

**École polytechnique de Louvain**

# **Design for Manufacturing in FabLab of a Plastic Shredder**

**Enhancing Accessibility and Reproducibility**

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# Abstract

The growing issue of plastic waste has become a significant concern in today's society. The primary solution to this problematic is to eliminate unnecessary waste and keep plastic circulating by reusing, repairing and recycling it. This latter includes collecting, sorting, cleaning, shredding, and melting plastic into new objects.

This project specifically aims at manufacturing a plastic shredder based on the one that was designed by Precious Plastic, an organization that provides open-source information to enable individuals and communities to set up their own small-scale plastic recycling facilities. However, the current design of the Precious Plastic shredder requires advanced skills and access to specific machines. In this project the shredder is therefore redesigned in order to enhance the accessibility of its manufacturing to a broader audience. As it still requires machines that are not in every household, the design of the machine will be made so that it can be manufactured in a FabLab. This collaboration between Precious Plastic and FabLabs creates a mutually beneficial relationship because FabLabs are located all around the world, enabling a global presence of the Precious Plastic project.

As a result of this thesis, a shredder prototype was built to shred take-away plastic containers and PLA. Its performances are lower than the ones of the original shredder as it produces bigger plastic flakes due to the larger thickness of its blades. These latter consisted in the biggest redesign challenge of the project and it was chosen to replace the steel by a hard plastic (POM) and some aluminium reinforcements. However, the objective to increase the manufacturability in FabLab was reached with 92.4% of the parts that were built in a FabLab compared to 0.8% for the initial shredder. The prototype can from now on be used as a test bench for further testings and improvements.

# Terms and Abbreviations

|                  |                                                                                                                     |
|------------------|---------------------------------------------------------------------------------------------------------------------|
| 3D printing      | The process of creating objects from three-dimensional digital models, by thinly layering a material (such as PLA). |
| CNC              | Computer Numerical Control                                                                                          |
| FEM              | Finite Element Method                                                                                               |
| FabLab           | Fabrication Laboratory                                                                                              |
| HDPE             | High-density polyethylene                                                                                           |
| Laser cutting    | A technology that uses a laser beam to cut through or engrave materials with high precision.                        |
| LDPE             | Low-density polyethylene                                                                                            |
| MakiLab          | The FabLab of Louvain-la-Neuve                                                                                      |
| MPO              | Mixed polyolefins                                                                                                   |
| OSB              | Oriented Strand Board                                                                                               |
| PE               | Polyethylene                                                                                                        |
| PET              | Polyethylene terephthalate                                                                                          |
| PLA              | Polylactic acid                                                                                                     |
| PMD              | Plastic packaging, Metal packaging, and Drink cartons                                                               |
| POM              | Polyoxymethylene                                                                                                    |
| PP               | Polypropylene                                                                                                       |
| Precious Plastic | A project that focuses on providing information to develop plastic recycling machines and communities               |
| Prototyping      | The process of creating a preliminary or working model of a product, system, or design concept.                     |
| PS               | Polystyrene                                                                                                         |
| PVC              | Polyvinyl chloride                                                                                                  |
| UTS              | Ultimate tensile strength                                                                                           |

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# Introduction

The main objective of this master thesis is the design for manufacturing in a Fabrication Laboratory (FabLab) of a plastic shredder, enhancing its accessibility and reproducibility. The goal is to demonstrate the feasibility of the concept through the development of a functional prototype.

The growing issue of plastic waste has become a significant concern in today's society. The accumulation of plastic waste is threatening our environment, our human health and fauna and flora. Effective change is needed to face the plastic waste problematic.

The primary solution to the plastic waste problem is to eliminate unnecessary plastic waste from our society. Therefore, it is crucial to reuse, repair, and recycle plastic in order to keep it circulating in the economy for as long as possible. In this project, the focus is on the recycling aspect, which includes various steps such as collecting, sorting, washing, shredding, and melting plastic [1]. Specifically, this project is centralized on the critical step of shredding plastic.

According to a report of Plastic Europe<sup>1</sup>, "Plastics waste recycling rates are 13x higher when collected separately" [2]. This shows the impact of implementing separate waste collection systems. By collecting waste separately, it is possible to bypass the need for additional sorting processes and directly proceed to recycling. In this way, waste loss is minimized and the likelihood of waste being incinerated is reduced [2]. Sorting in Louvain-la-Neuve is currently done very poorly by citizens and the city is thus not motivated to add more sorting trash bins. An initiative creating a separate sorting system for the plastic shredder that directly recycles plastic waste is one of the needed solutions to face the plastic waste problem in Louvain-la-Neuve.

This project is based on the plastic shredder designed by Precious Plastic. This organization aims at providing open-source information that enables individuals and communities to set up their own small-scale plastic recycling facilities. However, the current design of the Precious Plastic shredder requires advanced skills and access to specific machines such as a laser cutter for steel, welding equipment, milling tools; this makes it difficult for people to build their own machines themselves. By redesigning the shredder, the

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<sup>1</sup>a leading trade association representing plastics manufacturers active in the EU plastics industry.

objective is that a broader audience will be able to participate in the Precious Plastic movement and establish their own recycling initiatives within their communities.

However, building a shredder will still require a minimum number of machines that may not be available in most households. This is where the FabLab comes into play as an ideal environment for this project. By adapting the design of the shredder to be compatible with the tools available in FabLabs, the gap between the required machinery and the resources accessible to individuals can be bridged.

The FabLab environment appeals to a community of makers who are passionate about building things themselves. Additionally, with the growing popularity of 3D printing, there is a keen interest among FabLab users to recycle their own 3D printing plastic waste. This collaboration between Precious Plastic and FabLabs creates a mutually beneficial relationship, empowering makers to construct their own recycling machines while simultaneously addressing the plastic waste issue in a more accessible and sustainable manner. On top of this, FabLabs are located all around the world, this enables to scale more easily the Precious Plastic project globally.

The first part of this master thesis establishes the contextual background, discussing the plastic waste context, Precious Plastic and FabLabs. It also provides a state-of-the-art analysis of plastic shredders, explores recycled plastics' properties, and introduces relevant engineering design and prototyping methods.

The second part is centralized on the design and prototyping of the shredder. The goal is to create a modular prototype for testing and evaluating different possible solutions. For each part of the shredder alternative solutions to the Precious Plastic shredder are investigated. Through iterative testing and refinement, a final concept is validated and manufactured, followed by an analysis of its performances.

The third part of this paper is a critical discussion that evaluates the developed solution, highlighting its advantages and drawbacks compared to the original Precious Plastic shredder and sheds the light on the further perspectives of this project. Eventually, the aim is to create a well-documented project that enhances accessibility and reproducibility of the plastic shredder.

**Special note:** All the project documentation, including files for laser cutting, 3D printing, and CNC manufacturing, were created with the software Fusion360 and Easel and can be found on the following link in the project section: [`https://openhub.fab-manager.com/#!/.`](https://openhub.fab-manager.com/#!/) The language Python was used to generate the accompanying graphics in this work. An artificial intelligent tool, ChatGPT, has been used to rephrase and correct the spelling of some parts of the text.

# Part I

## Background



# Chapter 1

## Context

### 1.1 Plastic

Plastic objects are named after a number between 1 and 7 placed into a triangular “chasing arrows” symbol. This enumeration indicates what type of plastic has been used for manufacturing the product and can help sorting the plastic waste for recycling [3]. Figure 1.1 shows which plastic corresponds to each of the seven categories and explains what type of products are usually made with it.

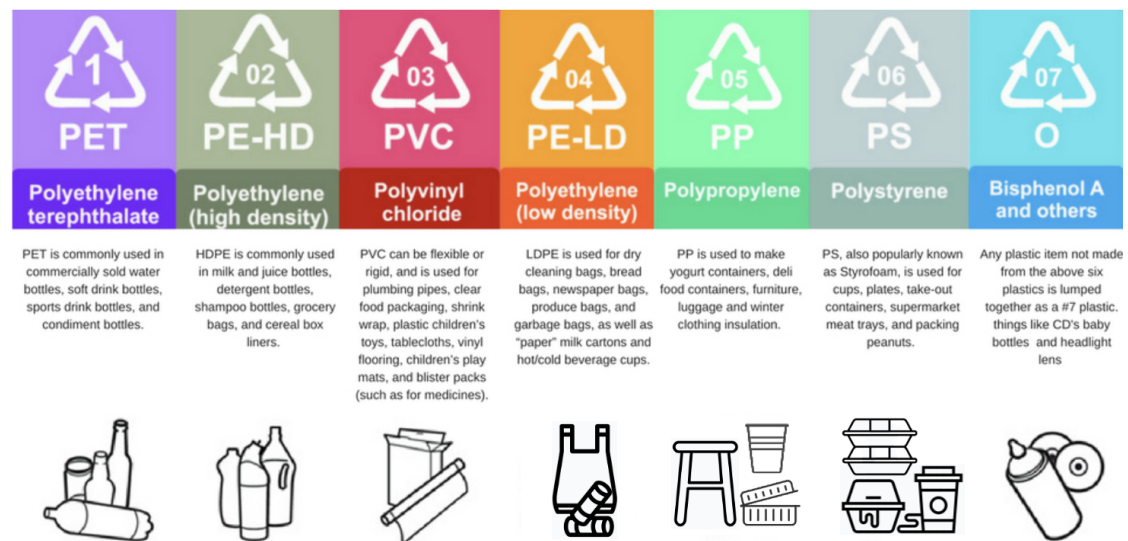


Figure 1.1: Types of plastic enumeration and usual manufactured products [4].

### 1.1.1 Production

#### Global

In 2021, the global plastic production amounted to 390.7 million tons among which 90.2% were fossil based, 8.3% were post-consumer recycled and 1.5% were bio-based [2]. This number is 15 million tons bigger than the one from the year 2020. Figure 1.2 shows the distribution of this production by type of plastics. China produces almost one third of the world's plastic and is the biggest producer of plastic worldwide (29% in 2020 and 32% in 2021). It is followed by North America (18% in 2020 and 2021) and Europe (19% in 2020 and 15% in 2021). Almost half of the plastic production (44%) is used for packaging while the rest is mainly used in construction (18%), automotive, electronics, households and agriculture.

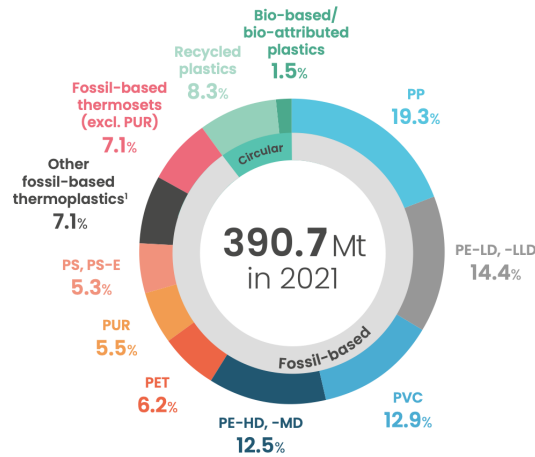


Figure 1.2: Distribution of the global plastics production by types of plastic [2].

#### Belgium

In Belgium, the polymer production and plastic conversion industry holds a significant position as a key manufacturing sector [5]. It amounts to 4.7% of the European plastic converting industry. Figure 1.3, shows that the most commonly used polymers in Belgium are PP, HDPE and LDPE next to PET and PVC. Similarly to what was observed on a global scale, the major part of plastic used in Belgium is for packaging.

At the end of a plastic object's life several things can be achieved, giving the waste more or less value. The object can either be reused, recycled (mechanically, physically or chemically) or incinerated with energy recovery. If none of this is done, the object is disposed of, buried for example [6, 7]. In 2020, 39% of the plastic waste was recycled in Belgium while the rest was either incinerated (59%) or disposed of (2%). This is a good performance compared to Europe where 23% of the plastic waste was disposed of [5].

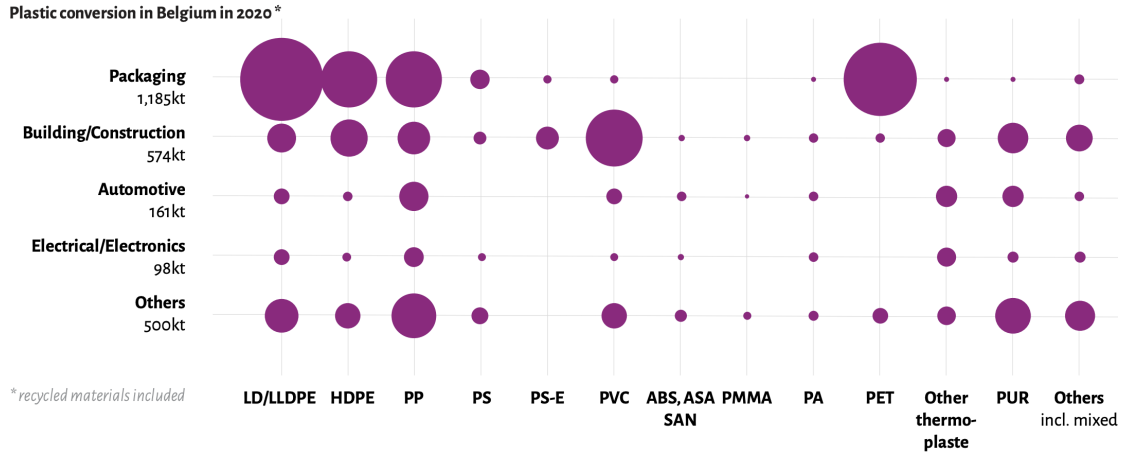


Figure 1.3: Plastic conversion in Belgium, 2020 [5].

### 1.1.2 Recycling

#### Recycling of PMD

In Belgium, there are five sorting centers for what is called the PMD<sup>1</sup> trash (Plastic packaging, Metal packaging, and Drink cartons). There, the trash bags are opened and waste is sorted. In the Valtris center [8], waste is divided into sixteen fractions: aluminium, Tetra Pak<sup>2</sup>, PS, HDPE, PP, steel, PE films, MPO, clear PET, PET containers, blue PET, colored PET, opaque PET, other films, small aluminium and residuals. This latter represents 16 to 17% of the incoming waste and is burned with energy recovery. The other fractions must have 95% of purity to be sold to a company (Fostplus [10]) who sells them again to recycling centers in Belgium or Europe. The sorting of PMD waste is highly automatic enabling the Valtris sorting center to sort 12 tons of waste per hour, which amounts to more than 7000 trash bags.

#### Louvain-la-Neuve: City Trash Bins

The proper recycling of plastic waste, when well sorted by citizens, is evident as it finds its way to sorting and recycling centers. However, it becomes interesting to examine areas where citizens do not correctly sort their waste. Examples of such locations are airports, train stations, streets or parks. In this matter, the city of Louvain-la-Neuve, where the project is held, can be considered.

In Louvain-la-Neuve's streets, two types of trash bins are available: one for residual waste and another for PMD waste. The former is collected and incinerated, the latter is collected by Fostplus and sorted for recycling. However, the city reports that sorting is done very poorly by the citizens who put waste in the wrong trash bin. This is the

<sup>1</sup>Called PMC (Plastique, emballages Métalliques et Cartons à boissons) in French.

<sup>2</sup>A type of thick card and plastic container in which milk or other drinks are sold [9].

reason why the city does not wish to add more trash bins than there already are. As the residual waste bags are not sorted before incineration, a lot of plastic is directly burned, bypassing the recycling process.

## 1.2 Precious Plastic

### 1.2.1 Description

In response to the realization that merely 10% of the world's plastic is recycled, Dave Hakkens established Precious Plastic to combat plastic pollution. The difficulty in recycling plastic is caused, among others, by the diversity of plastic types and the cost of collecting, transporting and facilities building [11].

The Precious Plastic initiative [12] was created in 2013. It is an open hardware project that focuses on plastic recycling. The main idea behind this project is to reduce plastics waste while counting on people to bring about the necessary change. From January 2020, the Precious Plastic Universe was released with the objective to create an alternative global recycling system by using machines, platforms and knowledge.

To address this plastic problem, Precious Plastic is divided in five spaces that are connected and dependant on each other.

- Workspace: plastic waste gets transformed into raw materials or products. One or several machines are used (Shredder, Extrusion, Sheetpress, Injection and Mix).
- Collection point: plastic is gathered from different places to be processed in a workspace.
- Community point: the local recycling network connects and grows.
- Machine shop: moulds, parts and machines are produced and built.
- Member: has the role to help with plastic collection, spreading the word or purchasing recycled plastic products.

All these spaces together form the Precious Plastic Universe consisting in a local network which offers an alternative recycling system.

