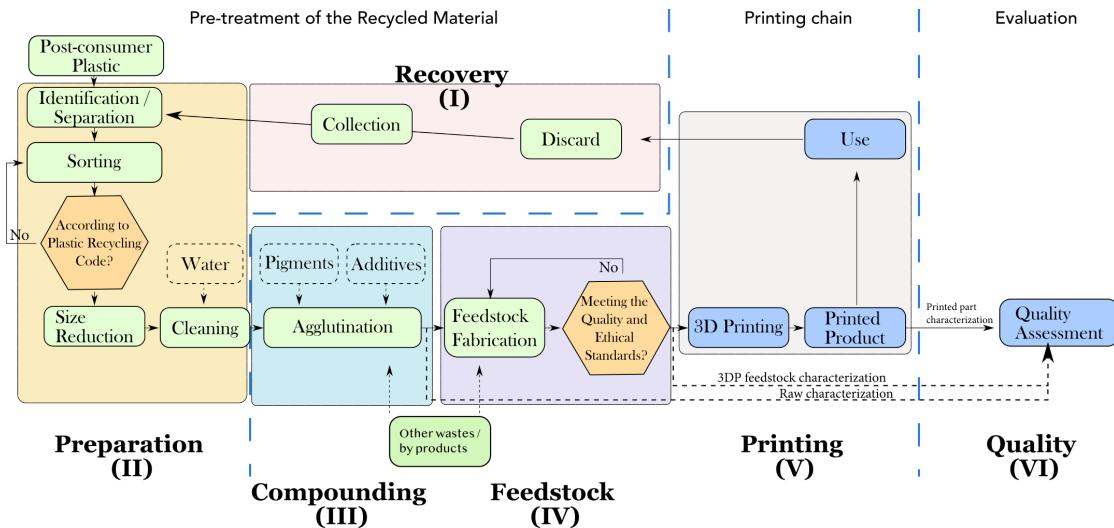


Figure 5: DRAM

In a general overview, the **Recovery (I)** phase concerns the logistic operations to consider to collect the plastic wastes to be reused in DRAM. The **Preparation (II)** phase corresponds to the actions and strategies to identify, separate, sort, size reduce and clean waste plastic to guarantee adequate quality for DRAM. The **Compounding (III)** phase refers to the development of mono- and composite-materials. The **Feedstock (IV)** phase identifies the actions to fabricate the material usable for the printing process, either filament for Fused Filament Fabrication (FFF) or the particle size for Fused Granular Fabrication (FGF). The **Printing (V)** stage identifies applications and process improvements for the recycled printed part. The **Quality (VI)** phase identifies the multi-level technical characterization performed to the recycled material.

In the DRAM methodology, consumers have an economic incentive to recycle. This is because they can use their waste as feedstock for a wide range of consumer products that can be produced for a fraction of the conventional cost of the equivalent products. Moreover, 3D printing is especially well suited because it enables the production of parts with (almost) no waste, and could reduce the waste related to the material by more than 40 %, reusing 95% of the unused material ([Petrovic et al., 2011](#)).

Currently, most of the cost of 3D printing is associated with filament ([Wittbrodt et al., 2013](#)). By recycling raw materials such as Polylactic acid (PLA), one of the most frequently used materials in 3D printing, it is possible to reduce the carbon dioxide emissions that are incurred by transport to landfills or shipping to customers, offering environmental benefits ([Santander et al., 2020](#)).

A large number of products can already be manufactured with AM, which affects the geographical spread and density of global value chains ([Laplume et al., 2016](#)). It is expected that the reach of AM printable products will be much greater in the future, as the production of multi-material and built-in functionalities (e.g. electronics) will be possible to a large extent. In addition, the production of spare parts can be carried out on-site, modifying the role of suppliers in the production lines ([Zanoni et al., 2019](#)). Matt et al. ([2015](#)) explored the stages of

distributed model factories and decentralized production types ranging from distributed capabilities to cloud production. Thus, the need of transport will be much more carefully because the fact that AM will enable decentralization of production to localities near customers or in the most extreme distributed scenario at the customer's premises (Bonnín Roca et al., 2019; Petersen and Pearce, 2017; Wittbrodt et al., 2013). Moreover, AM technology makes it possible to reduce market entry barriers, reduce capital requirements and achieve an efficient minimum scale of production to promote distributed, flexible forms of production (Despeisse et al., 2017).

The distributed manufacturing/recycling approach enables an alternative option from an economy-of-scale to an economy-of-scope, where the products are highly personalized satisfying niche communities or even individuals (Hienerth et al., 2014; Petrick2014?). For these reasons, the AM technology could be a driver for a shift in manufacturing from globally distributed production to local facilities. Significant efforts are being made by industry and the scientific community to move AM techniques from rapid prototyping and tooling stages towards direct digital manufacturing (DDM) (Gibson et al., 2010; Holmström et al., 2016), with the concomitant environmental and social benefits. Nevertheless, Niaki et al. (2019) demonstrated that environmental and social benefits are not the key preferential factors in the adoption of AM technologies in different industrial sectors. Only the economic factor remains relevant in the AM implementation, considering time- and cost-saving as the most important reasons.

4.3 Positionnement of Use case for OMDF Functions

Considering the Open Manufacturing Demonstrateion Facilities functions established in the Deliverable XX.X, the Green fablab proves the following functions:

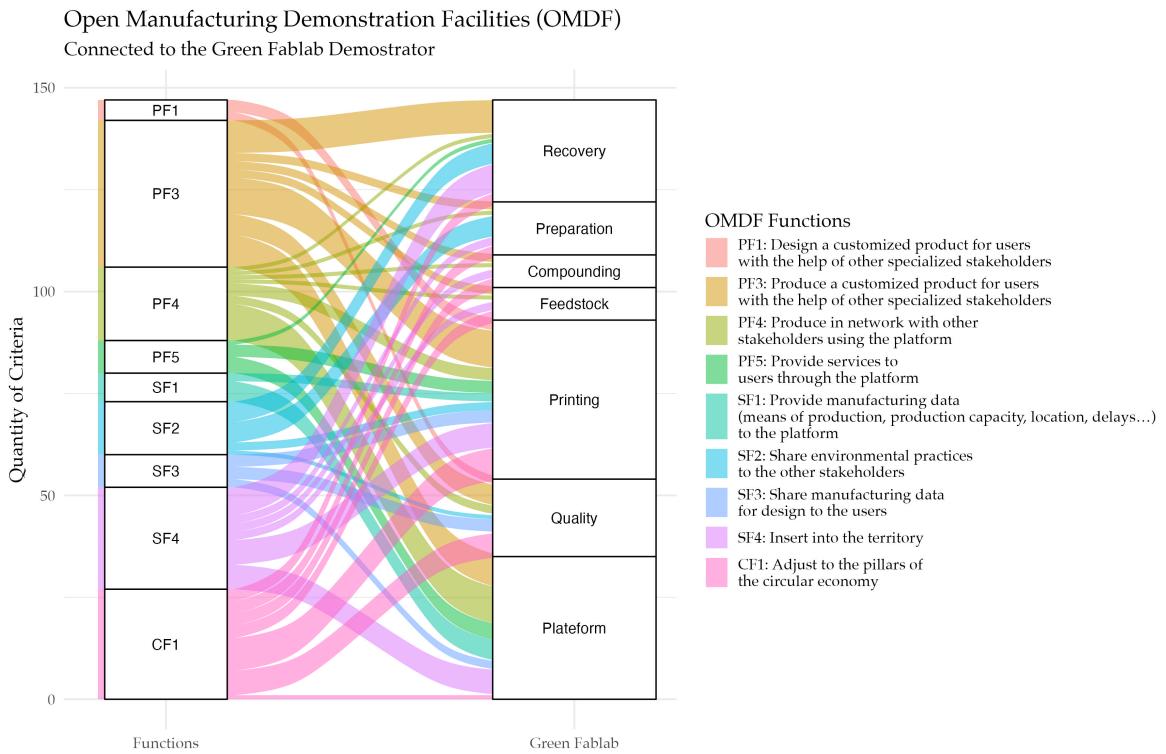


Figure 6: Connection of the 'Green Fablab Use case with the Open Manufacturing Demonstration Facilities (OMDF) functions

4.3.1 Hypothesis of UL case for deployment in reality

The implementation of the Green Fablab needs to be done considering certain assumptions and simplifications to reduce the complexity of this socio-technical system. The following assumptions were assumed in terms of geographical scale, material recollection and manufacturing aspects:

- From a material perspective, only certain types of plastic wastes are considered. Specifically, Polyethylene terephthalate (PET), High density Polyethylene (HDPE), Polypropylene (PP) and Polylactic Acid (PLA). The major reason is from the technical perspective relies on the availability of these materials at the local area around the physical demonstrator.
 - PLA is one of the most used plastics in 3D printing. Thus, as plastic waste source, PLA waste can be found from printed prototypes or 3D printed parts discarded.
 - HDPE is one of ???
 - PET
- The sorting, separation and cleaning process of plastics wastes are critical processes of the recycling. Therefore, this recycling system considers it as a high because the collected

material corresponds to a non-contaminated waste. For example, discarded 3D printing parts used for prototyping.

- From a geographical point of view, only plastic waste collected from the smart collectors was considered. Nevertheless, as MVP use case demonstrator, this model can be extrapolated to schools and high schools in the Lorraine region (France) have been considered, and the route of recovery and delivery considered is obtained in the work of ([Santander et al., 2020](#)).

The 3D printing activities carried out in these establishments have a specific purpose of making product prototypes and mock-ups, which allow to generate testing activities, design evaluations, functional evaluations, corrections. Therefore, after a short lifetime, 3D printing can be a source of significant amounts of plastic waste due to printed parts that do not possess the desired quality, unused raw materials, or products that have already fulfilled their life cycle ([Alexandre2020?](#))

4.4 Technical characterization of the 3D printing of recycled demonstrator

4.4.1 Recovery I

The first step in the implementation of the Green Fablab OMDF is the activity of *Recovery I*. This phase aims to establish a minimal baseline logistic operations to consider to collect the plastic wastes to be recycled in the process. In the scientific literature, the recovery is one of the main activities to be considered in the recycling process given that this structures a supply chain that certainly is variable (i.e. in function of the public support to sort the material in the specific points of collection). This process is the first step to create a closed-loop supply network approach for the distributed manufacturing ([Santander et al., 2020](#)).

The collection tasks consists of collecting plastic waste at different established points, which are then transported to a treatment center where it is recycled. The collection and recycling process aims to generate a recycling micro-network at the local level (neighborhood scale), which allows the recovery and revaluation of plastic waste through 3D printing. This allows to save impacts related to the traditional treatment of plastic waste, as well as to increase the recycling capacity in the city, giving more independence over the recycling process. Figure 7 illustrates the process model considered.

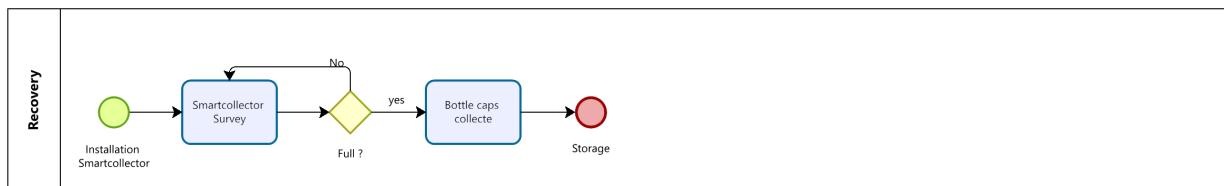


Figure 7: Recovery processus of the Green Fablab

The main difficult relies in the pertinent identification and the quality state of the plastic waste. Therefore, in the framework of the INEDIT project, the UL case demonstrator developed

a “smart collector prototype” as illustrated in the Figure 11. The complete documentation of the technical device can be found in the following open access reference ([Gabriel and Cruz, 2023](#)). Given the possible implementation in other contexts, the source files are shared in open-source repository with the purpose that open communities to take advantage the experiences developed at the Université de Lorraine. Eventually, the open communities can propose improvements and better versions.

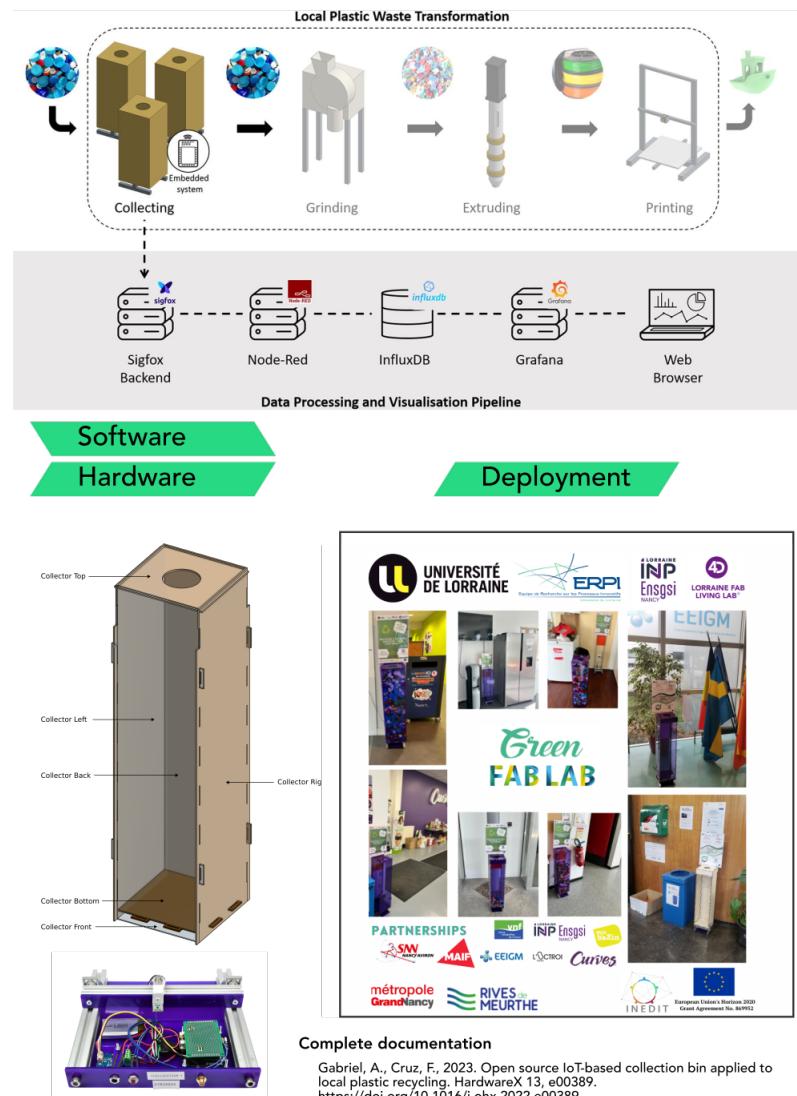


Figure 8: Description of the developed Smart collector

This is a relevant strategy given the cross-line of Industry 4.0 and circular economy, which is opening up fields such as smart waste management systems options to improve the effectiveness of different materials, including plastic waste ([Ranjbari et al., 2021](#)) using information technology tools with the advent of the Internet of Things (IoT) [Rejeb et al. \(2022\)](#). Smart

waste management system (SWMS) consists of public garbage collectors with embedded technology that is used to monitor real-time level of garbage bins in public places ([Bano et al., 2020](#)). The interest of this system is to optimize the path for the garbage collecting van that eventually reduces fuel cost. However, this work is mainly based on simulation. Therefore, there is an avenue to simplify experimentation in this domain using common open-source technology (hardware and software) ([Pearce and Mushtaq, 2009](#)) to implement projects that require heavy infrastructure such as routers and a gateway to deploy in the territory.

The main functional requirement of the smart collector is to collect and provide data about plastic waste production in order to design a local and distributed recycling chain of value. However, the smart collector may be used in various use cases such as:

- Monitoring the quantity of any other product that is collected over a large area.
- Generating data about behavior to more precisely dimensions public infrastructure.
- Monitoring the transformation and recycling process inside the transformation unit to follow the state and quantity of raw material and final product.
- Initiating a digitization process in the waste management process as the information system element present here is flexible and commonly used in various types of projects.

The device uses a controller compatible with batteries and use WAN technology to avoid the deployment of routers for data acquisition. Although using various types of sensors allows us to achieve better results ([Catania and Ventura, 2014](#)) by crossing data, the main indicator remains the weight.

The process illustrated by the [?@fig-abstract](#) can be described in the as follows:

1. **Smart Collector installation:** The first step is to identify the main actors in the neighborhood through meetings, visits and interviews in order to propose integration into the recycling network by installing a smart collector on their premises.
2. **Supervision:** The monitoring is done through a dashboard that provides direct information sent by the smart collector. This allows to know the weight of each installed smart collector, allowing to have an approximation of its degree of occupancy.
3. **Receiving and storing plastic waste:** The storage area must be organized and functional with respect to the needs of the demonstrator.
4. **Plan and execute the collection:**

In the scientific literature, the reverse logistic and closed loop supply chains have been extensively studied in the scientific literature. For instance, ([Santander2021?](#)) evaluated the benefits of a near loop and closed loop recycling network focused on additive manufacturing, mainly producing recycled filament. The main results show an economic and environmental benefit of sourcing filament from recycled plastic rather than purchasing exported virgin filament.

4.4.2 Preparation II

The second phase of the corresponds to the actions and processes to identify, separate, sort, size reduce and clean waste plastic to guarantee with the purpose to obtain feedstock material that is adequate for the distributed recycling process.

The plastic waste preparation process aims to conditioned the collected plastic to the requirements of 3D printing. For this process 3 main sub-processes are considered:

- **Identification and Sorting:** These two processes aim to identify the type of plastic given the regular standard for the polymer industry. The process of identification and separation of plastics is done manually and allows to separate the plastics that can be used as raw material for further production processes.
- **Cleaning:** This process is aims to remove the traces of any other substance that may be present in the plastic waste. In this way the processing machines will not be exposed to possible anomalies linked to material impurities.
- **Size reduction:** The size reduction process is carried out to possible obtain an adequate granulometry. This process allows to adapt the plastic waste for the direct injection process and/or the extrusion process.
- **Drying phase:** This step prevents the formation of bubbles in the recycled material when it is melted during the following extrusion or densification step ([Niaounakis2013?](#)). Moreover, complete elimination of water prevent hydrolytic decomposition of the molecular chains during the melting or plasticization, so that the treated material has to be as dry as possible.