The goal of Precious Plastic is thus not to build industrial machines but to gather all around the world local communities together in order to face the plastic waste problematic.

### 1.2.2 Distributed and Open-Source Design

#### What is it?

The accessibility to a project depends on three factors: Shareable Design, Available Materials, and Replicable Manufacturing. Those three factors can be found on the Distributed

Design Radar (Figure 1.4). The farther from the center, the more accessible the project is.

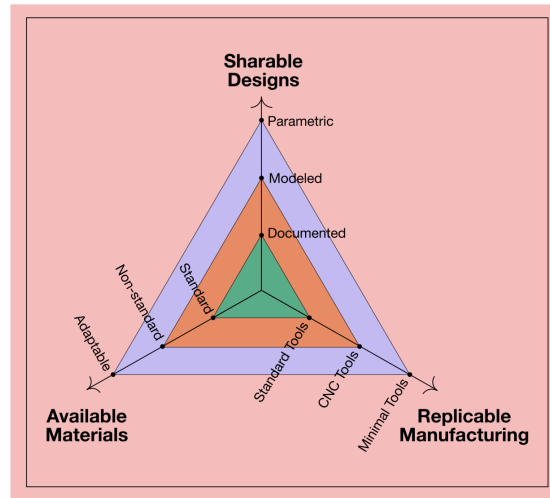


Figure 1.4: Distributed Design Radar (*This is distributed design* p.95 [13]).

**Shareable Design** refers to the type of information that is shared. There are three categories: parametric, modeled, and documented information. The ultimate objective is to achieve a parametric design so that the project can be adapted to any situation [13].

**Available Materials:** The more materials are available, the more accessible the project is. The goal is to use materials that can be adapted from any available material instead of using standard materials that may not be available worldwide.

**Replicable Manufacturing** involves the tools necessary for producing the required components. These tools can be categorized as Standard (Domestic) tools (e.g. A Hammer), CNC (Computer Numerical Control) tools and minimal tools. Ideally, the minimal amount of tools should be required to be able to replicate a design easily. Working with CNC tools simplifies the replication process compared to standard tools because CNC manufacturing is automated and computer-controlled. With access to the project files and CNC tools, reproducing a design becomes straightforward [13].

**Open-Source Design** is a collaborative approach where information, code, drawings, and source materials are freely shared among a community. The concept of open-source design is often based on volunteers who are creating and refining a design, while not necessarily being concerned about profitability [14]. It is also about sharing experience and knowledge in order to make a project evolve based on people’s feedback. Openness can have three forms, each inducing involvement and contribution from the community: transparency leads to observation, accessibility to co-development and replicability to co-production. It is a necessary mean for innovation [15].

Open-source design and distributed design both focus on collaboration, accessibility and sharing of knowledge. By combining these two design principles, projects can benefit from the collective intelligence and diverse expertise of a global community. This collaboration stimulates innovation and increases the accessibility to solutions.

### **Applied to the Precious Plastic Project**

The project of Precious Plastic is based on knowledge exchange. People around the world share their experience and collaborate to make the project grow. Precious Plastic is an entire community that gives tips and tricks to improve the project together [16]. There is a dedicated Discord server<sup>3</sup> where the different participants of the project can easily get in touch, share their experience and ask questions to each other. The project evolves thanks to the return of experiences from different members of the community and the global sharing. Moreover, the Precious Plastic Bazar is a website where everyone can sell or buy parts of or the whole machines and even objects that have been made with the machines [18].

Distributed Design is applied to the Precious Plastic project through well-documented instructions and designs, utilization of both standard and non-standard materials that are widely available, hence enabling replicable manufacturing processes by using Standard Tools and CNC tools.

### **1.2.3 The Machines**

Initially, four machines were designed by Precious Plastic in order to recycle plastic [19]. Blueprints and explanations on how to build them can be found on the Precious Plastic website.

The Shredder (Figure 1.5a) cuts plastic items into small flakes that are then used by other machines to build new objects. The extrusion (Figure 1.5b) is a continuous process where plastic flakes are used to create raw material in the shape of a plastic filament. With the injection machine (Figure 1.5c), plastic flakes are melted and injected into a mould to create small objects. In the compression machine (Figure 1.5d), objects are formed by heating plastic within an oven and gradually applying pressure using a carjack to shape it within a mold.

Nowadays, the machines development is still ongoing. A new set of machines has been released. They are named the *pro machines* and can be used to set up a recycling business by dealing with heavier loads of plastic. There are three machines: a shredder, an extrusion and a sheet press.

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<sup>3</sup>Discord is a US-based social platform that allows users to communicate through voice and video calls, text messaging, and file sharing in private chats or within communities known as "servers" [17].

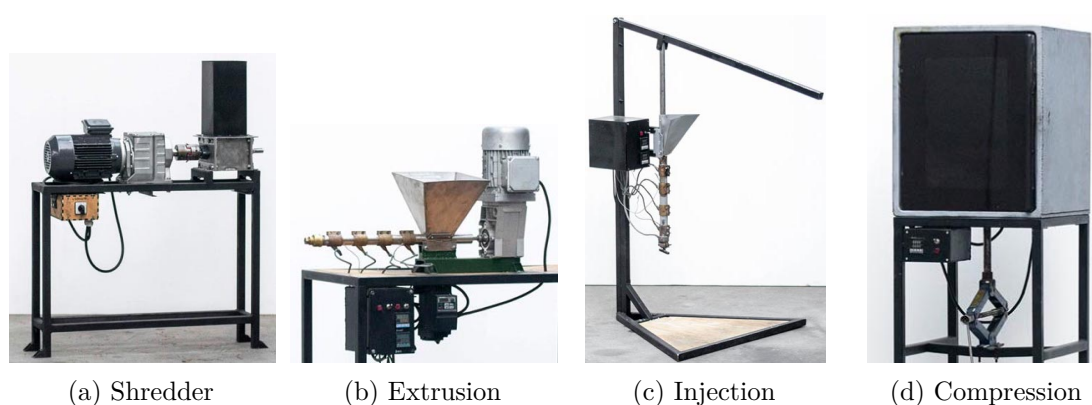


Figure 1.5: Precious Plastic Machines [19].

### 1.2.4 Built by the Community

#### Machines

Figure 1.6 shows examples of shredders built by the Precious Plastic community. None of them are identical as the project is such that everyone can adapt the design to their wishes.



Figure 1.6: Examples of shredders built by the Community [20].

#### Objects Made with the Machines

Figure 1.7 shows some examples of objects that were made using the Precious Plastic machines. Plastic can be used to make a lot of things as can be seen by the diversity of objects.

- Furniture: chairs, tables, step-stools, benches, planters, joints, door handles, suspension lamps, etc.
- Household items: wall clocks, coasters, wall holders, knives, containers, plant pots, vases, phone holders, clipboards, games (tracks, tic-tac-toe, chessboard, Jenga),

bottle caps, magnets, storage boxes, photo frames, centerpieces, bottle openers, soap-dishes, cups, notebooks, bowls, key-chains, mouse pads, etc.

- Art pieces: wall decorations, sculptures, cylinder stands
- Accessories: buttons, rings, necklaces, dog leashes, earrings, pins, cards, desk organizers, cards wallets, spinning tops, watches, hair combs, plectrums, etc.
- Others: Christmas ornaments, surf board racks, screwdriver sets, pens, USB drives, stamp coins, glasses, medals, etc.



Figure 1.7: Objects made with the Precious Plastic machines [18].

### 1.3 The Makilab

The Makilab is the Louvain-la-Neuve’s FabLab. A FabLab, or **F**abrication **L**aboratory, is a workspace equipped with numerical machines to manufacture (almost) anything [21]. The FabLab program was founded by the MIT in 2001 and has spread rapidly around the world. Nowadays, there are more than 2000 labs in over 149 countries [22].

The three main aspects of FabLabs are:

- Accessibility: FabLabs are open to everyone, and the access is not expensive.
- Open-source: the aim of FabLabs is that people collaborate and share ideas together.
- Similarity: The same numerical machines can be found in every lab. The typical available machines are 3D printers, laser cutters, CNC millers, and vinyl cutters.

By combining these three aspects, FabLabs have developed the concept of *Do It with Others*.

A FabLab is the ideal place for making prototypes, testing, and design. With numerical machines, it is possible to “turn data into things and things into data” [13]. Having numerical machines allows sending data to other countries and producing locally.



Table 1.1 provides a list of the available machines in the Makilab, their characteristics, and examples of what can be created with them. The water jet cutter is not part of the usual FabLab machines but it can be used in the Makilab and is nowadays more and more commonly found in FabLabs.

| Machine                                             | Dimensions                                                                 | Material                                                                                 | Examples                                                          |
|-----------------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| 3D printers<br>UltiMaker 2+<br>UltiMaker 3<br>Sigma | (l x w x h)<br>22.3 x 22 x 20.5 cm<br>23 x 19 x 20 cm<br>21 x 29.7 x 21 cm | PLA, 2.85 mm diameter                                                                    | Plastic made objects                                              |
| Laser cutter                                        | 90 x 60 cm (100W)<br>60 x 40 cm (80W)                                      | Glass, wood, plastic, paper, cardboard, leather, acrylic, plexi-glass, ceramic, no metal | Modeling, simple structures, boxes                                |
| Vinyl cutter                                        | 70 cm of width                                                             | Vinyl, copper tape, textile                                                              | T-shirt flex and lettering, stickers                              |
| CNC miller                                          | 600 x 840 x 140 mm                                                         | Wood (pine, MDF and others), aluminium, acrylic, ...                                     | Machining of parts, creation of molds, low relief                 |
| Water jet cutter                                    | 305 x 460 mm                                                               | Metal, glass, plastic, composites, tile, rubber, foam                                    | Machining of parts with a complex shape and out of hard materials |

Table 1.1: Specifications of the machines of the Makilab [23, 24].

## PLA

Polylactic acid, PLA, is the plastic that is used in the 3D printers of the MakiLab. Nowadays, PLA is one of the most consumed bioplastics in the world. Its applications range from 3D printing in maker spaces to various industries such as transportation, automotive, electronics, and biomedical. As the market for biopolymers continues to expand annually and new requirements arise, the demand for PLA also increases. However, PLA belongs to the seventh plastic category. It is currently not separated in the sorting centers and neither recycled [25]. Therefore the recycling of PLA is an important topic that should be assessed.

## 1.4 Use Case

The plastic currently used in the Precious Plastic machines primarily consists of household materials such as PP, PET, PS, HDPE or LDPE. For this project, it is crucial to identify a use case or cases corresponding to one or several plastic types, with the aim of positively

impacting plastic recycling in Belgium and more specifically in Louvain-la-Neuve. From the given context, there are two potential ways for having an impact. First, by focusing on the plastics that are wrongly sorted by citizens in public spaces, such as take-away food containers (Figure 1.8a). This case applies well to this student city where take-away food is consumed in large quantities (see Appendix A). Secondly, by targeting PLA which is commonly used in the 3D printers owned by the MakiLab or others (Figure 1.8b).



(a) Take-away food containers [26].



(b) PLA objects [27].

Figure 1.8: Use cases

### Plastic collection

The first use case involves collecting plastic used by restaurants in Louvain-la-Neuve for their take-away food. A comprehensive investigation revealed that for some restaurants, take-away food accounts for half of their sales, with food containers primarily made of PET, PP and PS materials. The collection of these containers relies strongly on the willingness of citizens to bring their plastic waste to designated trash bins in Louvain-la-Neuve. To assess whether people would be inclined to separate this plastic waste from the regular PMD trash bins, a survey was conducted (see Appendix A). The survey results indicate that 97% of the students residing in Louvain-la-Neuve are willing to do this separate collection, mainly driven by ecological reasons. Furthermore, 86% of the students are willing to bring these plastic containers to a specific trash bin if it's conveniently located. Among them, 50% are willing to clean the containers before depositing them in the trash bin. Plastic containers collection could be done with one or several specific bins placed in the street, or through the setting of a deposit system in collaboration with the city's restaurants.

For the second use case, plastic can be collected from the Louvain-la-Neuve's FabLab where five 3D printers are available for the students and general public use. The PLA waste is composed by the failed prints, the supports and adhesion plates that are created only to help the printing but also by the successful prints that are not needed or wanted anymore.

## Chapter 2

# State of the Art

### 2.1 Principle of Shredding

A shredder is used to reduce the volume of an object [28]. There are various types of shredders: industrial shredders can be used for recycling and product destruction, paper shredders can cut sheets of paper into strips or fine particles, scrap metal shredders reduce the size of scrap metal, and wood chippers produce wood chips [29].

Shredding can be defined as the set of actions leading to the division of a solid mass into cuts of smaller dimensions. It is done by applying external mechanical constraints and therefore increasing the free energy of the material, which will transform into surface energy, enabling the cutting.

When a material is deformed, the deformation can either be elastic (linear) or plastic (non-linear) as shown in Figure 2.1. A plastic deformation is irreversible and the material can not recover its original shape. When the constraint is greater than a critical value (called yield strength), the deformation becomes plastic. And when it is greater than the fracture strength, the material breaks. The applied constraints are a consequence of contact forces that can be of different types: compression, shear, torsion, flexion, traction and friction.

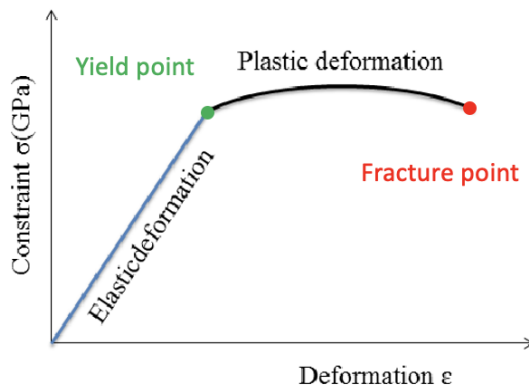


Figure 2.1: Stress-Strain curve [30].

### 2.2 Types of Shredders

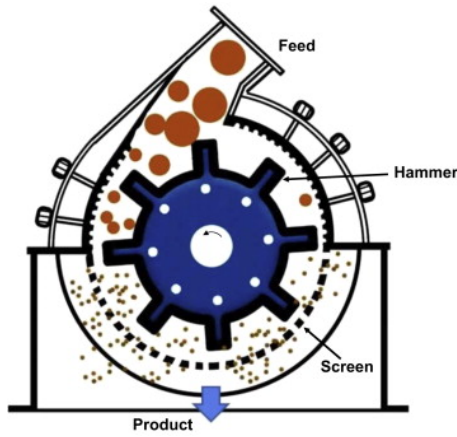
There are several types of shredders that will fit the needs of different materials and types of constraints. In order to shred plastic,

a blade shredder as presented by Precious Plastic is often considered, and shear stresses are used. However, as the steel used for the blades is quite difficult to replace, it is interesting to consider other types of shredders [31].

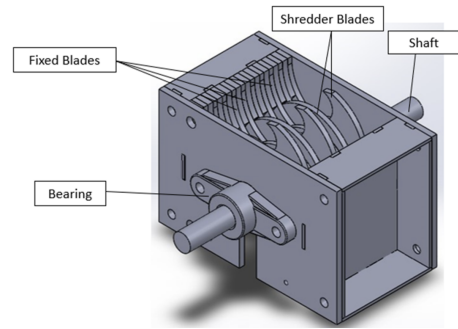
Shredders are here classified according to the size of the outgoing flakes they produce.

### Large Cut Shredders

The **hammer mill shredder** is made of swinging metal bars called hammers. They are fixed to a high-speed rotor and shred the material through impacts. It is a simple process that can be adapted to perform different operations like shredding but also crushing or pulverizing [32]. This kind of shredder is used for shredding all types of cereals and dry products. It also allows grinding hard materials like stone, rock, or glass [33]. Figure 2.2a illustrates the hammer mill.



(a) Hammer mill [34].



(b) Blade shredder [34].

Figure 2.2: Large cut shredders.

The **blade shredder** uses the rotor-stator principle to shred the material. Both parts are composed of several blades that impose a shear deformation on the material. The shredding process occurs when the shaft and the blades rotate. Figure 2.2b shows an illustration of the blade shredder. It is mainly used for shredding soft materials that have fibers, like vegetables, plants, plastics, and paper.

The **universal shredder** is, like the hammer and blade shredder, a single-shaft crusher. It is special because the rotor-stator couple can be changed easily (blades, hammers, disks). It works at high speed and can be used for pre- and post-shredding. A large range of materials can be cut by the universal shredder thanks to its flexibility: paper, files, data media, textiles, wood, cables, plastics, packaging.