4.4.3 Compounding III

The *Compounding* phase is related to the operation, strategies in the development of composite materials using recycled feedstock intended to be use in a printing process. There have been several literature reviews about the technical aspect of composite materials in the additive manufacturing context [Mohan et al. \(2017\)](#).

Special attention has been paid on material extrusion technologies in the production of polymer/composite feedstocks as it is economical, environmentally advantageous and adaptable to flexible filament material ([Singh et al., 2017](#)). For example, [Mohan et al. \(2017\)](#) presented a review on composite materials and process parameters optimisation for the fused deposition modelling (FDM) process for improving the mechanical properties (i.e. tensile strength, fatigue). [Brenken et al. \(2018\)](#) reported a detailed summary of mechanical properties of printed parts for different composite material for fused filament fabrication. Five majors strategies are elucidated from the literature review such as:

In the context of the Green Fablab demonstrator of INEDIT project, the focus is to study the 1) mono-recycled material and 2) the virgin-recycled blend material. The development of recycling niches of mono-material where the additive manufacturing can be implemented is key to study. Different studies in laboratory conditions have been made to show the technical feasibility of recycling. They include HDPE [Kreiger and Pearce \(2013\)](#), Biomass-derived poly(ethylene-

2,5-furandicarboxylate) (PEF) ([Kucherov et al., 2017](#)), PLA ([Cruz Sanchez et al., 2017](#)), Linear Low Density Polyethylene (LLDPE)/ low density polyethylene (LDPE), ([Hart et al., 2018](#)), thermoplastic elastomer (TPE) ([Woern and Pearce, 2017](#)). In fact, Hart et al. (2018) demonstrated the reconstitution of residual polymeric packaging waste from Meals-Ready-to-Eat (MREs) generated by soldiers around the world into additively manufactured appliances. One conclusion of these studies is the positive technical use of recycled mono-material for additive manufacturing purposes.

However, it has to be highlighted that one major assumption of these studies relies in that the material used is already sorted, cleaned and using a same type of discarded product. For INEDIT project, the interest is to take into account the inner variability that could be in the recovery process, concerning the type of material given the fact, while there are seven types of recycling symbols for each type of polymer, one major constraint in the current systems is that each manufacturing company have a patented use of the additive in the polymer matrix, in order to fulfil its initial function of the product.

4.4.4 Feedstock IV

The Feedstock III phase refers to the processes in order to transform the plastic waste into usable material material for the fabrication stage. Two outputs are seen in this etape: 1) the filament feedstock and 2) the pellet feedstock. The use of filament or pellet material are in coherence with the machine process used in the fabrication (cf section 4.4.5). The figure XX present the modeling of the process:

The filament and pellet production process makes it possible to produce the necessary raw material from plastic waste. The production of these intermediate products allows the use of different technologies related. Before using these products (filaments and pellets) it is necessary to carry out evaluation tests to assess the geometrical characteristics that are necessary in the printing process.

Figure XX and table present the technical characteristics of the material equipement

4.4.5 Fabrication process - Technological mix to valorize the recycled material

In this step, the major output is the valorisation of the plastic waste material using different two alternative paths: 1) Desktop injection process, and 2), 3D printing process. As matter of the validation of the demonstrator at TRL 6 level, the ambition of the demonstrator in the INEDIT project is to experiment and prove a technological ecosystem mix that seeks to valorise in a distributed approach different plastics for different purposes and stakeholders. Therefore, the initial choice is these two paths to create objects injected and 3D printed parts that are useful to the local ecosystem of the demonstrator. The technologies are presented in the following paragraphs.

4.4.5.1 Desktop injection moulding

Injection moulding is one of the most used technique to form plastic materials.

The major point in the ‘Green Fablab’ case is to propose a manual recycled aspect to possible reuse the plastic waste into sheet.

4.4.5.2 3D printing process: Fused Filament & Granular Fabrication (FFF & FGF) In the era of the additive manufacturing technology, without a doubt, the material extrusion-based systems such as the fused filament fabrication (FFF) has been one of the prominent processes. In fact, the technological development of open-source 3D printers is creating more affordable Additive Manufacturing (AM) machines for society in different applications. It provides the possibility of mass diffusion of this technology, and consequently, AM is being recognised as a disruptive that could up-end the last two centuries of approaches to design and manufacturing Birtchnell and Urry (2013).

In the Green Fablab demonstrator, we have two types of material-based systems:

- 1) Fused filament fabrication (FFF) and 2) Fused Granular Fabrication (FGF):

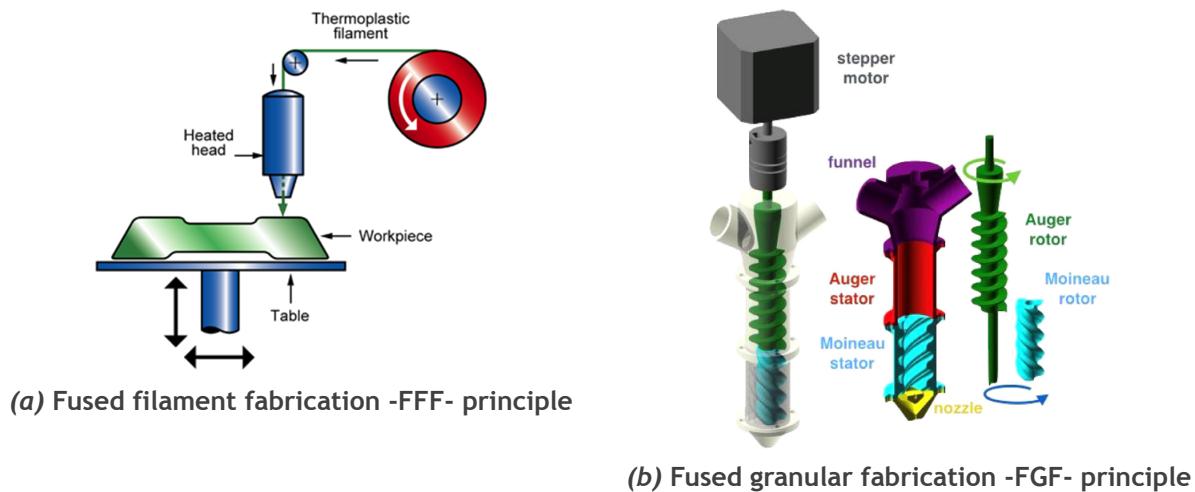


Figure 9: Additive manufacturing of material-extrusion based systems

The filament fabrication was developed and patented in 1989 by Scott Crump as *Fused Deposition Modelling*, and since 2009, the technology became open source (Crump1992?), known as Fused Filament Fabrication, to establish the difference between the registered mark. A schematic representation of this technology is presented in Figure 10. This process usually uses thermoplastic polymer filaments that are heated until a temperature slightly higher than the melting temperature at the nozzle of the machine, reaching a semi-liquid state. At this point, the polymer is extruded on the platform to create the first layer of the object and after that, the polymer continues to be printed on top of the previous layer, so that, filament fuses with the previous layer and then is solidified at room temperature after printing Cruz Sanchez et al. (2017).

At the green Fablab

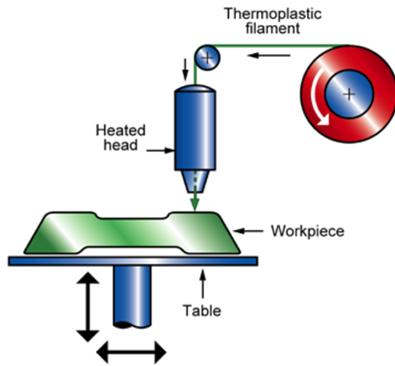
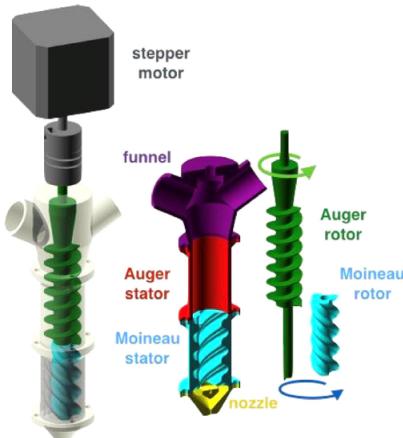


Figure 10: Fused filament fabrication -FFF- principle

For the

On the other hand, the Fused Granular Fabrication is a direct extrusion systems of pellets is a key technical advancement to facilitate the use of recycled material in the printing process. Volpato et al. (2015) describes the development of a piston driven extrusion head that can extrude polypropylene granules into a filament. The head was designed to minimize the volume of material fused during the extrusion process and reduce the effect of material degradation. Canessa et al. (2017) developed a mini extruder for pellets or granules of recycled plastic that can be used in a RepRap FDM 3D printer for rapid prototyping. The use of Moineau pump technology to add precise volumetric control to the extrusion of pellets opens extraordinary new possibilities. It is important to mention that a Moineau pump has to be coupled to a first stage Auger screw. This ensures a continuous feed of melted plastic with-out inclusion of air bubbles, since the Moineau pump itself cannot guarantee such condition. However, it is also important to highlight that currently this technology is the phase of laboratory experimentation and initial market diffusion. The complexity



(a) Fused granular fabrication -FGF- principle

Figure 11: Additive manufacturing of material-extrusion based systems

This machine has a compression screw which makes pellets or granules of thermoplastic materials feasible to be 3D printed.

Gigabot X XL machine extruder has a long barrel with 3 heating elements or zone which helps in uniformly melting and viscosity control of the thermoplastic. T1 being the heating block near the nozzle while T2 being in the middle of T1 and T3. Gigabot X XL is equipped with nozzle of 1.75mm diameter which provides good deposition rate. As 3D printing smaller cross-section is very hard without a cooling system near the nozzle [13],[14] therefore a cooling system was designed, 3D printed using ABS material and installed onto the system Figure 1

4.4.6 Quality Assessment VI

The quality assessment phase is the process to assess the technical feasibility of the recycled part.

5 Operationalization of DIT process for the Use Case

5.1 Integration of the 3D Printing Recycled Plastic

Explanation of the INEDIT project but focusing on the Open Manufacturing Demonstration Facilities process

Steps ID	Steps Description	Corresponding ID_DIT process
STEP 1 - RECEIVE DESIGN AND SPECIFICATION	Information about materials, finish, colour, texture, etc. from the INEDIT platform are sent to the manufacturing centre chosen by the ERP module and the Sustainability Driven Orchestrator (SDO). The expected files to be imported are: CAD file of the object, colour and texture, technical requirements identified in the design phase.	7_1
STEP 2 - VALIDATION OF THE TECHNICAL SPECIFICATIONS OF MODEL TO FABRICATE	Furniture producers or FabLab with the support of 3D printing technical experts evaluate the printability (if the part can be printed with the available technology) as well as validate the design.	7_2
STEP 3 - IDENTIFY LOCAL SOURCES OF PLASTIC WASTE	This step starts identifying local sources of plastic waste at least 2 km far from the production site. Designers and technicians will evaluate the quantity and quality of possible plastic wastes that could be used as secondary raw material.	9_2
STEP 4 - PUT IN PLACE SMART COLLECTOR	By using the Smart Collector developed by UL in the local areas (< 2 km) it is enabled to collect plastic waste from the sources identified before.	9_6
STEP 5 - TRANSPORT WASTE MATERIAL TO THE RECYCLING FACILITIES	All the recycled plastic waste is collected and transported to the recycling facilities	9_9
STEP 6 - ADEQUATION AND PREPARATION OF THE MATERIAL, MATERIAL PRINTABILITY VERIFICATION	The collected material has to be adequate in order to be utilised as recycled feedstock (sorting of usable material, cleaning, etc). The treated material needs to be tested and validated (evaluation on usage and printability).	10_4
STEP 7 - PATH PLANNING-3D PRINTING	Path planning software generates the best printing strategy to reduce the material used and time. The high-tech solution developed by UL manufactures using at least 30% of recycled plastic the product in the previously chosen manufacturing centre.	5_1_2
STEP 8 - POST PROCESSING	If needed, a post-processing phase refines the product in terms of aesthetic quality in order to meet customer requirements. Some parts need to be assembled in the manufacturing site before shipping to the customer.	5_1_2
STEP 9 - TEST BY USE	The DIT innovation space enables the designer to test the just realized prototype, to ensure proper functioning in real conditions.	6_1_1
STEP 10 - RE-DESIGN AND AFFINATION OF FABRICATION	If the test by use of the prototype fails, the failure is improved and corrected, repeating the process (re-involving the necessary stakeholders and the technologies used).	5_2_2
STEP 11 - VALIDATION	The use case ends validating the product printed, first by the manufacturer and the designer, second by a responsible entity for verification of design feasibility that provides safety and environmental certification and lastly by the customer use (feedback).	6_1_2

5.2 Step 1 - Receive Design and Specification

The first step in the reception of the design models and specifications from the INEDIT platform. The starting point of this activity is the downloading the respective documents that contains the 3D model to be manufactured by the use case as presented in the Figure 12.

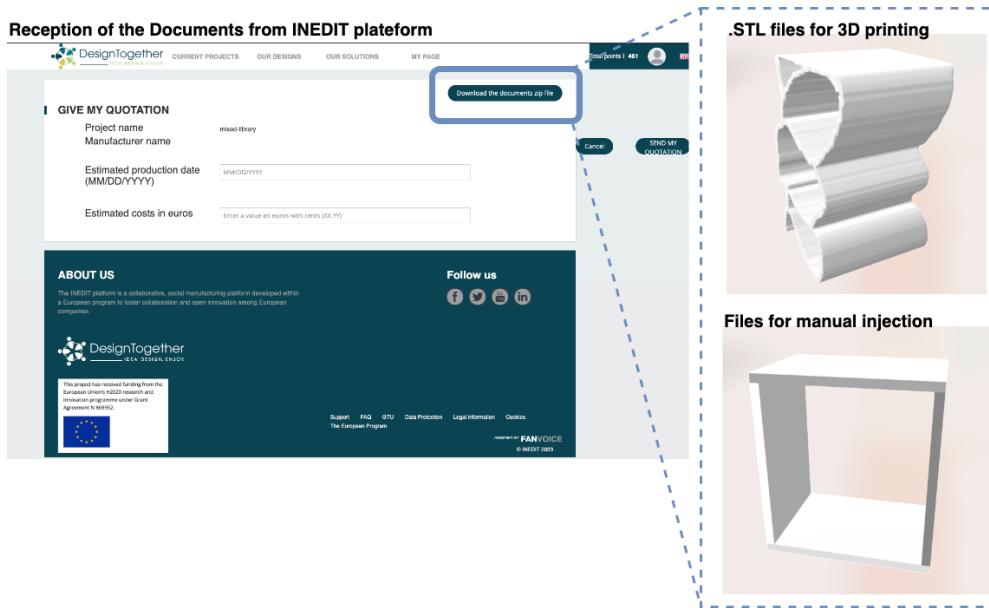


Figure 12: Reception of the exploitable documents for the fabrication process

One of the outputs of the co-creation phase of INEDIT is the creation of a first initial model that can be exploitable in the open manufacturing process. In that way, the model is received taking into account the specific requirements of the customer, and the required inputs to determine if the technologies available in the demonstrated have the capacity to produce the product. In the case that it cannot be produced, it is necessary to notify immediately together with the arguments why it cannot be produced and offer ways of improvement.

5.3 Step 2 - Validation of the technical specifications of model to fabricate

The main purpose of the second step is to establish the criteria for the validation specifications of the model to fabricate. In the case of the Green FabLab, three main criteria were established:

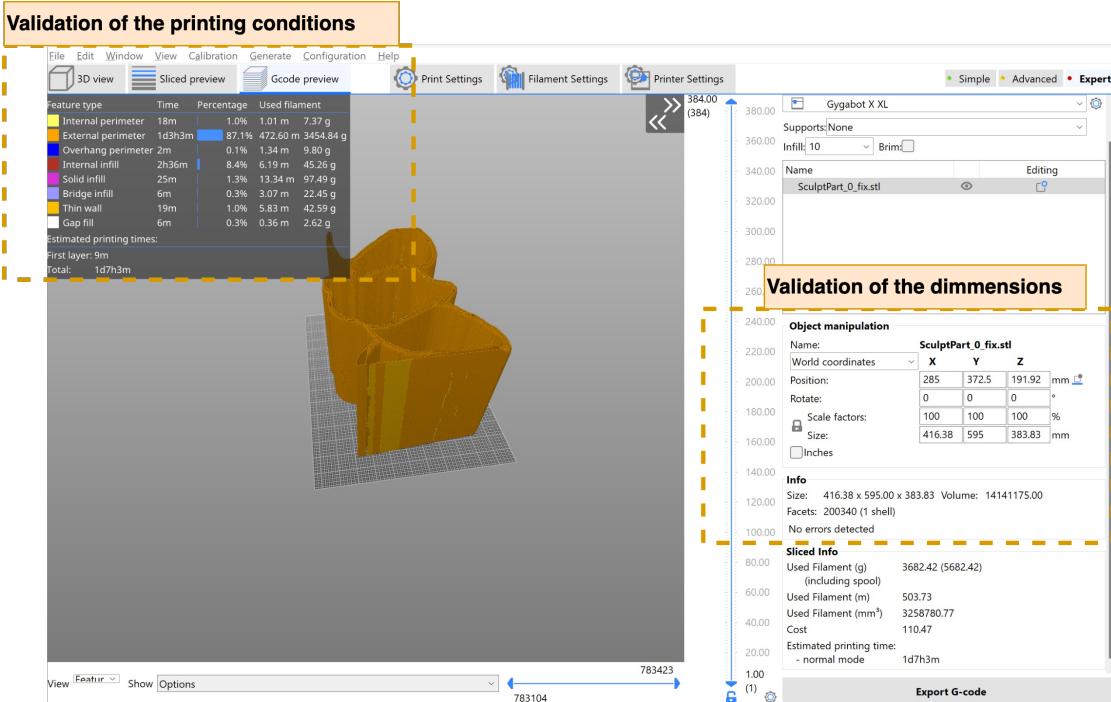


Figure 13: Validation of the printing conditions

1. Concerning the dimmensions
2. Concerning the material
3. Concerning the printability

Using the software for the , we are in measure to validate the global dimmensions of the proposed part. This needs to be in the range of the maximal working dimensions of the 3D printers. Another aspect, relies on the orientation of the part.