### Small Cut Shredders

The small cut shredders produce flakes with size range from 10 to 1000  $\mu\text{m}$ . All the technologies used to obtain small flakes have the same action mode. They use impact crushing forces and are suitable for shredding soft materials. There are two main types of small cut shredders: the free grinding body mills and the mills without free grinding media.

### Extra-Small Cut Shredders

The extra-small cut shredders produce flakes with size range from 5 to 10  $\mu\text{m}$ . The forces used to obtain extra-small flakes are compression, shear, and impact.

### Choice of Shredder

Let's see which type of shredder would better suit the need for shredding plastic. Firstly, flakes should be around 1mm big so the choice goes to a large-cut shredder. Secondly, the universal shredder is complex and will not be chosen despite its effectiveness in shredding plastic. Indeed, the goal being to build a shredder that is easy to manufacture, it is preferable to avoid the complications associated with a versatile shredder. The choice narrows down to the hammer and blade shredders. According to the literature, the blade shredder is commonly used for plastic shredding. It uses shear forces and is well-suited for soft materials like plastic. On the other hand, the hammer shredder relies on impact forces and is more suitable for hard materials. Therefore, the decision is to use a blade shredder, following the example of Precious Plastic.

## 2.3 The Precious Plastic Shredder

This section provides an overview of the various components of the Precious Plastic shredder (Figure 2.3) and describes how each part is manufactured.

### 2.3.1 The Shredding Box

Figure 2.4 presents a detailed illustration of the shredding box, highlighting the names of its distinct components. The manufacturing details and materials used for each part are described in Table 2.1, following the specifications provided by Precious Plastic.

**Required material:** Steel sheets of 3, 5 and 6 mm thickness, a meshed grid, 2 bearings, 4 bolts for the bearings, 2 long bolts for the fixed blades, 8 bolts for the shredding frame, 4 bolts for the sieve supports.



Figure 2.3: Precious Plastic shredder [12].

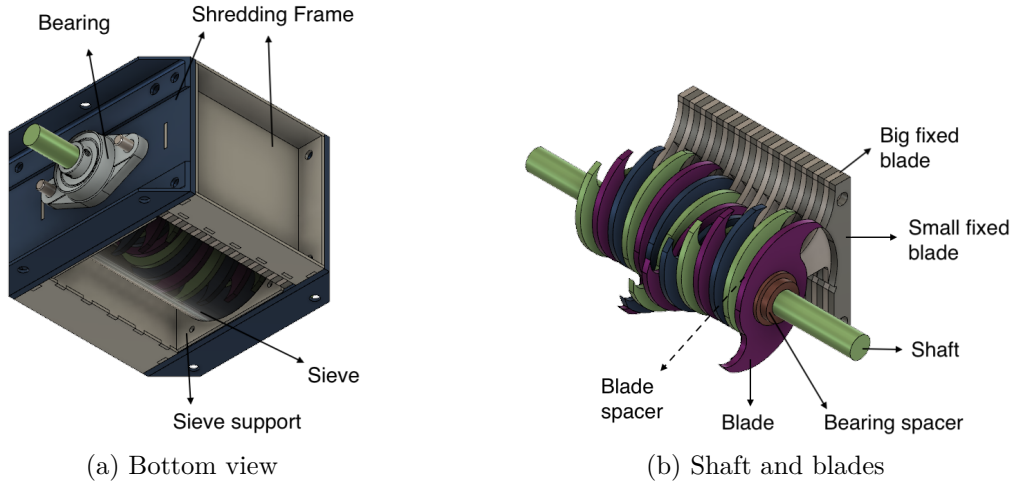


Figure 2.4: Detailed view of the shredding box [12].

| Piece(s)                                             | Precious Plastic fabrication                                    | Material |
|------------------------------------------------------|-----------------------------------------------------------------|----------|
| Blades, blade spacers, fixed knives, bearing spacers | Laser cutter or sander (for steel), grinding                    | Steel    |
| Shaft                                                | Machining lathe                                                 | Steel    |
| Shredding frame, sieve supports                      | Laser cutter or sander (for steel), drilling, welding, grinding | Steel    |
| Sieve (mesh grid)                                    | Welding                                                         | Steel    |

Table 2.1: Shredding box.

### Blades

Figure 2.5 illustrates a drawing of the blades of the Precious Plastic shredders, along with its dimensions (provided in mm). The shredder features a single shaft with 14 blades on it.

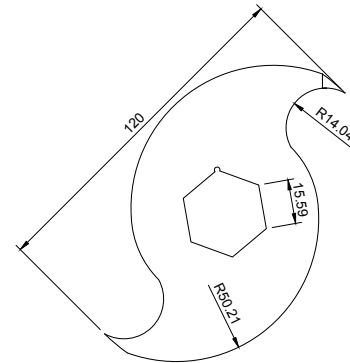


Figure 2.5: Plans of the Precious Plastic basic blade [12].

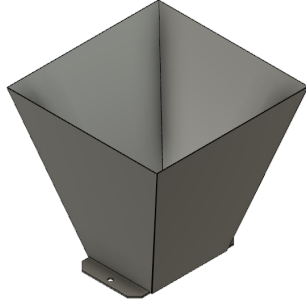
### 2.3.2 The Hopper

The required fabrication processes for the hopper are summarized in Table 2.2, while Figure 2.6a provides an illustration of the hopper.

**Required material:** Sheet metal, 2 bolts.

| Piece(s) | Precious Plastic fabrication              | Material    |
|----------|-------------------------------------------|-------------|
| Hopper   | Metal cutting (sawing), grinding, welding | Sheet metal |

Table 2.2: Hopper



(a) Hopper



(b) Framework

Figure 2.6: Hopper and frame [12].

### 2.3.3 The Frame

The required fabrication processes for the frame are summarized in Table 2.3, while Figure 2.6b provides an illustration of the frame.

| Piece(s) | Precious Plastic fabrication              | Material    |
|----------|-------------------------------------------|-------------|
| Frame    | Metal cutting (sawing), grinding, welding | Sheet metal |

Table 2.3: Framework

**Required material:** Steel tubes with a square (hollow) section.

### 2.3.4 Power Supply

The power supply of the shredder is shown in Figure 2.7. According to Precious Plastic, the motor should have a minimum nominal power of 1.5 kW and a minimum nominal torque of 300 Nm for the shredder. The desired rotation speed for the shredder is approximately 70 rpm. If the motor has a higher rotation speed, a reduction system can be incorporated to decrease it accordingly. The electronic box contains all the necessary wiring and devices for motor control. A device for reversing the motor rotation can be included in this box.

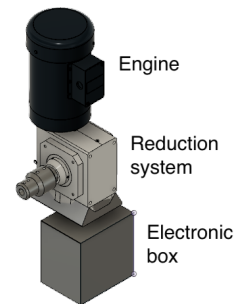


Figure 2.7: Power supply [12].

### 2.3.5 Improvements Made in the Shredder Pro

Precious Plastic designed a new shredder named *the Shredder Pro*. It is a double-shaft shredder with a nominal power and torque of 3-4 kW and 1.1-3 kNm, respectively, and an output speed of 15-25 rpm. The shredder pro is capable of effectively shredding various types of plastics (such as HDPE, PP, PS) in any shape, ranging from 0.7 to 12 mm in thickness.

This new shredder is very robust, reliable, and easy to clean compared to the previous one. It features adjustable meshes that enable the shredder to handle both the shredding and granulating (further refining and reduction of materials) phases commonly found in industrial shredding systems. However, when it comes to granulation, it is not as efficient as a dedicated industrial granulator. On the downside, this new shredder is more challenging to construct than the previous model. It needs access to suitable machinery and expertise, as well as a high-powered motor. This renders the shredder pro slightly more difficult to assemble. Considering the project's objective of creating a shredder that can be easily constructed in a FabLab, the primary focus of this project is on the basic shredder model.

## 2.4 Properties and Recycling of Plastic

Table 2.4 summarizes the properties of some considered plastic types. The density, Ultimate Tensile Strength (maximum stress that a material can withstand while being stretched or pulled before breaking), Melting temperature and Young modulus (measures the tensile or compressive stiffness, corresponds to the slope of the linear part of the stress-strain curve, Figure 2.1) are given.

| Material | Density<br>[g/cm <sup>3</sup> ] | $\sigma_{UTS}$ [MPa] | Melting temperature [°C] | Young modulus<br>[GPa] |
|----------|---------------------------------|----------------------|--------------------------|------------------------|
| PET      | 1.29 - 1.39                     | 55 - 60              | 200 - 260 [35]           | 2.8 - 3                |
| HDPE     | 0.952 - 0.965                   | 26 - 31              | 130 - 137                | 1.07 - 1.09            |
| LDPE     | 0.917 - 0.932                   | 13.3 - 26.4          | 98 - 115                 | 0.172 - 0.283          |
| PP       | 0.897 - 0.906                   | 26 - 50              | 151 - 167                | 1.18 - 1.41            |
| PS       | 1.04 - 1.05                     | 35.9 - 51.7          | 177 - 280 [35]           | 3 - 3.5                |
| PLA [36] | 1.00 - 3.41                     | 20 - 30              | 135 - 181                | 1.06                   |

Table 2.4: Properties of plastics [37].

### Polyethylene Terephthalate (PET)

PET has a good strength, lightness and is safe for being used in food packaging [38]. More precise mechanical properties are given in Table 2.4. PET is the only plastic that can be recycled in a closed loop, specifically in a bottle-to-bottle recycling process.



This means that PET bottles can be recycled and transformed into new PET bottles, promoting a circular economy for this particular plastic. It is still safe for being used in food packaging after recycling [38].

Even though PET can be recycled at 100%, the recycling loop of PET is not infinite. Recycling degrades the mechanical and thermal properties of PET due to factors like moisture absorption, biological contamination, oxidation, thermal degradation, and high temperatures. Chemical and mechanical degradation contribute to the deterioration of chemical resistance and melt viscosity, which can lead to brittleness and loss of melting elasticity behavior [39].

### **High-Density Polyethylene (HDPE) and Low-Density Polyethylene (LDPE)**

HDPE has a high strength-to-density ratio [40] and requires thus a high force for being shredded compared to other plastics. LDPE is very flexible and can be hard to shred because it gets folded easily between the blades. The properties of HDPE and LDPE are given in Table 2.4.

According to a study [41], the mechanical properties of recycled HDPE and LDPE plastic waste are similar to those of their virgin materials. The study revealed that the recycled HDPE exhibits superior tensile properties and impact resistance than recycled LDPE, although they are approximately 10% lower than their respective virgin polymers. There is a significant potential for recycling HDPE and LDPE [41].

### **Polypropylene (PP)**

Polypropylene offers numerous advantages: it is affordable, food-safe, tear-resistant, fatigue-resistant, and chemically inert. It serves as an excellent electrical insulator and can be used as an alternative to PVC. However, it is brittle at low temperatures and sensitive to UV radiation [42]. Its properties are similar to PE but slightly harder and more heat-resistant (see Table 2.4).

The average results of a study [43] indicates that the tensile properties of virgin PP and recycled PP, as well as the mixtures of both, are comparable. However, when it comes to impact properties, it was observed that the recycled polymers absorb less energy compared to virgin polypropylene. Therefore, while recycled polypropylene can be a suitable replacement for virgin polypropylene in applications that primarily involve tension stresses, it may not be as suitable for applications subjected to impact stresses.

### **Polystyrene (PS)**

Polystyrene, whether in solid or foamed form, has distinct mechanical properties. It is hard and brittle, making it rigid but prone to breakage under high stress. With a

relatively low melting point, it can be easily molded and formed when heated above its glass transition temperature. Polystyrene also exhibits flow behavior, allowing for extrusion and shaping into intricate details. However, it has poor barrier properties against oxygen and water vapor.

Contrary to a common misconception, polystyrene is actually highly recyclable and has a significant potential for circularity. It can be recycled using similar methods as other plastics, including mechanical recycling and dissolution. PS has the ability to be recycled back into its original monomer, styrene, which is a unique characteristic. Through innovative chemical recycling processes, styrene can be recovered in high yields and maintained in a "virgin" state of purity [44].

### **Polylactic Acid (PLA) - Bio-Based Plastic**

The properties of PLA in Table 2.4 are the ones of 3D printed PLA. They depend on different parameters. The properties found in Table 2.4 correspond to an infill density of 40%, an extrusion temperature of 220°C, a raster angle of -45/+45 and a layer of thickness 0.1 mm [45, 46].

A study [47] shows that the tensile strength of recycled PLA is reduced by around 11% in comparison to virgin PLA. This decrease in tensile strength is a result of the thermal degradation of the PLA molecular chain that takes place during the injection molding process. The molecular chain breaks when exposed to heat during the processing stage.

### **General Properties of Recycled Plastics**

The specific properties of recycled plastics are primarily determined by the input stream and the process parameters employed during recycling, such as sorting, washing, and filter-based extrusion.

As mentioned above, the properties of most plastics are impacted when they undergo recycling, resulting in a process known as downcycling. Typically, a piece of plastic can be recycled approximately 2 or 3 times before its quality declines to the point of becoming unusable. Moreover, in each recycling cycle, additional virgin material is introduced to enhance the quality of the recycled plastic. This is done to ensure that the recycled product can compete with new, durable, and fresh goods in the market [48].

## **2.5 Engineering Design Methods**

An engineering design problem can be seen as a decision problem with an additional unknown. A decision is a choice that has to be made considering uncertain events and consequences. Engineering design is the creation of an unknown object that is better than the available choices. Therefore, the information does not have the same use in

engineering design and in decision-making [49].

Engineering design has a generative effect. It consists of three things: having a desired unknown object, introducing choice alternatives, and having rules. The different engineering design methods are presented thereafter [50].

### 2.5.1 Combination of Techniques or Objects

Engineering design by combination is an established approach that involves merging two existing and accessible solutions to create a new solution. This method reduces uncertainty and eliminates the need for redesigning the technical aspects before their combination. [51].

There are two types of combination methods: combination by reunion and combination by mutual adjustment [51]. The former combines two techniques or objects without modification. An example is a Swiss army knife where existing tools are assembled without modifying them. The latter includes the modification of the combined techniques or objects, such as a hammer that is build with wood and stone that have to be modified before assembling.

There are two main applications for this engineering design method: handiwork and emergency solution. Both are quite common, the latter consisting in the combination of available objects when access to the ideal solution is not possible. This method usually leads to more complex objects. It has the benefits to be intuitive and natural. However it has some limits; there are too many possible combinations and it does not favor a technical solution [51].

### 2.5.2 Systematic Engineering Design

Systematic engineering design is the most used design method nowadays. This method is distinguished by its clear and well-defined definitions of the objects being designed, this results in the minimization of uncertainties or unknowns involved in the process [52].

This method is based on functional analysis and uses functions. This implies that the needs must be defined precisely as wanted functions and not as technical solutions. Originality is an objective which means finding technical solutions that are not expected. In addition, there is an objective of having a good management of the design process implying that steps must be precise and controllable. In systematic engineering design, the part of unknown is decreased and rules about the needs are clearly set [52].

In systematic engineering design, there are three steps that can be done by different persons, helping the division of the work. Firstly, identifying functions that translate the needs. Secondly, looking for technical solutions. Thirdly, producing a physical design, called prototype [52].

## 2.6 Prototyping Methods

According to Kevin N. Otto and Kristin L. Wood, "A prototype is an artifact that approximates a feature of a product, service or system" [53]. There are different ways of building a prototype.

### 2.6.1 Iterative Prototyping

Iterative prototyping involves a continuous cycle of designing, creating prototypes, conducting tests, and refining various iterations of a product. It enables the sequential testing and refinement of a design and a prototype leading to a gradual achievement of the requirements. In addition, it promotes collaboration and is helpful to detect issues, manage uncertainties, identify errors and simplify parts. The performance of the prototype increases throughout the iterations, while the time to produce each iteration decreases [54].

There are five major benefits of using iterative prototyping rather than traditional methods. First, it is more efficient because the first working prototype is produced rapidly, enabling the engineers to identify problems and challenges that can not be easily foreseen during the design stage. Moreover, the major issues and flaws are identified early, minimizing the number of full redesigns and speeding the development process. Thirdly, as it relies on rapid prototyping technology such as CNC machine, laser cutters or 3D-printers, iterative prototyping has a low cost of product development. Fourthly, for every iteration, the prototype is thoroughly tested giving a good knowledge of which details of the design works well or not and reducing the probability of having defective products on the market. Finally, with iterative prototyping, the users are involved earlier in the process. Therefore, based on their feedback, the product can be made more user-friendly [55].