Concerning the printability, based on the characteristics of the material and the variables of the machine (namely, the temperatures of the barrel, the rotation of the stepper motors and the diamter of the nozzle). Different tests of printability were made in order to have a baseline of usable printed part as illustrated in the Figure 14.

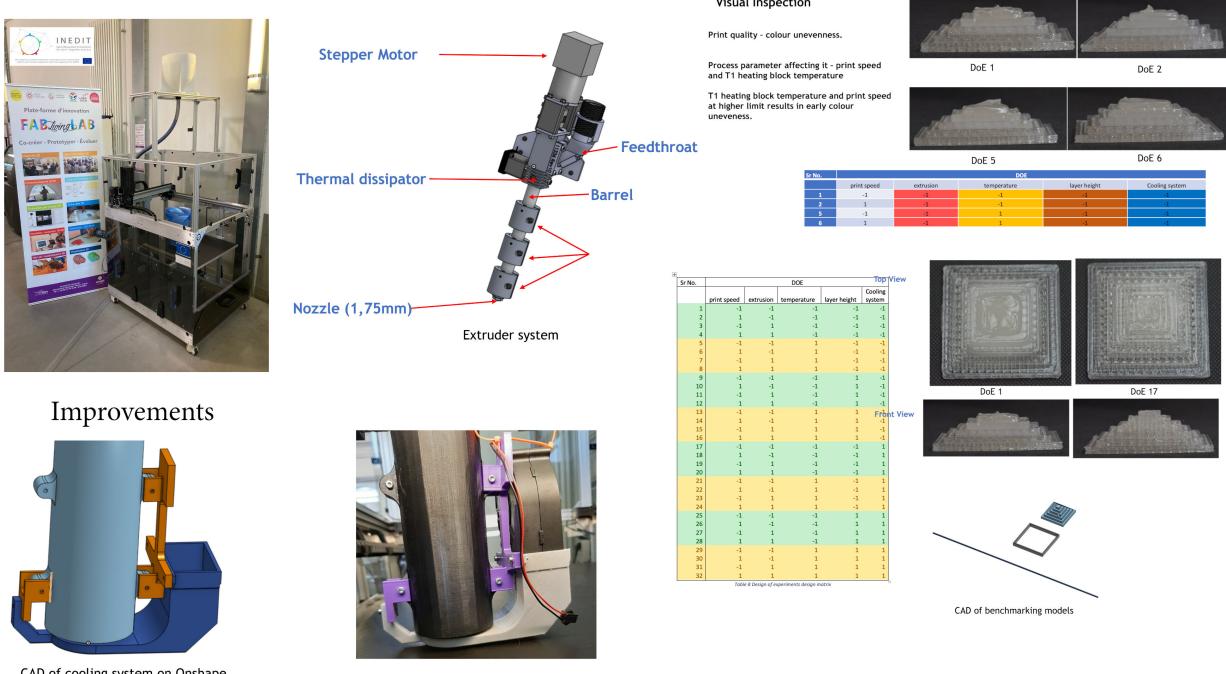
The test of printability consist in the selection the technical parameters of the machine () Using a Design of Experiments (DoE) approach, and a basic benchmarking models (for instance lines, cubes, pyramides in Figure 14b), it is possible to identify the errors in the printing process.

5.4 Step 3 - Identify local source of plastic waste

This step seeks to establish a first network of plastic wastes source from the local ecosystem. The task of the identification of local source of plastic is fundamental as the first stage in the recovery process.

As illustrated in the Figure 15, the methodological approach included the following steps:

1. Pre-diagnosis of the territorial context,



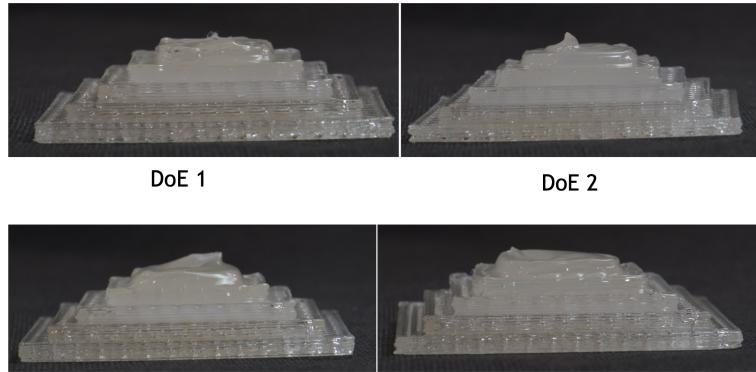
(a) Test of printability

Visual Inspection

Print quality - colour unevenness.

Process parameter affecting it - print speed and T1 heating block temperature

T1 heating block temperature and print speed at higher limit results in early colour unevenness.



DoE 5

DoE 6

Sr No.	DOE				
	print speed	extrusion	temperature	layer height	Cooling system
1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	-1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	-1

(b) Validation of the printability

Figure 14: Experimental protocol to validate the printability tests.

2. Identification of the actors,
3. Analysis of the actors' involvement and implementation of the smart collector, and finally,
4. Implementation & monitoring.

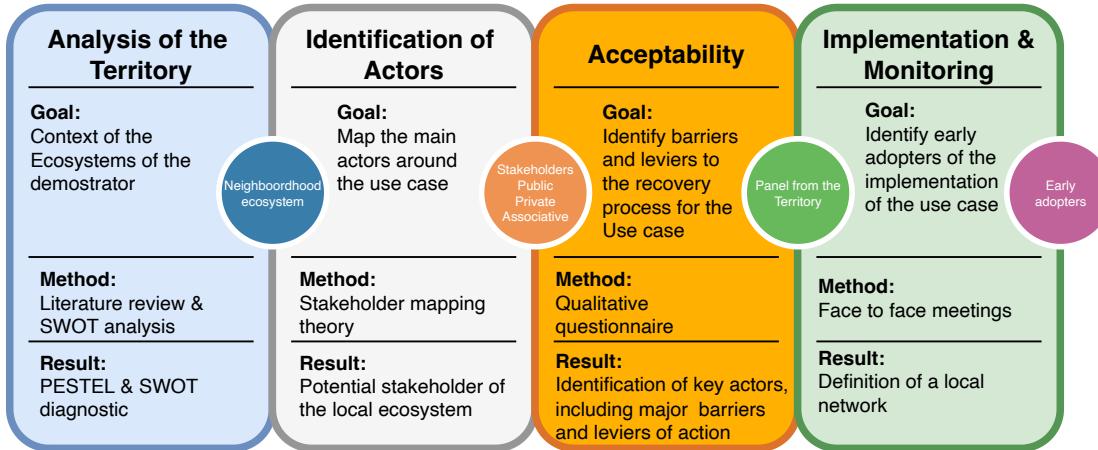


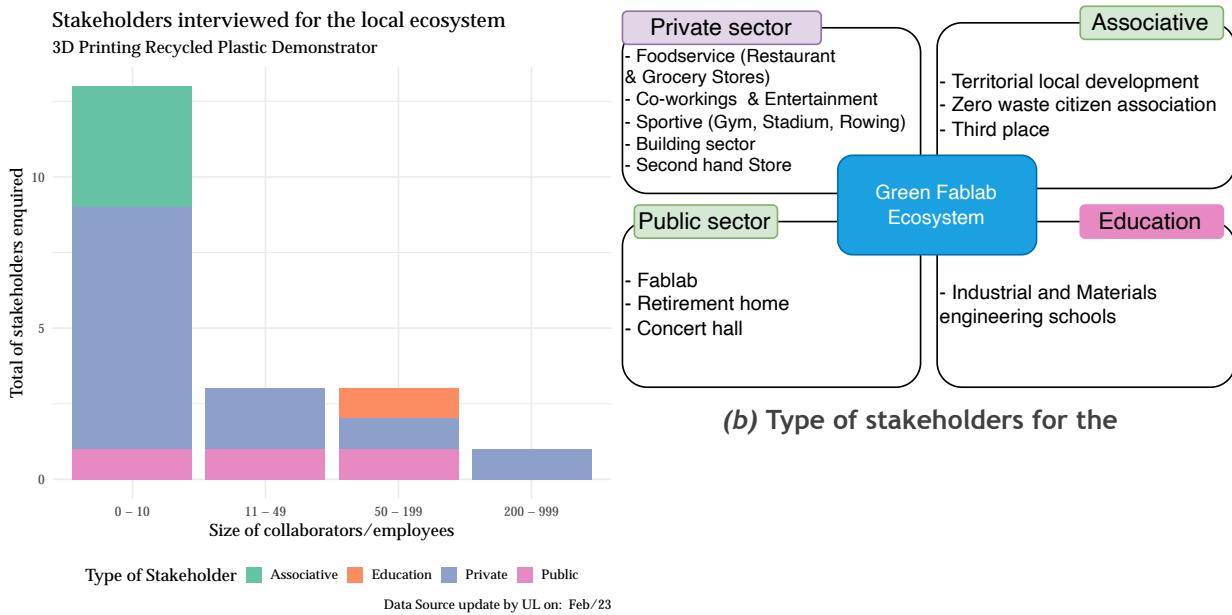
Figure 15: Methodological steps for the identification of local sources of plastic wastes

Regarding the pre-diagnosis phase, the purpose was to align the INEDIT project with the territorial context. To do so, between XX-2021 and YY-2022, the UL team had exchange with key actors of territorial development agencies and associations (Annex XX for more details) and the priorities in terms of sustainable development. The main output of this phase was the establishment of an initial Swot-Pestel analysis for the implementation of a local recycling network of plastic waste at the neighborhood of Rives de Meurthe at Nancy.