### 2.6.2 Evolutionary Prototyping

It is a variant of iterative prototyping in which the design is not replaced but only refined to transition into a final product. This type of prototyping can be preferred when the used resources must be minimized and the cost very low [54]. It is one of the most popular prototyping models. In which, the system is primarily split into several independent modules with required functionalities. This is especially suitable for large projects that can be easily broken down [56].

### 2.6.3 Parallel Prototyping

Parallel prototyping consists in designing several concepts, building them at the same time and finally comparing them. It is the preferred choice when the cost is flexible and exploration has more value. Parallel prototyping can lead to a lot of diversity [54].

# **Part II**

## **Design and Prototyping**

## Chapter 3

# Overview

Figure 3.1 shows an overview of the shredder as Precious Plastic builds it. The division in parts and sub-parts and the given names are the one that will be used throughout this whole part.

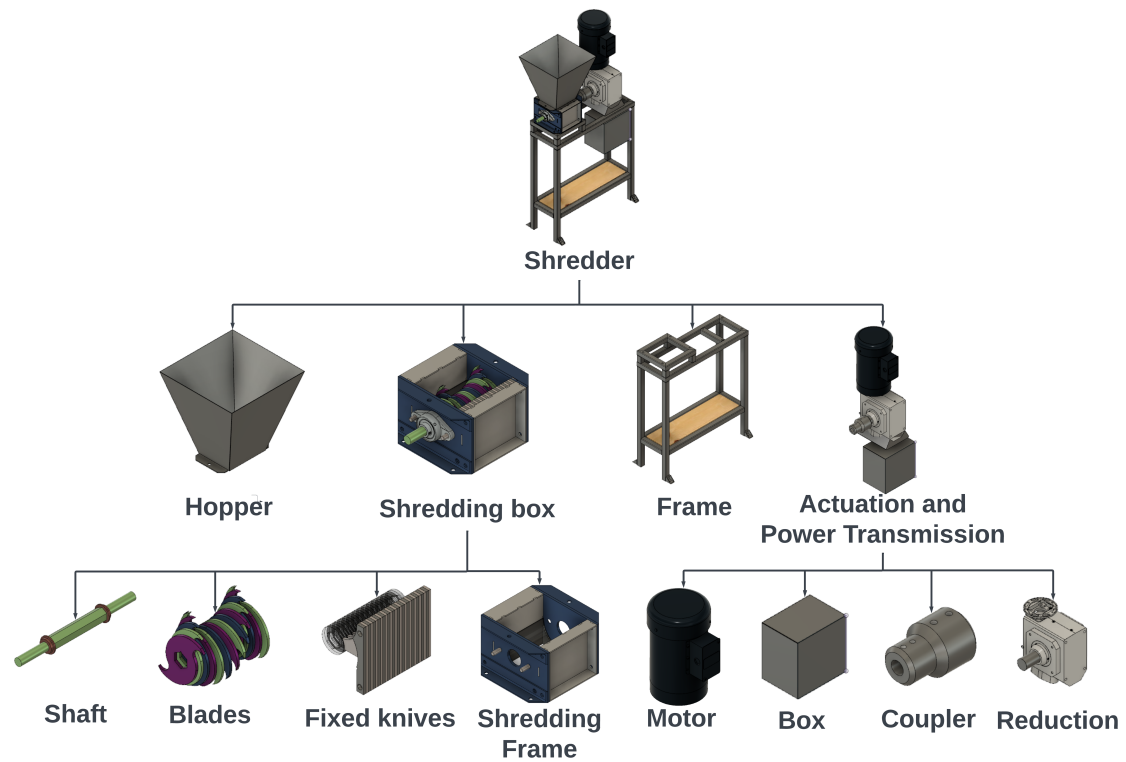


Figure 3.1: Shredder overview, division into parts and sub-parts.

### 3.1 Methodology

The design methods used for this project are systematic engineering design and combinations of techniques or objects if a part has to be reinforced with an existing object. For prototyping, the whole shredder is split into different parts (Figure 3.1) allowing the implementation of evolutionary prototyping. For each individual part or sub-part, iterative and parallel prototyping are used.

This project focuses on building a working prototype that should be flexible and easily disassembled for a simple change of parts if needed. It aims at being a research tool for future testings.

The methodology is to first analyse how each part is built by Precious Plastic based on the available blueprints and identify parts that can not be manufactured in a FabLab. Then the requirements and functions of these parts are identified and ideas of alternative ways to build them with the available machines are looked into. Afterwards, designs are produced and verified through scientific validation and the construction of scaled-down prototypes if needed. When validated, the parts are built and assembled. This process is illustrated in Figure 3.2 and will be applied to the different parts of the shredder in the chapters 4, 5 and 6. After this, Chapter 7 analysis the performances of the final shredder prototype.

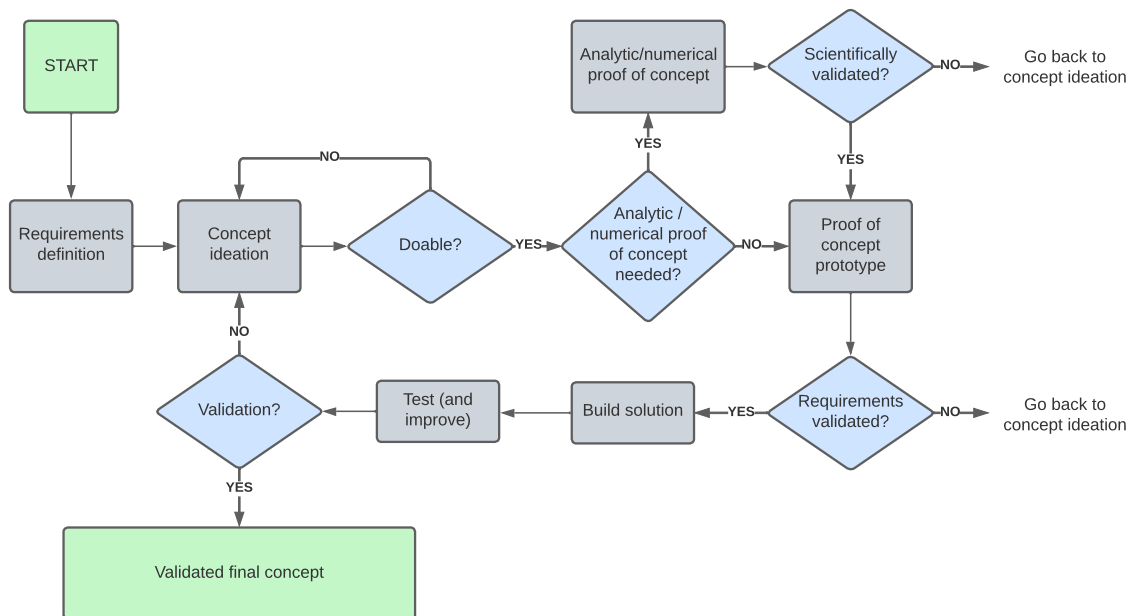


Figure 3.2: Flow chart design and prototyping process.

## 3.2 General Evolution of the Prototype

When the project started, a kit was already available (see Figure 3.3). It was composed of 14 blades, 14 small fixed knives, 13 blade spacers, 13 big fixed knives, 2 bearings, 2 small bearing spacers, 2 big bearing spacers, 2 side plates of the shredding frame and 1 partly hexagonal shaft.

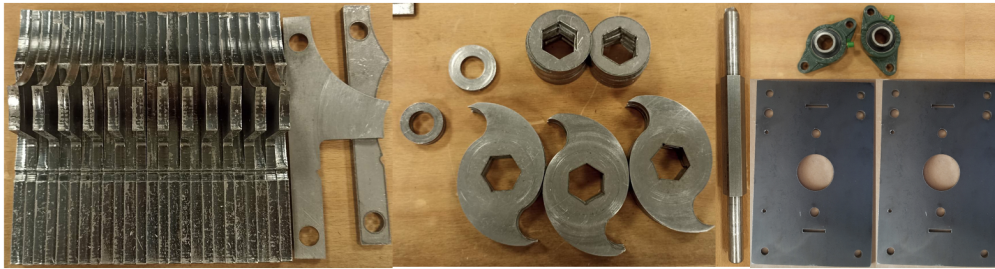


Figure 3.3: Starting kit.

This kit was completed with new parts to go towards a full shredder. The prototype evolved as the project progressed and 6 different versions were built.

### V1: Manual Shredding Box

The **objective** of this prototype was to have a functional shredder in order to conduct preliminary shredding tests on plastic to identify the potential difficulties. For building this prototype, a crank handle, a sieve and the missing sides of the shredding frame were added to the starting kit.

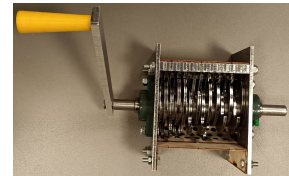


Figure 3.4: Manual Shredding Box (V1).

As it will be discussed in Section 4.1.4, multiple iterations were performed on the crank handle until the final version was achieved. The crank handle was the first manufactured part, which helped with becoming acquainted with the FabLab machines and the design and prototyping process.

The sieve is a grid beneath the blades that retains large plastic flakes in the shredder while allowing small flakes to pass through. Designing it for manufacturing in FabLab was challenging, and several iterations were made using different materials as explained in Section 6.3. An aluminum sieve manufactured using the CNC milling machine was finally chosen.

The two missing side plates of the shredding box, that are parallel to the shaft, play a crucial role in the box assembly as they determine the tightness of the bolts. Manufacturing them in wood has limitations because it is more prone to bending than steel. Indeed, in this first version, the tightening was inadequate because the two sides were tightened



differently, with the screws holding the fixed knives on one hand and two small wooden plates on the other hand. This tightening method has been revised during the building of the next version by incorporating large transverse screws.

The **key learnings** from this initial prototype were the understanding of the functionality and specifications of each component of the box, becoming familiar with the assembly process of the shredding box, and getting acquainted with the FabLab machines and the design and prototyping process.

### V2: Motorised Shredding Box

The **objective** of this prototype was to shred different types of plastic at various speeds and identify the ones that are the easiest to shred. A motorised actuation system was used in order to have a greater power than with a crank handle.

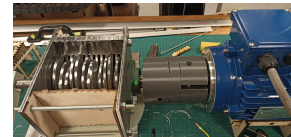


Figure 3.5: Motorised Shredding Box (V2).

A motor and a drive controller were purchased in this version of the shredder. The motor has a power of 2.2 kW (see Section 4.1.5) and the drive controller is used to vary the speed of the motor in order to experiment the impact of different rotation speeds. To connect the motor to the shredding box, a coupling system was designed. The challenging aspect of this part is ensuring that it fits perfectly on the two different shafts without needing to machine them.

It was quickly observed that in order to shred plastic, the engine needed to operate at a relatively high speed. The drive controller reduces the motor's frequency, resulting in a decrease in speed and power. To be able to shred plastic, a fast rotation is necessary, but this presents the disadvantage of causing the plastic parts to jump upwards instead of getting stuck between the rotating and fixed blades.

The **key learnings** from this prototype version were gaining knowledge about electric motors and drive controllers, as well as understanding their specifications. Additionally, the design of the coupling system provided valuable learnings about reinforcing a 3D printed component to withstand substantial efforts (as discussed in Section 4.2.1).

### V3: First POM Elements

The **objective** of this prototype was to analyze the possibility of replacing the steel elements with polyoxymethylene (POM), a robust plastic suitable for laser cutting in a FabLab.



In this version of the prototype, a few blades and fixed knives, and a side plate were manufactured in POM. Different shapes

Figure 3.6: First POM Elements (V3).

of blades were created to assess the tip shape's impact on the shredding performance (see Section 5.4.1). To make the comparison between POM blades and steel blades easier, the shredding box was divided into two parts (Figure 3.6). Both manual and motorized tests were conducted on this prototype.

The **key learning** was that POM blades are effective in shredding plastic, but those with sharp tips showed signs of rapid deformation. Furthermore, it was evident during the evaluation of various blade shapes that possessing a sharp edge and ensuring the blades' grabbing function are crucial factors. In addition, it was identified that replacing steel by POM for the sides of the shredding frame was doable.

#### V4: Complete Shredder

The **objective** of the fourth version of the prototype was to develop a frame and a hopper (Figure 3.7).

The frame was designed to provide structural support and hold all the components together. It is crucial for stabilizing the motor and the shredding box, as they experience significant stress when the motor is activated. The frame was constructed using the CNC milling machine and is assembled with a system of pins that allows fast and easy disassembly and modifications if needed (see Section 6.4). Prior to developing the frame, clamps were used for fixation during testings.

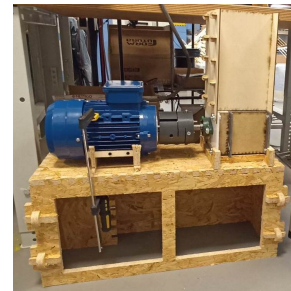


Figure 3.7: Complete Shredder (V4).

As previously mentioned, the high rotational speed of the blades causes the plastic to jump upwards. To address this issue and ensure that the plastic remains inside the shredding box, a hopper was implemented. The hopper also serves as a safety measure to prevent hands, hair, etc. from going into the shredding box. More information about the hopper can be found in Section 6.5. This fourth version of the shredder enabled to conduct new tests in a safer manner.

The **key learnings** of this particular version includes the utilization of pins for assembling different parts and the application of CNC with a new material called OSB. These learnings likely contributed to advancements in the assembly process.

#### V5: POM Shredding Box

After testing the POM blades in version 3, it was determined that a reinforcement of its tips was necessary. Various ideas were explored, and the **objective** of this prototype was to test the concept of using aluminum claws to protect the blades' tips (see Section 5.4.2). After validating the concept through testing on a few blades, all the blades were produced in a similar manner.

The fixed knives and blade spacers made of POM had already been tested in version 3 of the prototype and were fully developed in this version. The small fixed knives were reinforced with aluminum, following the same principle as for the blades. The sides of the shredding frame were laser-cut from POM. To prevent their bending on the side facing the stator, a wooden structure composed of small boxes was added. Additionally, a new sieve was created with the exact width to accommodate the new blades (Figure 3.8).

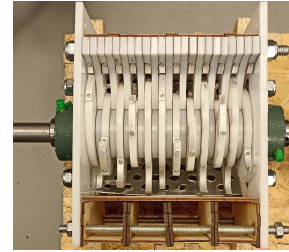


Figure 3.8: POM Shredding Box (V5).

This version is the one that was eventually selected. Hence different types of plastic were tested on this shredder prototype and the steel shredder was reassembled to compare the performances of shredders with POM and steel blades. Quantitative tests were also conducted to analyze the mass flow rate, the wear on the blades and fixed knives, and the quality of the resulting flakes. It was observed that the shredder frequently experiences jamming issues. The use of a reduction system would help avoiding this problem. Such a system would decrease the speed and increase the torque of the shredder. See Chapter 7 for further information.

The **key learning** from this version was that a shredder with POM components and some aluminum reinforcements functions effectively. The blades demonstrated suitable sharpness for cutting plastic and resistance to high loads. However, it was observed that certain parts experienced wear and that frequent jamming incidents occurred.

### V6: Reduction System

The **objective** of this version was to design a reduction system in order to increase the torque transmitted to the shredder shaft. The reduction system involved utilizing a belt and two pulleys (Figure 3.9). The pulleys were crafted from laser-cut wood, and their individual layers were glued and screwed together (see Section 4.2.2). The frame underwent a redesign to ensure that the two shafts were appropriately spaced and that the shredding box could smoothly slide over the frame, allowing a proper stretching of the belt.



Figure 3.9: Reduction System (V6).

While the system initially performed well, it encountered limitations when transmitting a high power. At higher power levels, the belt ceased to be driven by the small pulley, and after a while the small pulley itself cracked. These challenges revealed the need for further improvements in the reduction system.

**Key learnings** were gained regarding the complexities of manufacturing a FabLab-made reduction system, including the machinable materials and the stretching of the belt.

## Chapter 4

# Actuation and Power Transmission

### 4.1 Actuation

#### 4.1.1 Requirements definition

|             |                                          |
|-------------|------------------------------------------|
| Function    | Actuate the shredding box.               |
| Objective   | Simple conception and minimum cost.      |
| Constraints | Generate enough power to shred plastic.  |
|             | Enable changes in rotation speed.        |
|             | Enable to change the rotation direction. |
|             | Standard system.                         |

Table 4.1: Requirements for the design of the actuation system.

#### 4.1.2 Concept Ideation

##### Crank Handle

As a first step, the shredding box was powered manually. The initial idea involved 3D printing a crank handle in three separate components: a handle, a lever arm, and a connecting part for linking it to the shredder shaft. Alternatively, the lever arm could be constructed from multiple layers of laser-cut wood, which was preferred due to the faster and more cost-effective nature of laser cutting compared to 3D printing. A second idea proposed using the Shaper Origin<sup>1</sup> milling machine to create the lever arm from a single wooden plate with a thickness of 20 mm, eliminating the need for gluing several layers of thinner wood. A third idea suggested utilizing a standard metal bar for the lever arm, combined with a 3D-printed connecting part for the assembly with the shredding shaft. This approach eliminated the requirement for a separate handle. Finally, the idea was to use aluminum for the lever arm, resulting in a two-part crank handle composed of the

---

<sup>1</sup>A freehand CNC milling machine that indicates and corrects the milling trajectory.

lever arm and the handle. The connecting part was unnecessary, as a screw was used to attach the handle directly to the shaft.

### Motorized system

As a second step, the shredder was motorized. The two options were to either use a single phase or a three phase motor. When doing some research, it was identified that three phase power supply was suitable for high loads such as electric motors and single phase motors are better for loads such as lighting and heating [57]. In addition, single phase motors can directly be connected to the plug and their rotation direction is difficult to change. In opposition, three phase motors' spin direction is easy to change and they need an additional device to convert the single phase supply into a three phase supply. This device is a drive controller which is used to control the behavior of an electric motor [58]. It can start and stop a motor, make it turn forward and in reverse, control its rotation speed, etc.

#### 4.1.3 Analytical Proof of Concept

##### Motorized system

Precious Plastic advises working at a rotation speed of 70 rpm. They also recommend using a motor with a power of approximately 2.2 kW. Based on Equations 4.1 and 4.2, this corresponds to a torque of 300 Nm.

$$P = T \cdot \omega \quad (4.1)$$

$$\omega = \frac{2\pi N}{60} \quad (4.2)$$

where :

- $P$  is the power delivered by the motor in  $[W]$
- $T$  is the torque of the motor in  $[Nm]$
- $\omega$  is the angular velocity of the motor in  $[rad/s]$
- $N$  is the angular velocity of the rotor in  $[revolution/min]$

To compute the required torque for plastic shredding, the inequality of Equation 4.3 was used. It asserts that the force applied to the plastic by one blade must exceed the ultimate shear strength of the plastic.

$$\frac{F_c}{S} \geq \tau_r = \frac{\sigma_{UTS}}{\sqrt{3}} \quad (4.3)$$

where :

- $S = w.t$  is the cutting area in  $[m^2]$

- $t$  is the thickness of the plastic in  $[m]$
- $w$  is the width of the cutting edge of the blade in  $[m]$
- $\tau_r$  is the ultimate shear strength of the cut material in  $[Pa]$
- $\sigma_{UTS}$  is the ultimate tensile strength of the cut material in  $[Pa]$

The minimal required cutting force for one tooth is:  $F_{c,min} = \frac{\sigma_{UTS}}{\sqrt{3}} S$

The corresponding exerted torque on the tip of the blade is:

$$T = F_{c,min} \frac{D}{2} \quad (4.4)$$

where  $D$  is the diameter of a blade.

The ultimate tensile strength,  $\sigma_{UTS}$ , of the considered plastic types are provided in Table 2.4. PET has the most critical value, with an upper limit of  $\sigma_{UTS} = 60$  MPa. The Precious Plastic blades have a width of  $w = 5$  mm and a diameter of  $D = 120$  mm. It was assumed that the shredder should be able to cut plastic with a maximum thickness of  $t = 3$  mm.

This results in a torque of  $T = 31.18$  Nm. By following the advice of Precious Plastic to use a rotation speed of 70 rpm, the corresponding required power is 228.54 W.

The torque and power requirements were initially calculated for a single tooth. However, due to the random arrangement of the blades (as discussed in Section 6.3.1), there may be instances where up to three blades need to shred plastic simultaneously. Consequently, the torque and power requirements must be multiplied by three. This adjustment yields torque and power values of 93.54 Nm and 685.62 W, respectively.

Furthermore, a margin of 25% for losses due to friction and heat among others must be taken into account [59], the power requirement can adjust accordingly:

Adjusted Power Requirement = Power Requirement / (1 - Loss Margin)

The adjusted Power Requirement is about 915W.

Since most motors typically operate at speeds of 1500 rpm or 3000 rpm, a gear reduction system would be necessary to achieve the desired speed of 70 rpm. The gear reduction system may introduce additional losses. It is challenging to provide an accurate estimation of the power loss without specific details about the gear system being used. A motor with a slightly higher power rating should be considered to compensate for potential power losses in the gear system. A motor of at least **1 kW** is thus advised.

#### 4.1.4 Proof of Concept Prototype

##### Crank Handle

A proof-of-concept prototype was built and tested for all four ideas. Figure 4.1a depicts the prototype corresponding to the first idea, which functioned effectively for shredding LDPE but broke when used with PLA. Figure 4.1b illustrates the prototype for the second idea, aiming for increased durability through a one-piece lever arm made from a single wooden piece. However, it broke when subjected to HDPE, as the applied force was not aligned with the wood's grain direction. The third idea, shown in Figure 4.1c, featured a 3D-printed connecting part reinforced with hot glue. Despite the reinforcement, it failed under the exerted loads. The fourth idea is represented in Figure 4.1d, where the squared hole serves as a placement and securing point for the shredding shaft. A scrap aluminium bar was used so only the holes for the handle and the shaft have been machined with the CNC.

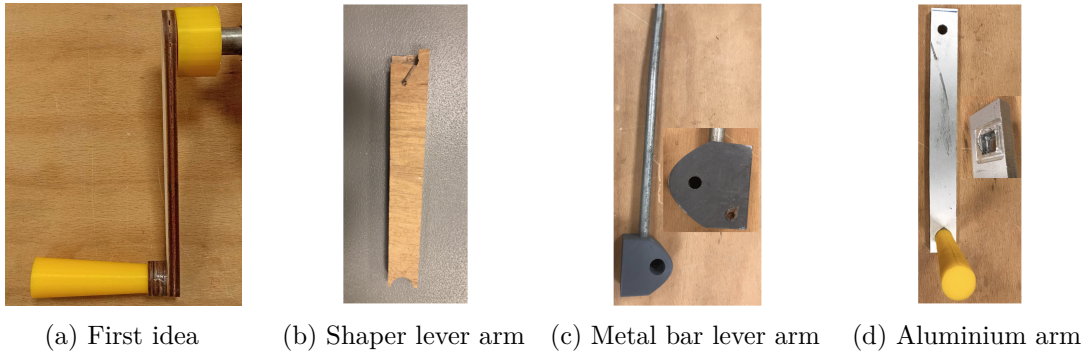


Figure 4.1: Crank handle proofs of concept.

#### 4.1.5 Final Concept

##### Crank Handle

The selected final concept is the crank handle with the lever arm made out of aluminum. It fastens well to the shredder shaft through the tightening of a screw (see Figure 3.4).

##### Motorized System

###### *Electrical Scheme*

Electrical terminals and cables were utilized to establish connections between the controller, plug, and motor. First, an old charging cable was employed for the link between the plug and the controller. Subsequently, a three-phase cable from a washing machine was used to connect the controller and the motor. Both used cables are not shielded and have a cross section of  $2.5 \text{ mm}^2$ . Figure 4.2 illustrates the configuration of the connections

between these three components.

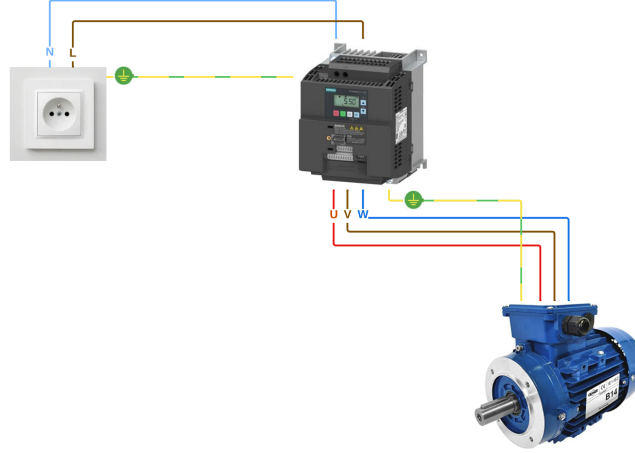


Figure 4.2: Electrical cabling scheme.

#### *Motor Choice*

The needed requirements for the motor are presented in Table 4.1. To select the motor, the advice of Precious Plastic was followed and a motor of 2.2 kW was chosen. This choice was also influenced by the experiences of the Precious Plastic community, where motors with power ratings of 2.2 kW and higher have been successfully used [60].

For this power, the standard motors are three-phase motors. Indeed, three-phase supply is adequate for this kind a large loads. In addition, changing the rotation is easier with a three phase motor and is part of the requirements for the actuation system.

The specific motor model selected is an asynchronous three-phase motor operating at 230/400 V. It possesses a power rating of 2.2 kW and operates at a speed of 3000 rpm. For further details, please refer to the following link: Cerem Motor Datasheet.

#### *Drive Controller Choice*

In this case, as a three-phased motor was selected, using a drive controller was a need to go from a single phase supply coming from the plug to a three-phase supply going into the motor. Moreover, in an experimental point of view, controlling the rotation speed of the motor is interesting. For the shredder application, it may also be useful to use the motor in reverse in case the shaft gets stuck in too thick plastic pieces.

The selected drive controller is a Siemens variable-frequency drive. Its data-sheet can be



found in Appendix B. This drive controller exceeds the performance requirements for its intended use. The reasons for choosing an over-performing device are the experimental and reliability needs. This latter was much needed because the project was short timed and could not afford to be delayed by a quality or delivery problem. Once the testing stage of the project is done and the required working speed is fixed, there is no need to use such a drive controller anymore, one can buy a cheaper drive controller and a reducer.

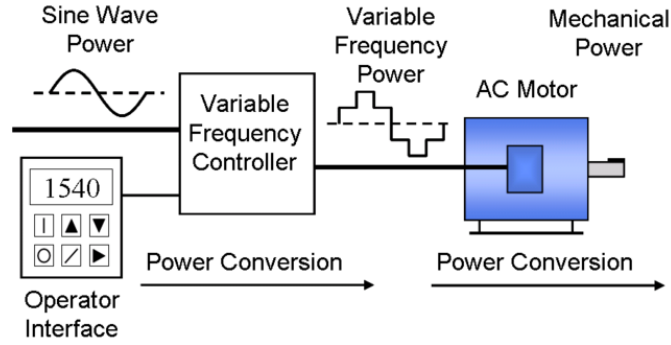


Figure 4.3: Variable-Frequency Drive [61]

As illustrated in Figure 4.3, a variable-frequency drive controls the speed of the motor by varying the frequency of its input power [62]. Equation 4.5 shows the relations between the angular velocity, the frequency and the power. They are directly proportional.

$$\omega = 2\pi f \quad P = \omega T \quad (4.5)$$

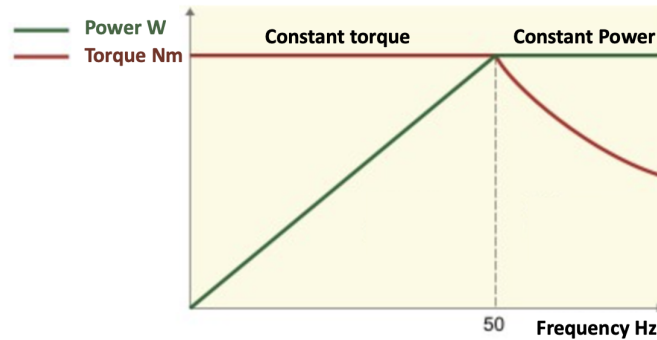


Figure 4.4: Power and torque evolution with frequency [61].

There are several potential relations between the motor power and torque and the frequency. Changing the drive controller's mode allows to select the wanted relation. In this project, the basic mode of the drive controller was used. Figure 4.4 shows the

evolution of the motor torque (in blue) and power (in red) with the frequency. While this latter is under the rated frequency of 50 Hz, the torque is maximum and constant ( $T = 7 \text{ Nm}$ ) and the power is linearly increasing. When the motor works above the rated frequency, the torque is decreasing and the power is maximum and constant ( $P = 2200 \text{ W}$ ).

## 4.2 Power Transmission

### 4.2.1 Coupling System

#### Requirements

|             |                                                     |
|-------------|-----------------------------------------------------|
| Function    | Connect the shredding shaft to the motor shaft.     |
| Objective   | Simple conception and minimum cost.                 |
| Constraints | Enable good alignment and tightening of the shafts. |
|             | Resist to loads, vibrations and chocks.             |
|             | Having a direct coupling.                           |

Table 4.2: Requirements for the design of the coupling system.

#### Concept Ideation

The coupling system would be manufactured using 3D printers. To reinforce the parts, some screws would be added, preventing the layers of the 3D-printed object from coming off. For the motor part of the coupling system, the shaft includes a pin that can be used to ensure the tightness of the 3D-printed part on the shaft. For the shredder part of the coupling system, the shaft has a squared tip that can be used.

The first idea was to manufacture a rigid coupling system similar to the one used by Precious Plastic (see Figure on the right). It is fastened to the shafts using screws (one per shaft) that apply pressure on a flat surface of the shafts. The system must have the appropriate diameter for each shaft and a flat surface on each shaft is needed.



This solution could easily work for the shredder side with screws pushing on the squared part of the shaft. However, there is no flat surface on the motor shaft.

A second idea was to utilize a flexible system (see Figure on the right). It is designed to have some flexibility, correcting the potential misalignment of the shafts.



In this second idea, the tightening is done using one screw per shaft. The screw is positioned perpendicularly to the shaft, exerting radial pressure to fasten the component tightly onto the shaft. This method is suitable for the motor shaft. Additionally, incorporating a hole to accommodate the motor pin further enhances the effectiveness of the

fixation. However, this approach may not be adequate for the shredder shaft, as it lacks a pin and due to the relatively low friction between plastic and metal surfaces. a layer of high-friction material can be introduced between the shaft and the coupling system, ensuring a better connection.

### Proof of Concept Prototype

It was decided to construct a coupling system based on the second idea. After conducting some tests, the motor side of the coupling system was validated as it was well tightened on to the motor shaft, thanks to the presence of the pin. However, the initial attempt for the shredder side, with only one perpendicular screw, did not provide sufficient tightness around the shredder shaft. Even increasing the friction using an intermediate material did not resolve the issue. Consequently, a new version of the shredder side was designed, incorporating screws and bolts for tightening onto the squared part of the shaft. This second iteration of the coupling system draws inspiration from the first presented idea and has been successfully validated.

### Final Concept

The final configuration of the coupling system is depicted in Figure 4.5. It performs well at low speed but its strength is limited to transmitting a maximum power of 440 W. Indeed, when pushing it to its limits, it fractured at a rotation speed of 630 rev/min corresponding to a frequency 10.5 Hz. It cracked at the pin corner, where the forces are concentrated. As a consequence, this concept should be further developed, maybe with new printing parameters or the use of other materials and manufacturing machines.

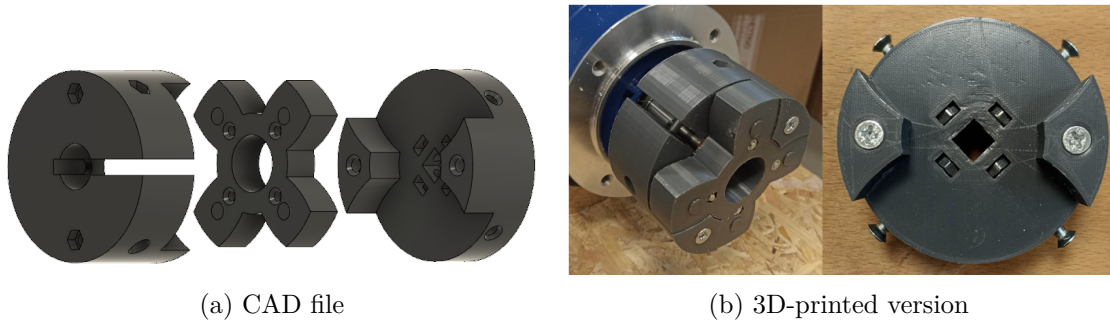


Figure 4.5: Coupling system, final concept.