Based on this first step, it was possible to identify relevant stakeholders in the local ecosystems to inquire on the issue of plastic wastes source. First, they needed to be in a geographical range perimeter (less than 2km around the facilities) following the observations of ([Cruz Sanchez et al., 2020](#); [Santander et al., 2020](#)). Limiting the geographical perimeter of collection helps in the reduction of environmental impact because of the reduction of transport impact. Second, the diversification of the actor profile that can be sensitized to the participation of the collection (general public, employees, students) and/or stakeholder's status (Public, Private, Associative) where the smart collector can be deployed. These two elements were essential to consider because the experimentation seeks to establish a baseline of the recovery process given the uncertainties of participation of the local context and the sensitization to the management of the plastic by the general public.

A total of 23 actors were interviewed in the period of time of XX-2020 - YY-2022, of which 21 by physical or telephone interview and 2 by electronic questionnaire. They were mainly companies (X% small and Y% medium size), associative entities, academic sector. The diversity of the public was an interesting criterion for the study. Participants in the economic, cultural and social dynamics of the district through their membership in the local association of economic actors of the territory.

The scope of activity of most of the respondents is local (at the level of the neighborhood or



(a) Local ecosystem interviewed about the implementation of a 3D printing recycled demonstrator

Figure 16: LLocal ecosystem enquired

city) which may reflect a strong territorial anchoring and a commitment to local concerns and issues (waste management, social welfare, local job creation...). The majority of their business decisions are made locally, which reduces the risk of depending on the interests of entities outside the territory.

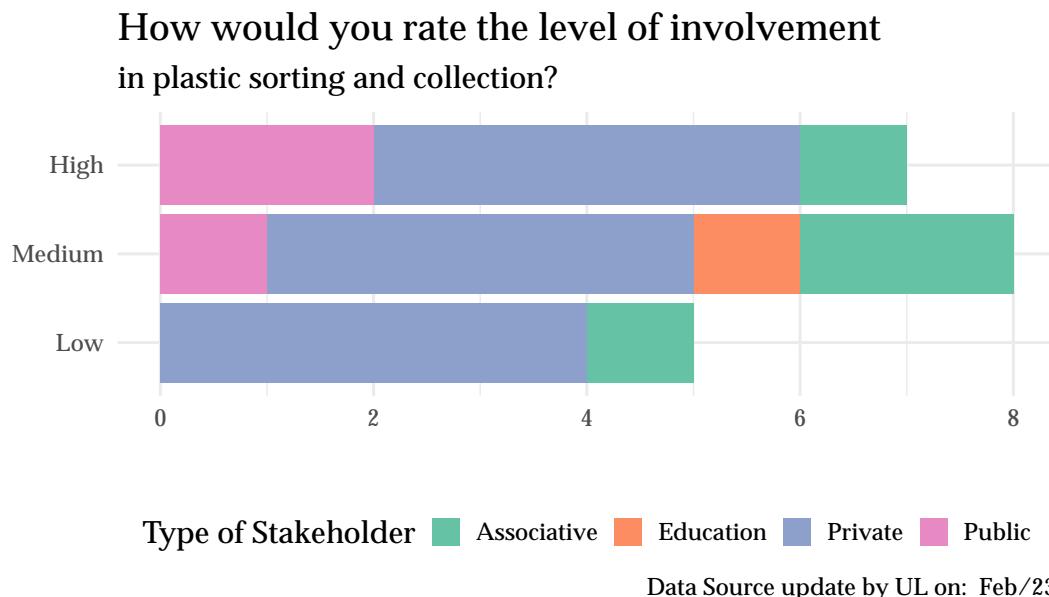


Figure 17: Local ecosystem interviewed about the implementation of a 3D printing recycled demonstrator

To do this, we identified the role of each actor, then the sources of plastic waste collection, and then identify the sources of 3D printing and potential synergies with LF2L. In order to achieve these results, an exchange with key actors in territorial development was necessary.



Figure 18: Acceptability of the possible use of ‘smart collector’ for the

Thanks to this approach, we have identified eighth collection sites at the local territory for the deployment of the smart collector.

5.5 Step 4: Put in place smart collectors

In this step the main purpose is the deployment of a set of *smart collectors* around the neighborhood. Figure 19 presents the selected points around the Green FabLab for the installation of the prototype. The smart collector is produced and mounted manually. The specific details and step-by-step assemble process can be found in the technical paper ([Gabriel and Cruz, 2023](#)).

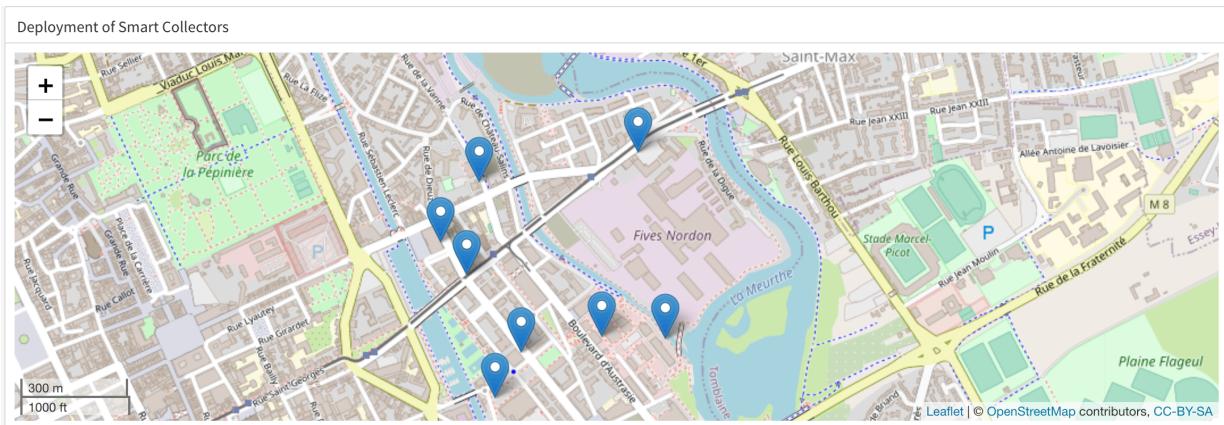


Figure 19: Deployment of the Smart Collectors.

The selection of the places were based on the steps 3. For the experimentation, 8 sites were selected for the deployment as listed in the Table 1.

Table 1: Selected points of deployment of the smart collector in the neighbourhood of Rives de Meurthe, Nancy - France.

ID	Name	Type	Potential public	Main activity
1	MCJ Bazin	Association	+300	Activités culturelles/loisirs
2	Octroi	Association	+1000	Tiers lieu, accueil de porteurs de projets et espaces de coworking
3	Curves	Private Enterprise	+100	Salle de sport
4	ENSGSI	University	300	Ecole d'ingénieurs - Enseignement supérieur et recherche
5	MAIF (bat.1)	Private Enterprise	50	Assurance mutuelle
6	EEIGM	University	500	Ecole d'ingénieurs - Formation et enseignement d'ingénieurs en Génie des Matériaux
7	Voie Navigable de France	Public Enterprise	50	Gestion du réseau des voies navigables de France
8	Sport Nautique de Nancy	Association	+100	Club de sport (aviron)

First, face-to-face meetings with the local actors were made to obtain the agreement for the installation of the prototype. As a relevant criteria, the installation needed to be in a location where the visitors/employees/customers of the selected point are able to see the device. We designed an appropriate communication that enables to explain the purpose of the device and connect to the information of INEDIT projet (see Figure 20)

Then, a system activation is putted in place to begin the collection gate. Once the smart collector is online, it is necessary to survey the online dashboard to control the waste plastic quantity. In the moment that the dashboard present a weight more than 3 kg, we mapped the collection point in the stage of '*to collect*' and we plan the recovery. The distance of the collection place is less than 2 km so is carried out by bicycle or on foot to avoid the possible impact produced for a combustion or electric vehicle. Once the recovery process is made, at the Green Fablab When the waste plastic is collected, it is stored at the facilities of the Green FabaLab before posterior treatment and adequation.

we have build a central collector where the material is stored before it is treated.