### 4.2.2 Reduction System

#### Requirements

The requirements can be found in Table 4.3.

|             |                                                                                                                                    |
|-------------|------------------------------------------------------------------------------------------------------------------------------------|
| Function    | Reduce the speed and increase the torque transmitted from the motor to the shredder.                                               |
| Objective   | Simple conception and minimum cost.                                                                                                |
| Constraints | The system should connect with the shafts of the motor and the shredding box.                                                      |
|             | The initial speed of the motor is 3000 rpm (nominal motor speed). The final output speed should be 70 rpm (wished shredder speed). |
|             | The initial torque of the motor is 7 Nm. The minimal required output torque is 100 Nm.                                             |

Table 4.3: Requirements for the design of the reduction system.

#### Concept Ideation

During the concept ideation phase, two main options were considered. The first one was to purchase a reduction system specifically adapted for the motor. A corresponding gearbox for the motor is described in Appendix C. The second option involved the use of a gear and belt system. V-belts were identified as the most commonly used type of belts due to their ability to transmit more power than flat belts for the same tension [63]. Although the second option demands more effort to succeed (including dimensioning and designing the system), it was chosen due to its significantly lower cost compared to the first option and the challenge of manufacturing a self-designed reduction system.

In the market, some readily available gear and belt systems are affordable. However, these systems are generally small and specifically designed for applications such as 3D printers. They typically offer reduction ratios ranging from of 1:3, with some reaching up to 1:5. Considering that a belt was already available in the MakiLab, the decision was made to manufacture custom pulleys using laser-cut wood. This approach enabled the design of pulleys with the desired reduction ratio and the incorporation of an appropriate connecting system to tighten the pulleys on both shafts. Additionally, the use of laser-cut pulleys allows for rapid iteration and adjustments during the development process.

#### Proof of Concept Prototype

The first step involved designing the toothed pulleys with the appropriate module and number of teeth to match the belt. The module, denoted as "m," can be known by dividing the reference diameter  $d$  by the number of teeth  $z$ :  $m = \frac{d}{z}$ . For this specific

case, the belt had the following specifications: a reference diameter of 226 mm and 142 teeth, resulting in a module of approximately  $m = 1.59$ . To facilitate the design process, the software "Engineers Edge" [64] was utilized. A small python program was written in order to know the required dimensions of pulleys for each ratio.

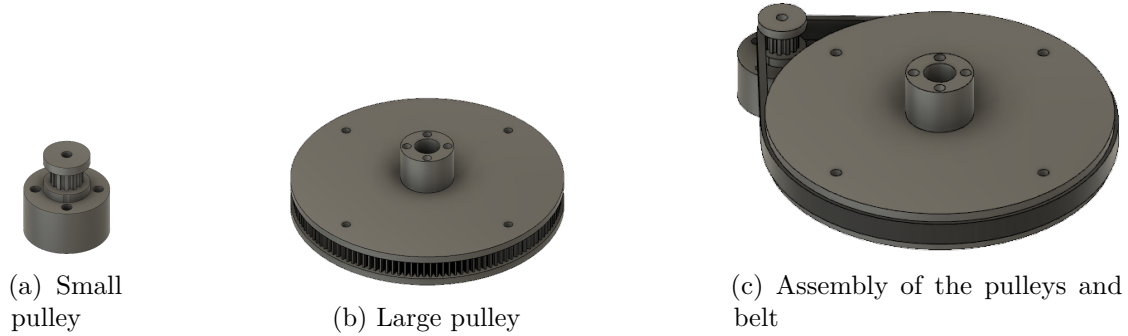


Figure 4.6: Reduction system with pulleys and a belt.

The teeth part of both pulleys were initially cut from scrap wood or cardboard, to verify their dimensions with the belt. Once validated, the complete design of the pulleys was conceptualized and then manufactured using wood (of a thicknesses of 3, 5 and 6 mm). Afterwards, the layers were glued and screwed together. An initial attempt was made with a reduction ratio of 10. However, after conducting several tests, a revised version was created with a reduction ratio of 5. This prototype is illustrated in Figure 4.6.

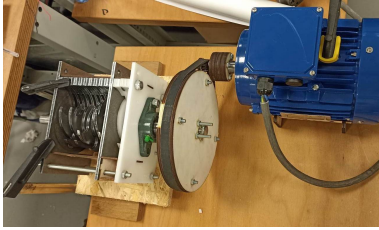
### Testing Results

Initially, tests were conducted on the device by clamping the motor and shredder onto a table (see Figure 4.7a). However, a problem arose as the belt was not sufficiently tightened. To address this issue, the frame design was modified to incorporate a sliding mechanism for the shredder box (see Figure 4.7b).

The pulleys with a ratio of 1:10 were not able to drive the belt. It was determined that this ratio was too ambitious for the intended application. At low speeds (and power), the pulleys with a ratio of 1:5 worked quite efficiently and successfully shredded PS plastic. However, when operating at higher speeds (over 360 rev/min,  $f = 6$  Hz) and requiring to transmit more power (264 W), the belt no longer remained driven by the small pulley. Ultimately, the wooden structure surrounding the motor axis that held the small pulley cracked at a higher power and frequency (352 W, 8 Hz).

Based on the observations and experiments, it can be concluded that wood is not sufficiently robust to withstand the stresses involved. It is evident that metal pulleys would be more suitable for the task. However, the challenge with metal pulleys lies in creating the appropriate slots for connecting them to the two different shafts. The

simplest solution would be to acquire the corresponding reducer specifically designed for this motor (see Appendix C).



(a) Version 1 (1:10 ratio)



(b) Version 2 (1:5 ratio)

Figure 4.7: Reduction system testing.

# Chapter 5

## Blades

This chapter focuses on the blades of the shredding box and analyses different solutions aiming at enhancing their manufacturability within a FabLab.

### 5.1 Requirements

|             |                                                                                                |
|-------------|------------------------------------------------------------------------------------------------|
| Function    | Shred plastic.                                                                                 |
| Objective   | Simple conception and minimum cost.                                                            |
| Constraints | Must Support the compression loads needed to shred plastic without entering in plasticity.     |
|             | Edges must be sharp and resist to wear.                                                        |
|             | Shred plastic in flakes with a maximum length of 10mm.                                         |
|             | Have a grabbing function in order to keep flakes bigger than 10mm circulating in the shredder. |

Table 5.1: Requirements for the design of the blades.

### 5.2 Concept Ideation

#### 5.2.1 Shape Analysis

Blades vary in size and in the number, shape, and length of their cutting edges. They can either shred in one direction or in the two directions (back and forth movement).

#### Blade Thickness

Blades' thickness impacts the shredder in various ways, including on the needed shredding force, the resulting stress concentration on cutting edges, the required safety factor, the specific cutting energy, and the shredding efficiency [65]. According to Dave Hakkens, the founder of Precious Plastic, thicker blades lead to increased strength and larger flakes

output [12, 65]. To verify this, a finite element method simulation was conducted on a steel blade while varying its thickness (ranging from 3mm to 7mm) under an applied force of 200N. The results of the simulation are presented in Table 5.2.

| Blade thickness             | 3 mm     | 4 mm     | 5 mm     | 6 mm     | 7 mm     |
|-----------------------------|----------|----------|----------|----------|----------|
| Max. von Mises Stress [MPa] | 24.34    | 21.29    | 15.3     | 12.9     | 11.3     |
| Max. deformation [mm]       | 4.287e-3 | 3.224e-3 | 2.578e-3 | 2.150e-3 | 1.844e-3 |

Table 5.2: Results of a FEM simulation on steel blade of varying thickness under an applied force of 200N.

The von Mises criterion states that plastic deformation occurs when the von Mises stress exceeds the ultimate tensile strength of the considered material, which is around 215 MPa for steel. However, in these simulations, no plastic deformation is observed. There is only a small elastic displacement on the order of 1  $\mu\text{m}$ .

This simulation confirms that thicker blades are more resistant to an applied force. The trade-off when choosing the blades thickness is therefore between having blades that are more resistant or blades that give smaller flakes.

### Number of Cutting Edges

In a study conducted by Sekar Ravi [65], it was found that having multiple cutting edges in shredder blades allows for faster plastic shredding. However, the drawback of these blades is that when they encounter a harder surface than usual, they fail to cut or bypass the plastic without cutting it. Instead, the blade initially strikes the hard surface, then reverses its rotation motion and almost immediately strikes the same surface with another cutting edge. This process can cause delays in shredding and leave uncut plastic waste that passes through the blade. Additionally, the reversing action of the blade can damage the cutting edges. To address these issues, the study suggests using blades with two cutting edges and a larger cutting area for enabling shredding with a higher force, resulting in improved shredding outcomes. Having less cutting edges per blade can be compensated by increasing the number of blades to have a shredding speed similar to multiple cutting edges and a larger cutting surface.

### Shape of Cutting Edge

The blades designed by Precious Plastic have a circular body as it facilitates smooth rotation. The cutting edge is inclined to follow the circularity, ensuring optimal contact with the material to be shredded. The tip of the cutting edge is designed to be sharp, enabling precise cuts. Blades must also have a grabbing function in order to keep not shredded plastic circulating. When considering a blade with two cutting edges, the ideal shape often takes the form of an S-shape, ensuring effective and efficient shredding of the material.



### 5.2.2 Alternative Materials

The blades of the shredding shaft consist in the most critical part to manufacture in a FabLab because they actually cut the plastic. Indeed, they are made out of steel in the current version of the Precious Plastic machine. As steel can not be machined in a FabLab, it is interesting to find some alternative materials for steel.

#### Aluminium

Replacing steel by aluminium is the first idea that arose. Indeed, it is the only metal that can be machined in the CNC present in every FabLab.

#### Polyoxymethylene

The polyoxymethylene is a thermoplastic that is used for its good mechanical properties: high strength, hardness and rigidity. It is usually used to manufacture precise parts that need high stiffness, low friction and dimensional stability [66]. POM can be machined using traditional methods (turning, milling, drilling) or a laser cutter, making it usable in a FabLab. It is sensitive to acid hydrolysis, oxidation and alkaline attack, making it susceptible to degradation in hot water [67]. On the downside, POM can have undesirable characteristics when burned, the flame is almost invisible in ambient light and is not self-extinguishing. Moreover, it releases formaldehyde gas, which is harmful for humans and environment (irritates nose, throat, and eye tissues) [68].

#### Wood

Some wood have very good mechanical properties. It is therefore a material to consider for the blade. Woods like ipe, lapacho or mahogany have very high hardness. However, they come from exotic trees and are not globally accessible. Other woods, with less satisfying mechanical properties but more availability, like oak, maple and ash, can therefore be considered [69]. Among them, it was decided to further investigate the potential use of oak as it is widely accessible. It must be highlighted that wood is anisotropic and has different properties whether the direction considered is perpendicular or parallel to the grain.

#### Epoxy Resin

Epoxy resins are thermosetting polymers that can be cured using different agents [70]. They are used widely in varied applications notably thanks to their good mechanical properties. Replacing the steel blades with molded epoxy resin blades was an option to be considered. The idea is that everyone who would like to build the shredder could be able to order a mold and use epoxy resin to manufacture the blades. However, The properties of epoxy resin alone are not good enough to be compared to steel ( $\sigma_{UTS,steel} \approx 500$  MPa  $\gg \sigma_{UTS,epoxy} \approx 80$  MPa [71]). Therefore, using some fiber or other reinforcement is a necessity. Epoxy can be reinforced using natural fibers such as ramie, birch, palm,

and eucalyptus [72, 73] but also glass, carbon or kevlar fibers [74]. Table 5.3 gives some obtained results of properties for epoxy resin reinforced with these latter fibers. Seeing these values, it is interesting to consider glass reinforced epoxy resin as a replacement for steel.

|                                   | Glass fiber | Carbon fiber | Kevlar fiber | Steel |
|-----------------------------------|-------------|--------------|--------------|-------|
| Tensile strength [MPa]            | 400         | 2000         | 1500         | 560   |
| Tensile fatigue failure [MPa]     | 200         | 1300         | 900          | 300   |
| Compression fatigue failure [MPa] | 300         | 950          | 400          | 300   |

Table 5.3: Properties of reinforced epoxy resin [37, 74].

#### *Reinforcement Using Glass Fiber*

The making process of glass fiber/epoxy resin composite laminated material is quite long. It includes applying a release agent on the clean mold, preparing the epoxy, building the surface, adding epoxy resin and glass fiber layer by layer and cutting the plies to give them the good shape [75]. There are 54 parts to build (blades, spacers, rotors) so this methods seems too complicated and too long. Moreover, the price of the material is not very accessible compared to buying the steel kit on the Bazar (epoxy resin 20€/kg [76], glass fiber 7€/m<sup>2</sup> [77] vs steel 300€/kit [18]).

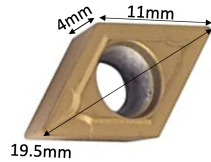
### 5.2.3 Reinforcement Through Metallic Deposition

The possibility of reinforcing 3D printed blades made of PLA by depositing metal onto them is being explored. Metallic deposition is a process in which a layer of metal is applied onto another material. Various methods are available for metallic deposition, including laser deposition which is adapted for plastic [78], direct deposition, cold spray, vacuum deposition for deposition on LDPE or HDPE [79], and physical vapor deposition adapted for deposition on wood. Each method requires specific equipment and products [80].

At UCLouvain, electrochemical deposition is available as a method for metal deposition. It enables the deposition of metal layers with a thickness going up to a few millimeters, unlike other methods that only deposit layers in the range of microns. However, electrochemical deposition is a time-consuming process, it typically takes about a full day for a deposition thickness of 1mm. It also requires the use of specific and hazardous chemical elements that necessitate precautions for the user protection. Additionally, the quality of the deposition is highly dependent on the used parameters. Hence this idea will not be developed further.

### 5.2.4 Reinforcement Through a Milling Insert

To reinforce the weakest part of the blade, which is the tip, an alternative approach is to use a metallic milling insert. This insert can be placed at the tip of the blade, providing additional strength and durability. One advantage of using a milling insert is that it can be easily replaced when it is too worn out.



A search was carried out to find milling inserts that are similar to those used for plastic machining and are reasonably priced. The Figure on the left illustrates a potential insert option, including its dimensions, which could be suitable for this application [81].

In order to find a way of fixing the insert to the blade, the following dimensions are taken into account: the fixing hole diameter of the insert is 4.4 mm and its thickness is 3.97 mm, the blades of the basic shredder of Precious Plastic have a thickness of 5mm. Figure 5.1 illustrates how the insert might be fixed to the blade. It is obvious that if this solution is continued, the blades' thickness should be increased because fixing the insert on a 0.6 mm wall is not reliable. To keep the size of the plastic flakes small, the thickness of the blades should not be increased too much hence this solution was not further developed.

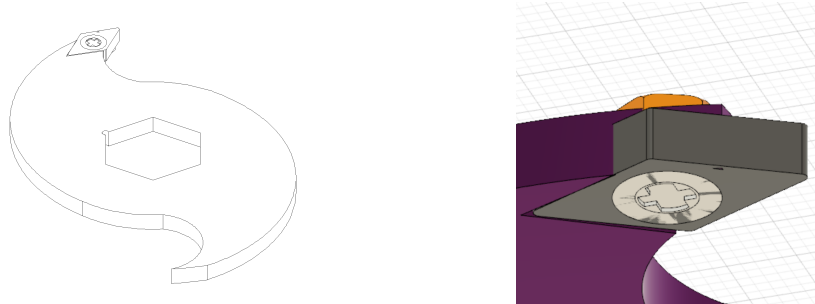


Figure 5.1: Fixation of a milling insert on a blade

### 5.2.5 POM Blades With Aluminium Insert

After testing the POM blades and seeing that they were not sharp enough and wearing out fast (see Section 5.4.1), it was thought that they could be reinforced with a metal layer. The idea was to make the tips of the blades smaller so that there would be space for claws to wrap them. These claws would be made of aluminium to allow the machining with the available CNC. They can be fixed to the blades with two bolts and screws, enabling an easy change in case of wear.

### 5.3 Analytic and Numerical Proof of Concept

The ideas that were selected for analytic and finite element method (FEM) validation are to make the blades in aluminium, POM and oak. The other ideas were either too complicated or not adapted to FabLab fabrication (metal deposition, milling insert, epoxy resin). It was chosen to keep the shape of the blades from the Precious Plastic design. The properties of the selected materials are given in Table 5.4. The analytical analysis compares the force required to buckle a blade with the force required to deform a plastic piece into full plasticity. On the other hand, the numerical simulation analyses the displacement of a blade under different forces and also compares the von Mises stress and ultimate tensile strength for different applied forces and for the different materials.

| Material properties     | Stainless steel | Aluminium | POM   | Oak (longitudinal) | Oak (transversal) |
|-------------------------|-----------------|-----------|-------|--------------------|-------------------|
| Density [ $g/cm^3$ ]    | 8.0             | 2.7       | 1.4   | 0.94               | 0.94              |
| Young's Modulus [GPa]   | 195             | 70.5      | 2.9   | 22.9               | 5.29              |
| Poisson coefficient [-] | 0.29            | 0.34      | 0.393 | 0.37               | 0.03              |
| Yield strength [MPa]    | 215             | 25        | 64.4  | 48                 | 4.74              |
| UTS [MPa]               | 505             | 58        | 80.5  | 295                | 7.9               |
| Shear modulus [GPa]     | 86              | 26        | 1.04  | 1.69               | 0.61              |

Table 5.4: Properties of the analyzed materials [37].