(a) Picture of the Smart collector at the collection point



(b) Communication strategy of the smart collector

Figure 20: Smart collector

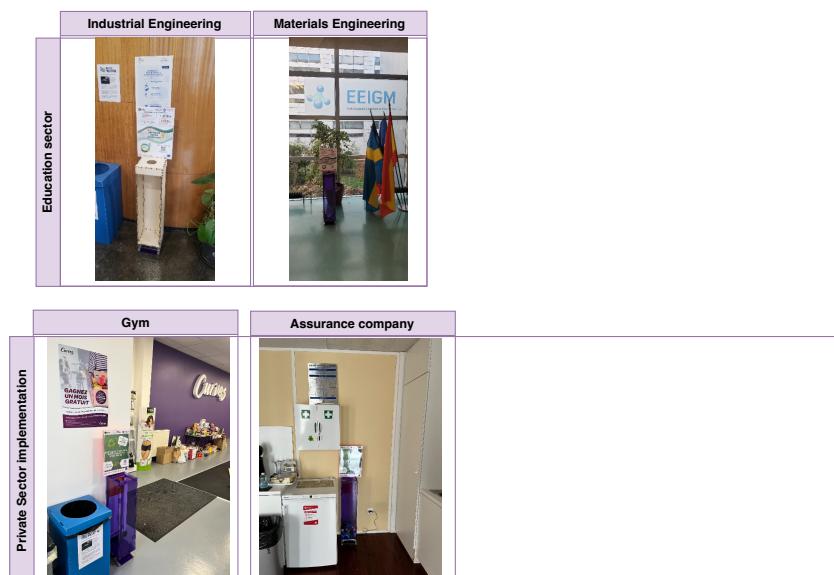


Figure 21: Smart collectors deployed in the territory

5.6 Step 5: Transport waste material to the recycling facilities

The recovery process took place once a week on average. The plastic waste is collected and transported to Green Fablab facilities, and then it is stored in a central collector as illustrated by the figure Figure 23.



(a) Central collector of plastic waste



(b) Communication flyer for the smart collector

Figure 22: Smart collector

Throughout the experimentation of the deployment, we have mapped the quantity of collected material. Figure 23 corresponds to the profile of quantity collection per month. In average, we have collected XX-kg per month.

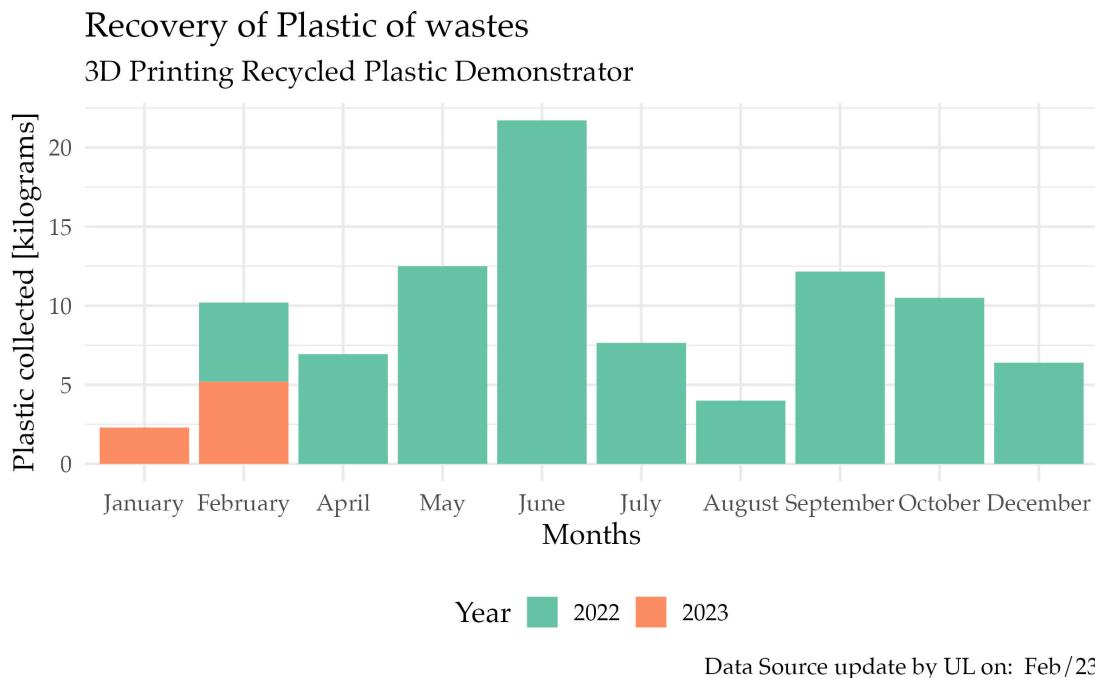


Figure 23: Recovery profile of plastic

i Key Performance Indicator of the Recovery process

In terms of *KPI* of the recovery, from February 2022 to February 2023, we have collected a total of 94.37 kg of plastic waste using 8 collectors in the territory of Rives de Meurthe, Nancy-France.

5.7 Step 6: Adequation and preparation of the material

This is the first stage carried out inside the Green FabLab. This stage is the set of activities required for the plastic waste to be adapted for further use. The Green FabLab works mainly with 4 types of plastic at the moment. The most common are high density polyethylene (HDPE) and polypropylene (PP), which are the main plastics used in the production of bottle caps and they are collected in the smart collector. The plastic waste from unused/damaged 3D printing parts are mainly of polylactic acid (PLA) are collected from mainly from the Lorraine Fab Living Lab. And finally, the plastic bottles also are collected which are polyethylene terephthalate (PET).

The preparation process begins with the separation and identification of each plastic collected. As already mentioned, the plastics used in the Green FabLab are 4 (HDPE, PP, PET and PLA) and are separated by type of plastic and colour. This process is carried out manually.

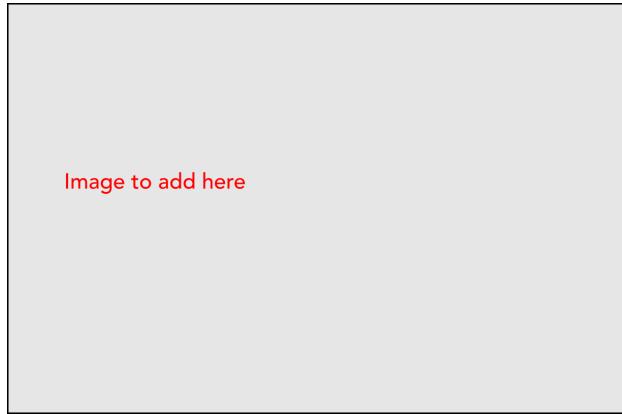


Figure 24: Photo of the sorting process

The second step is the cleaning phase. Cleaning and washing plastic cups and bottles is crucial step for effective recycling because plastics are mainly post-consumer waste, they are not in an adequate state of cleanliness. It is required that to ensure the plastic is as clean as possible because dirty material can affect the quality of the extrusion / printing process, which at the end affects the recycled product. Therefore, we aims to remove adhesives, leftover waste, and labels. HDPE and PP are mainly used in the plastic injection molding process, while PLA and PET (Mixed with 9% HDPE) are used in 3D printing.

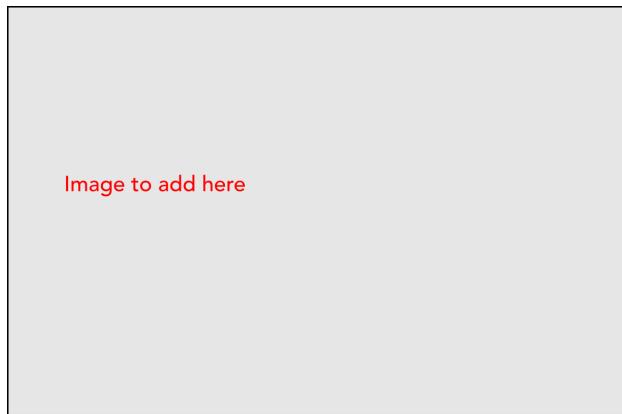


Figure 25: Photo of the cleaning process

In a first moment, the manual cleaning is used in the Green Fablab to remove the most of the majors contaminant present in the material. For plastic injection moulding, where mainly PP and HDPE are used, the plastic is washed in a sink with hot water.

The water consumption per gram is approximately $4L/1000g$. The drying of the plastic is done by natural convection in the open air.

For additive manufacturing, where mainly PLA, HDPE and PET blends are used, the cleaning process is much more controlled. The process is carried out in a small ultrasonic cleaning

machine, to ensure that impurities are removed. The cleaner ultrasonic machine wash 200gr de plástico en 1 L of water. This process takes 20 mins with a consuption of 2kWh.