#### 5.3.1 Analytic Proof of Concept

At first, beam theory was used to determine the critical buckling force of the candidate materials for the blades, and the needed forces for the different plastics to enter in plasticity.

The problem is modelled as shown in Figure 5.2a. The blade and plastic to shred are reduced to beams. The blade (in blue) is built in (yellow contact) at the contact point with the shaft. The plastic piece is simply supported (orange and red contacts) by the adjacent fixed knives.

From the book "Materials selection in mechanical design" [82], the needed forces on the plastic piece for it to enter in plasticity and be fully plastic are :

$$F_{onset} = \frac{CZ\sigma_y}{L_p} \quad F_{fully} = \frac{CZ_p\sigma_y}{L_p} \quad (5.1)$$

where

- $C = 4$  is a constant that depends on how the plastic beam is supported.



Figure 5.2: Analytical calculations, beam theory configuration.

- The section modulus  $Z = b_p h_p^2 / 6 \text{ m}^3$  quantifies the surface stress produced by a specific bending moment.
- The moment  $Z_p = b_p h_p^2 / 4 \text{ m}^3$  measures the resistance of the beam to fully plastic bending.
- $b_p = 3 \text{ mm}$  and  $h_p = 5 \text{ mm}$  are the dimensions of the rectangular cross section of the plastic beam.
- $L_p = 12 \text{ mm}$  is the length of the plastic beam.
- $\sigma_y$  is the yield strength of the considered plastic.

For the blade, the critical buckling force should not be overcome (see configuration in Figure 5.2b) :

$$F_{crit} = \frac{n^2 \pi^2 EI}{L_b^2} \quad (5.2)$$

where

- $n = 1/2$  is a constant that depends on the configuration of the beam.
- $E$  is the young's modulus of the considered material for the blade.
- The moment  $I = b_b h_b^3 / 12$  measures the resistance of the section to bending about a horizontal axis.
- $b_b = 5 \text{ mm}$  and  $h_b = 6 \text{ mm}$  are the dimensions of the rectangular cross section of the blade beam.
- $L_b = 60 \text{ mm}$  is the length of the blade beam.

A safety factor  $SF = 2$  is defined. To determine if a material can be used to shred the considered plastic, we have to ensure that  $F_{crit} > F_{fully} * SF$ .

The results are shown in Tables 5.5a and 5.5b. The properties used for the different plastic types are taken in Table 2.4. From these, it is observed that aluminium only would not never buckle before the plastic goes into plasticity. Oak would only buckle after LDPE and PLA of low density are deformed plastically. And POM would buckle after LDPE of low density goes into plasticity.

| Blade material     | $F_{crit}$ [N] |
|--------------------|----------------|
| Stainless steel    | 12029          |
| Aluminium          | 4349           |
| POM                | 179            |
| Oak (longitudinal) | 1413           |
| Oak (transversal)  | 326            |

(a) Buckling results

| Plastic type | $F_{onset}$ [N] | $F_{fully}$ [N] |
|--------------|-----------------|-----------------|
| PP           | 108-208         | 163-313         |
| HDPE         | 108-129         | 163-194         |
| LDPE         | 55-110          | 83-165          |
| PS           | 150-215         | 224-323         |
| PET          | 229-250         | 344-375         |
| PLA          | 83-125          | 125-188         |

(b) Plastic behavior results

Table 5.5: Analytical calculation results.

### 5.3.2 Numerical Proof of Concept

To complete the analytical calculation that only takes into account the Young modulus of the studied material, numerical simulations were conducted using Fusion360. In these simulations, the center of the considered blade was fixed, and forces of 100N, 200N, and 300N were applied to one of its cutting edges (refer to Figure 5.3). The simulation results for Stainless Steel, Aluminum, POM, and Oak (longitudinal and transversal) are depicted in the graphs shown in Figure 5.4.

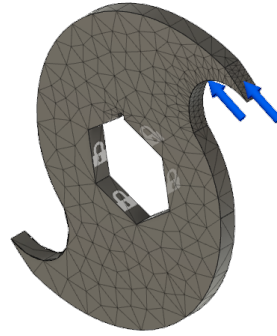


Figure 5.3: Numerical simulation configuration

The first graph on Figure 5.4 displays the maximum displacement experienced by the blade when subjected to the different forces. The second graph illustrates the difference between the yield strength of each material and the von Mises constraint obtained through the simulation. It is observed that POM exhibits the highest deformation, but it is only

deformed elastically since its yield strength consistently exceeds the von Mises constraint. On the other hand, Oak, with its transversal properties, undergoes plastic deformation, rendering it unsuitable for use. Furthermore, Aluminum exhibits a displacement rate similar to that of stainless steel, but its yield strength approaches the von Mises constraint closely.

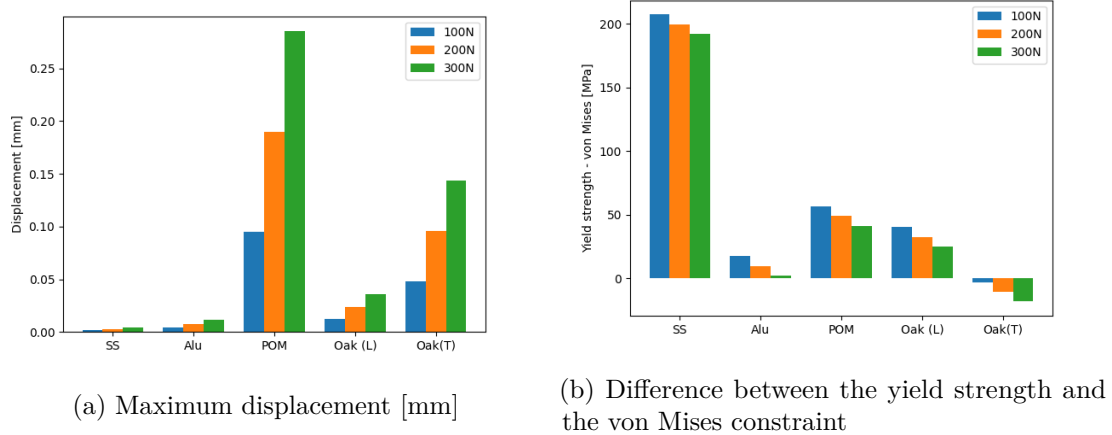


Figure 5.4: Simulation results for an applied force of 100N, 200N and 300N on Stainless steel, Aluminium, POM and Oak (longitudinal and transversal).

## 5.4 Proof of Concept Prototype

From the previous results, the choice was made to investigate further the use of POM to replace steel for the blades. Indeed, it is the studied material that resists better to plastic deformation.

### 5.4.1 POM Blades

First, the same shape as the one from Precious Plastic was used. It was immediately noticed that the sharpness of the blades was less present than with steel. Therefore, there were instances where the plastic was folded instead of shredded (Figure 5.5a). Moreover, after some long run testing, the blades were quite deformed as can be seen in Figure 5.5b. Then, different shapes of blades were tested. The squared one (Figure 5.5c) was not able to shred the plastic pieces because of the absence of grabbing function. The last blade (Figure 5.5d) has rectangle tips of 5 and 10 mm height. It shred plastic quite well (similar results to the ones shown in Figure 5.5e) but, as for the two first blade, it was wearing out fast and the sharp edges got rounded.

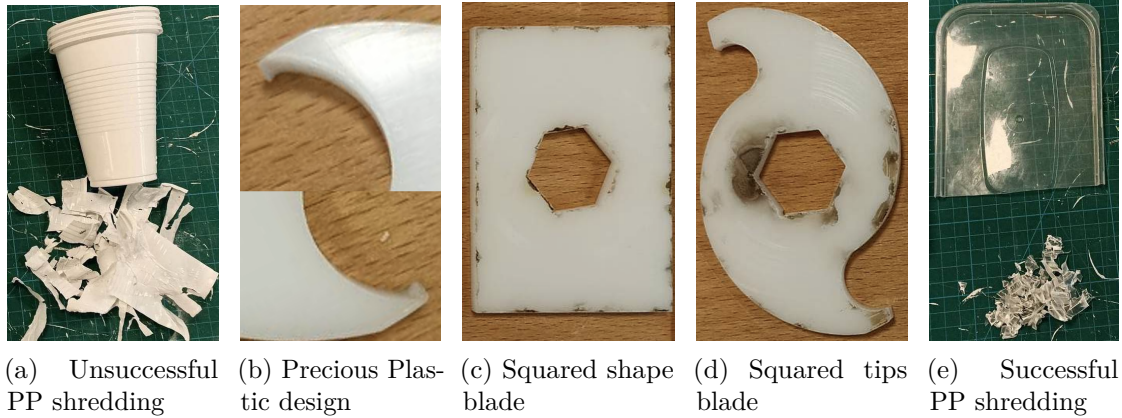


Figure 5.5: POM blades tried shapes and PP shredding results.

#### 5.4.2 POM Blades Reinforced With Aluminium Claws

Seeing the large deformations of the POM blade tips and the lack of sharpness, it was decided to reinforce the POM with aluminium and use the water jet cutter to prototype the claws because it is faster and more precise than the CNC. To validate the idea, a first prototype was laser cut in wood and the thickness of the aluminium claw was decided based on a test done with the water jet cutter. After a few iterations, the wooden prototype was validated (Figure 5.6a) and a first prototype was manufactured using laser-cut POM (6 mm thickness) and water jet-cut aluminium (6 mm thickness) (Figure 5.6b). Tests were conducted on the manual shredder. Each claw is fixed on the blade with two bolts and nuts.

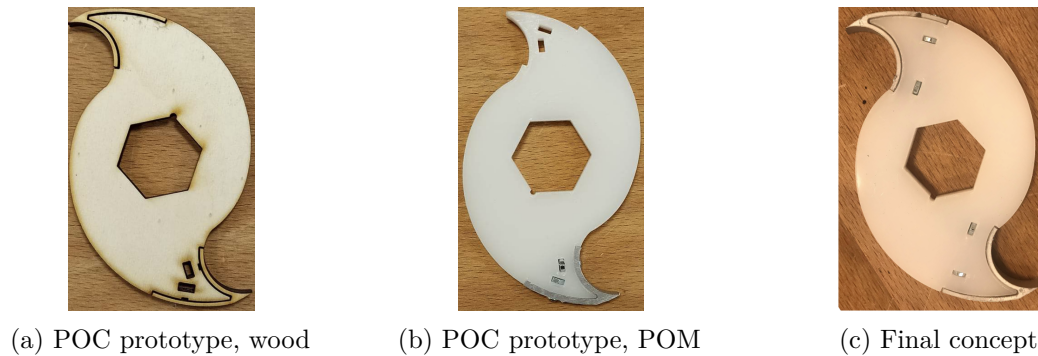


Figure 5.6: Blades in POM reinforced with aluminium claws

### 5.5 Final Concept

The prototype presented in Section 5.4.2 was validated. Only two changes were made towards the final solution (Figure 5.6c): the claw dimensions were increased in order



to have a longer sharp edge, and the blots were moved a bit for a better holding of the claw on the POM blade. During the shredding tests, the sharpness of the blades was immediately noticeable and the design was judged as satisfactory. Further information about the performance of these blades are presented in Section 7.2. It is important to notice that the water jet cutter that was used for manufacturing the claws is not present in every FabLab. However, it is more and more currently used in FabLabs and the design for the claws can be adapted to the use of the CNC machine.

## Chapter 6

# Shredding box, Frame and Hopper

The shredding box is composed of the fixed knives, the shaft and the support box.

### 6.1 Fixed Knives

#### Requirements

|             |                                                                                            |
|-------------|--------------------------------------------------------------------------------------------|
| Function    | Shred plastic.                                                                             |
| Objective   | Simple conception and minimum cost.                                                        |
| Constraints | Must support the compression loads needed to shred plastic without entering in plasticity. |
|             | Edges must be sharp and resist to wear.                                                    |
|             | Shred plastic in flakes with a maximum length of 10mm.                                     |

Table 6.1: Requirements for the design of fixed knives.

#### Concept Ideation

During the ideation phase of designing the fixed knives, inspiration was drawn from the final solution chosen for the blades. It involved manufacturing the parts using POM and reinforcing them with aluminum.

#### Proof of Concept Prototype

For the proof of concept prototype, a few knives were manufactured and tested on the third version of the shredder. This allowed the comparison of their efficiency with the steel fixed knives. The small and large fixed knives were laser cut in a 6 mm thick POM sheet. In this design iteration, only the small fixed knives were reinforced with aluminium as they require a sharp edge and bear the majority of the forces and stresses. First, a proof of concept prototype was made in wood as can be seen in Figure 6.1a. When the

concept was validated, a second prototype was made in POM (refer to Figure 6.1b). To achieve this, small square pieces (22x6mm) were CNC-cut from a 0.5mm thick aluminum plate. These pieces were then fastened to the blade using inserted bolts. It is important to avoid attaching them to the side of the blade to prevent increasing its thickness. The large fixed knives were not reinforced, but a future iteration could potentially incorporate reinforcement along the side edges.



(a) Wood knife



(b) POM knife

Figure 6.1: Small fixed knife reinforced with aluminium, proof of concept.

### Final Concept

After testing and validating the previously described concept, all the fixed knives were created in a similar manner and assembled together with two threaded shafts (Figure 6.2). As all the parts of the shredder box are made from the same POM sheet, the distance between two large fixed knives is equal to the thickness of a small fixed knife, and also to the one of a blade. To increase this distance between two large fixed knives and prevent friction between them and the rotating blades, 3D-printed blade spacers were incorporated (grey on Figure 6.2). These spacers are 0.36 mm thick and ensure that the small fixed knives are slightly larger than the rotating blades. More details about the calculation of this thickness are given in Appendix D.



Figure 6.2: All fixed knives assembled together with 3D-printed blade spacers

## 6.2 Shaft

### Requirements

|             |                                                                                                                                                                     |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Function    | Rotate and hold the blades and blade spacers.                                                                                                                       |
| Objective   | Simple conception and minimum cost.                                                                                                                                 |
| Constraints | Ensure that the blades do not rotate on the shaft.                                                                                                                  |
|             | Rotate properly while being supported by the bearings.                                                                                                              |
|             | The section that holds the blades and blade spacers must have the same length as all the blades and blade spacers together (with a maximum margin of error of 6mm). |

Table 6.2: Requirements for the design of the shaft.

### Concept Ideation

The Precious Plastic shaft has a unique design, combining hexagonal and circular elements, which requires it to be either purchased or machined. To simplify the shaft, an idea is to utilize a standard circular shaft readily available in various tinker shops. These standardized shafts typically have a diameter of 20mm and a length of 300/400mm, costing approximately 5€ [83]. Using a standardized shaft also means a change in the way the blades are attached to the shaft. Indeed, in the Precious Plastic solution, the blades do not rotate around the shaft thanks to its hexagonal shape. A possible solution would be to use friction mounting to keep the blades in their position. This kind of mounting is used for circular saws.

The design process for the mentioned idea did not advance beyond the ideation stage. It was determined that implementing the proposed concept would pose significant challenges and potential limitations in terms of functionality and practicality. This idea would have required remaking all the blades. Consequently, the decision was made to prioritize further design iterations of the other key elements of the shredder, as they held more promising prospects for successful implementation and achieving desired outcomes.

## 6.3 Shredding Frame

The shredding frame contains the four walls of the shredding box and the sieve.