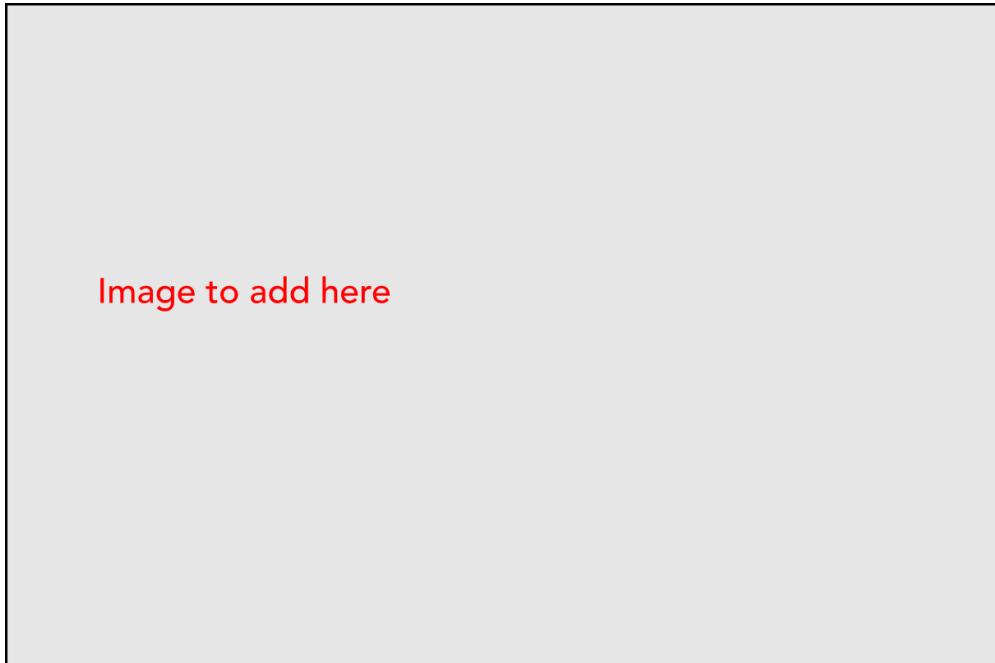


Figure 26: Photo of the Ultrasonic cleaning

The second step in the preparation of the waste material is the size reduction process. In this step, the washed and sorted plastic is sent through shredding machine where it is grounded into smaller pieces of plastic. A critical parameters in the control of the granulometry. The purpose of the size reduction is to obtain plastic waste where the granulometry correspond to the extrusion / printing. The plastic waste need to be in reduced from a range of between 25-50 mm to 3-5mm approximately after grinding. A cutting mill machine SM 300 Retsch® with a selectable speed range from 700 to 3,000 rpm was used. The selected speed was 1500 rpm. Normally we use a rotational speed of 1500 which produces an energy consumption of 0.7 kWh. The process takes 15 minutes per kilogram of material with a loss of approximately 10%. For direct additive manufacturing the optimum size for the granulometry for printing is between 3 and 5mm. Therefore, after shredding it is necessary to sieve.

In terms of plastic injection moulding, the plastic flakes can be slightly larger than those required for 3D printing.

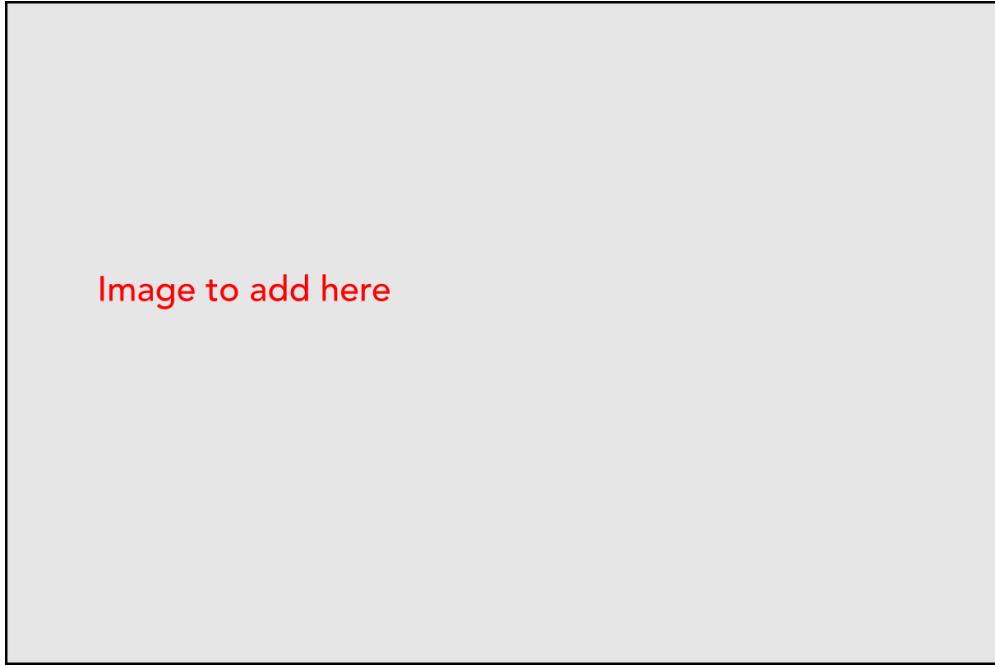


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Figure 27: Photo of the Shredding process

Filament is produced at 0.4 kg/h using 0.24 kWh/kg with a diameter $\pm 4.6\%$. 3Devo

To remove all the moisture from the plastic it is necessary to carry out a drying process in a conventional oven.

In the drying phase, the plastic is putted in the oven at 60°C during 15h with a consumption of 0,061 Kwh.

Finally, the drying process is last step to prepare the material.

5.8 Step 7: Path planning - 3D Printing

Once, we have the model to concerning the

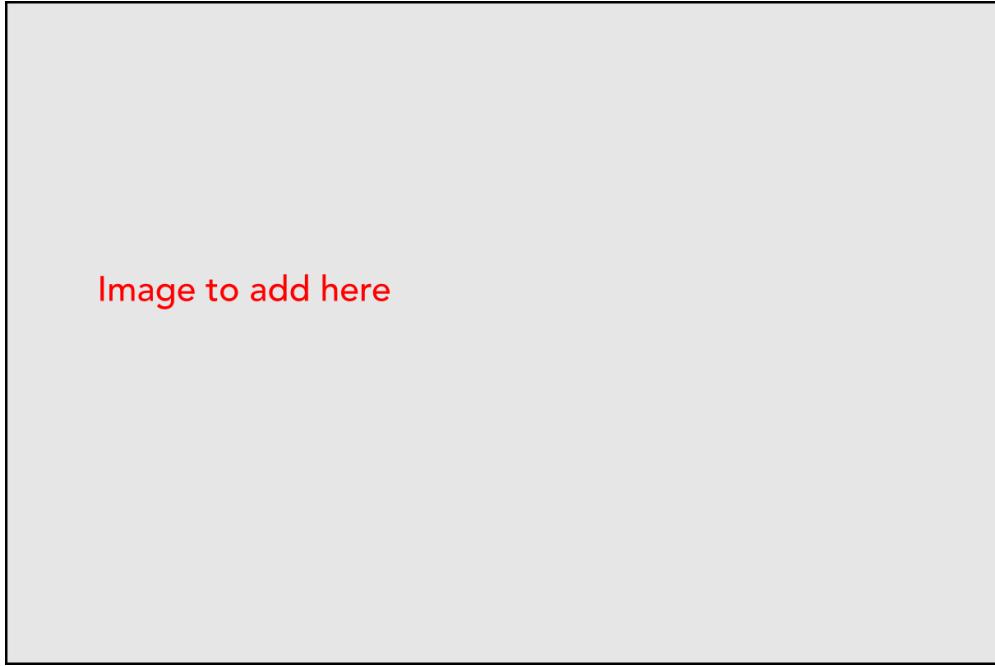


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Figure 28: Photo of the Slicer of the Gigzbot

5.9 Step 8 : Post-processing

Post-processing relies to the treatment of the injected and/or printed part. Regarding the injection part, the post-processing relies in the

Concerning the 3D printing part, one of the most

5.10 Step 9: Implementation Examples

5.10.1 Case Workbech 1

This user case aims the validation of the for personalization of the

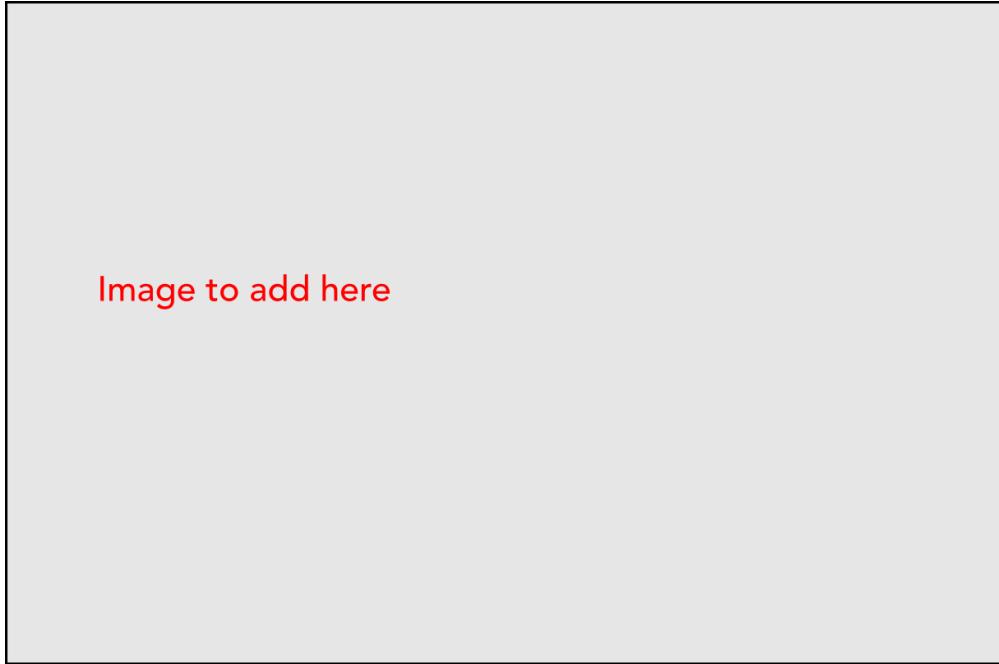


Figure 29: Photo of the Slicer of the Gigzbot

5.10.2 Case Workbech 1



Figure 30: Photo of the Slicer of the Gigzbot

5.11 Step 10: Re-design and improvements of fabrication

5.12 Step 11: Validation

6 Conclusions

Plastic waste as secondary resources and possibilities for a secondary market

Qualification of the waste

Mains challenges to tackle

Legislation of waste and

More examples needed in the recycling for education purposes

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