### Requirements

From Table 6.4, we know that the plastic flakes have to be smaller than 7 mm if they aim at being used by all the other Precious Plastic machines. This size is quite small and hard to reach with blades of thickness 6 mm. Therefore, the choice is to obtain flakes

|             |                                                     |
|-------------|-----------------------------------------------------|
| Function    | Hold the parts of the shredding box together.       |
| Objective   | Simple conception and minimum cost.                 |
| Constraints | Enable good alignment and tightening of the blades. |
|             | Resist to loads, vibrations and chocks.             |
|             | Filter the flakes with size of 10mm or smaller.     |

Table 6.3: Requirements for the design of the support box.

with a size of maximum 10 mm diameter that can be used in the compression, sheetpress and injection machines.

| Plastic flakes size | 0-30 mm     | 0-10 mm                                | 0-7 mm                                              |
|---------------------|-------------|----------------------------------------|-----------------------------------------------------|
| Works with          | Sheet press | Sheetpress<br>Injection<br>Compression | Sheetpress<br>Injection<br>Compression<br>Extrusion |

Table 6.4: Machines incoming requirements [84].

### Concept Ideation

Among the four sides of the shredding frame, the ones that are perpendicular to the shaft support all the weight of the box. They need to be strong and resistant, this is why it was an idea to build them in POM. The two other sides (parallel to the shaft) are needed to tighten the box properly. The first idea was to build them in wood but it is a material that bends easily. Hence, to avoid the bending, some reinforcement can be added perpendicular to the wooden sides.

For the sieve, different materials can be used: wood, cardboard, plexiglass, aluminium. In opposition to the steel used by Precious Plastic, it is quite complicated to curve these materials and constraint them to stay in the folded position. Therefore, to maintain them in a shape that follows the blades, the ideas were to change the shape of the additional sieve holders or to engrave some furrows on both POM sides.

### Proof of Concept Prototype

For the **perpendicular sides**, first a prototype was made in POM. It was holding everything together well. However, it was bending when the shredding box was tightened. For the **parallel sides**, 3mm wood was used. As expected it was also bending when tightening the shredding box. Therefore a prototype using reinforcements was made.

For the **sieve**, first, the Precious Plastic design was used with a wooden plate of thickness 3 mm instead of a metal plate of thickness 1.5 mm. To fold the wood, some

cutting was needed (Figure 6.3a). This had the downside of creating bigger holes than expected and the blades got stuck into them due to the too important thickness of the plate. As a second try, cardboard (2 mm thick) was used instead of wood because it does not need to be cut or bent (Figure 6.3b). However, it was complicated to obtain a well curved shape of the cardboard that was folded at some points and the blades of the shredder again got stuck into the sieve. As a third try, plexiglass (1 mm) was used (Figure 6.3c). Like wood, it is a material that is hard to bend and there was friction between the sieve and the blades. Finally, aluminium (0.5 mm) was used to make a thin and easily curved sieve (Figure 6.3d).

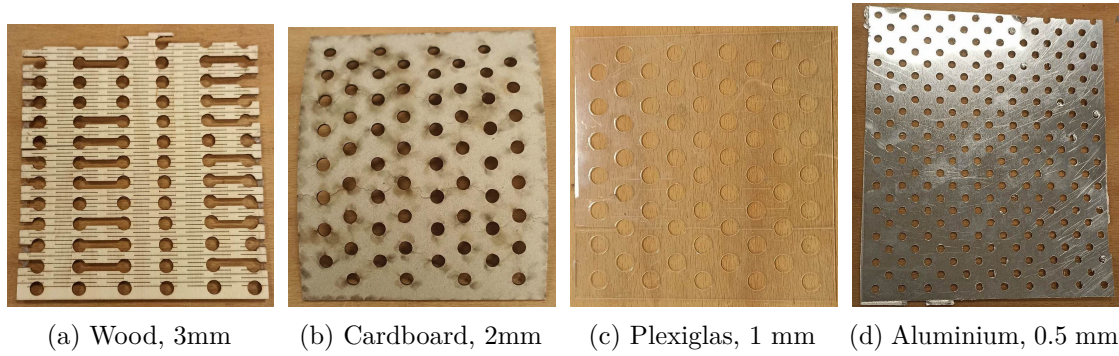


Figure 6.3: Sieve proof of concept prototypes.

### Final Concept

The final selected concept contains two POM sides identical to the Precious Plastic with some additional furrows for the sieve, two wooden sides including a few reinforcements. The four sides are machined with the laser-cutter (Figure 6.4a). The final sieve is manufactured in aluminum with the CNC and fixed using the two holders designed by Precious Plastic (wood 3 mm) in addition to the curved furrows. With holes of 10 mm diameter to let the plastic flakes go through (Figure 6.4b).

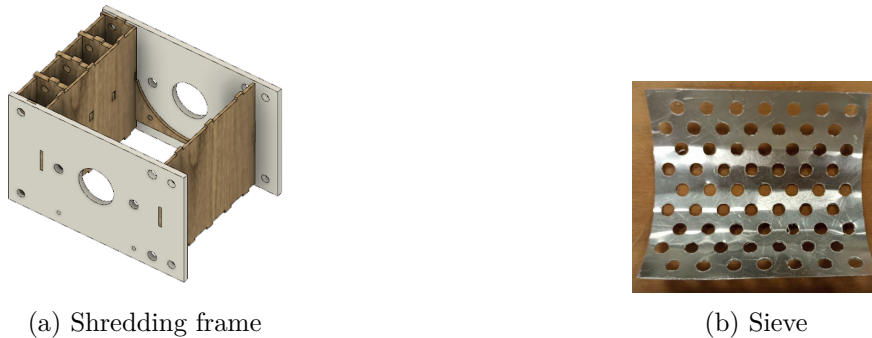


Figure 6.4: Shredding frame, final version.

### 6.3.1 Blades Positioning

After shredding some plastic, it was observed that the plastic was brought to one side of the shredding box by the blades. Indeed, these latter act as an endless screw (see Figure 6.5a), creating a plastic jam problem. The side blades therefore have to shred several layers of plastic at once which requires too much strength. After some research, it was discovered that others already encountered that issue and found a solution to this problem [85]. The idea is to place the blades more randomly as shown in Figure 6.5b. The positioning of the blades is shown in Figure 6.5c. The blades with one, two and three holes are represented in pink, green and blue respectively.

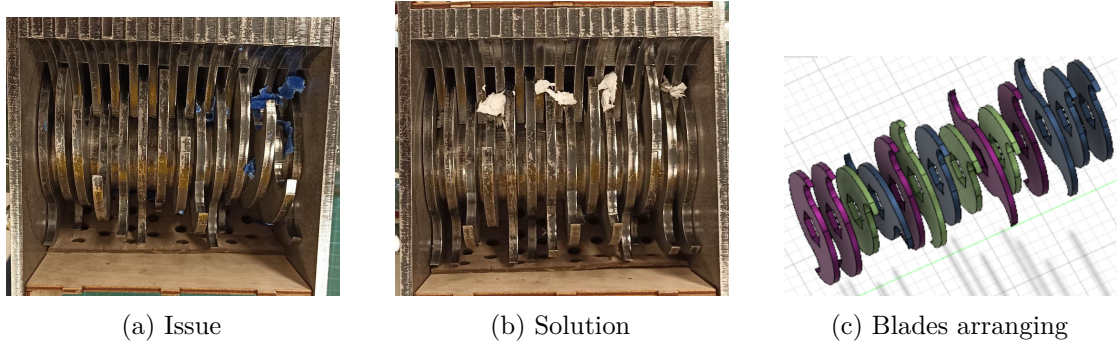


Figure 6.5: Jamming problem with blade positioning.

## 6.4 Frame

### Requirements

|             |                                                             |
|-------------|-------------------------------------------------------------|
| Functions   | Hold the shredder, the motor and the drive controller.      |
|             | Collect the plastic flakes.                                 |
| Objective   | Simple conception and minimum cost.                         |
| Constraints | Regain the forces generated by the engine and the shredder. |
|             | Hold approximately 25 kg.                                   |

Table 6.5: Requirements for the design of the frame.

### Concept Ideation

In order to construct the frame, inspiration was taken from cupboards built in the MakiLab. The selected concept utilizes holes and keys for assembly, as represented in the figure provided on the right. One of the advantages of this design is its easy assembly and disassembly that does not need additional parts made of a material different than wood.



### Proof of Concept Prototype

In order to validate the design and ensure the proper fixation of all parts, a prototype at a scale of 1:6 was constructed with the laser-cutter. This scaled-down version enabled the identification and implementation of necessary adjustments and refinements, resulting in the incorporation of several minor changes.

### Final Concept Version 1

A first version of the frame was designed for a direct coupling between the motor and the mill (Figure 6.6). The motor and shredder supports are embedded within the top plate of the frame and secured using small pins inserted into the supports beneath the top plate. Both the motor and shredding box are attached to their supports with bolts. Detailed drawings of the frame can be found in the Appendix .....

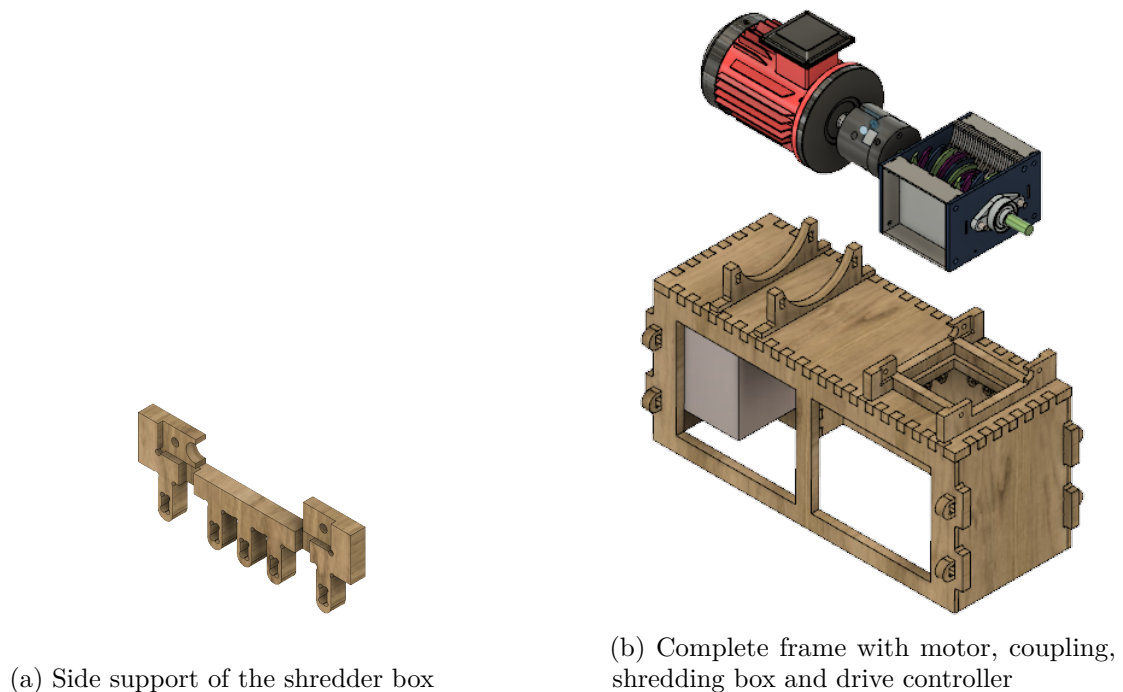


Figure 6.6: Version 1 of the frame for a direct coupling system.

### Final Concept Version 2

As mentioned in Section 4.2.2, a second iteration of the frame was required for incorporating the reduction system on the frame. Two significant modifications were necessary: first, the motor and shredder did not need to be aligned anymore, but separated by the inter-axis distance and second, the shredder box needed to slide on the frame to allow for putting the belt in tension. See Figure 6.7.



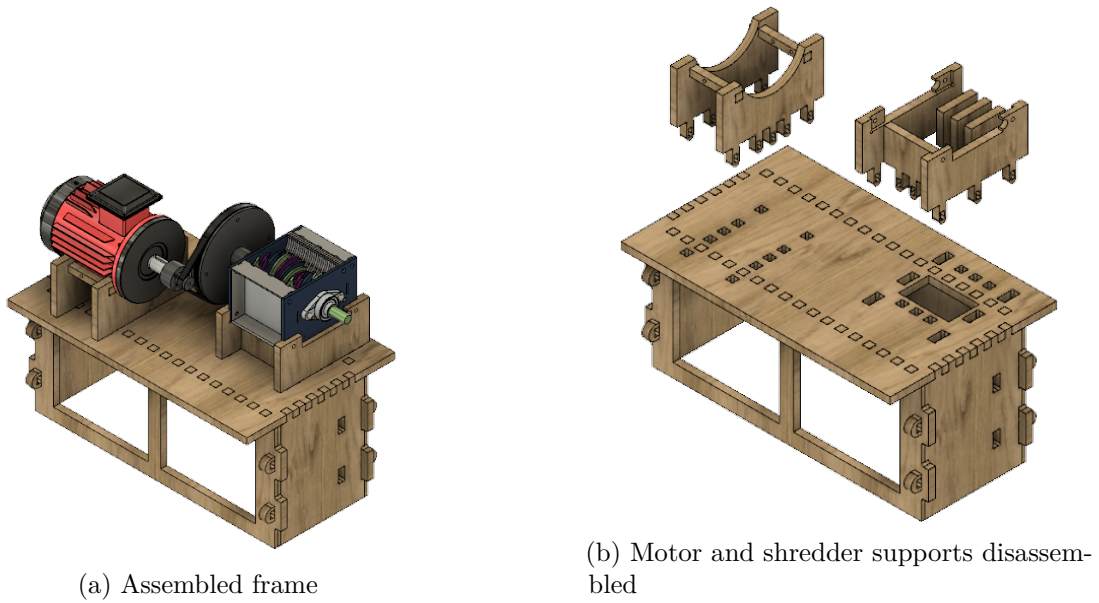


Figure 6.7: Version 2 of the frame for a coupling with pulleys.

## 6.5 Hopper

### Requirements

|             |                                                                |
|-------------|----------------------------------------------------------------|
| Function    | Guide the plastic towards the blades.                          |
|             | Prevent from injuries.                                         |
| Objective   | Simple conception and minimum cost.                            |
| Constraints | Attached to the shredding box or the frame.                    |
|             | Resist against vibrations and shocks of jumping plastic parts. |

Table 6.6: Requirements for the design of the hopper.

### Concept Ideation

At the time the motor starter being used instead of the handle, it became important to design a hopper for security reasons. The choice was to design a vertical hopper (Figure 6.8b) of height big enough so that no one could get hurt by putting their hands inside the shredding box. The hopper meant to be made of wood with the laser cutter (3 mm thickness). The four parts hold together thanks to 20 pins (Figure 6.8a). And the hopper is attached to the shredding box through bolts.

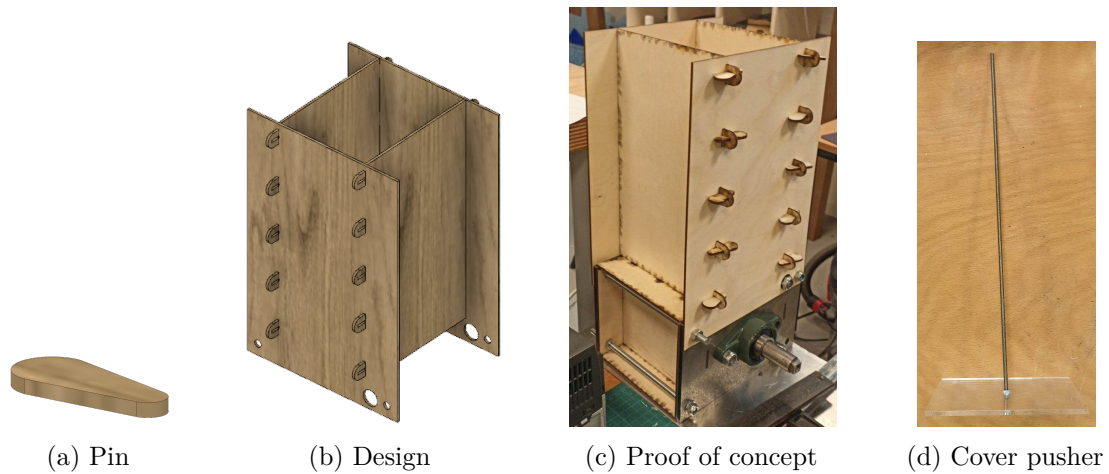


Figure 6.8: Hopper

### Proof of Concept Prototype

The hopper was directly built in real size, tried on the shredder and validated (see Figure 6.8c).

### Final Concept

The final concept includes a top part that disables the plastic flakes to go out from the top. It is attached to a threaded shaft enabling to push plastic close to the blades without too much risk (Figure 6.8d).

Overall, this solution is good. However, it can be improved by diminishing the number of pins used. Moreover, having at least two tilted sides could help dealing better with the flow of incoming plastic.

## Chapter 7

# Performances

### 7.1 Presentation of the Final Prototype

The final prototype of the plastic shredder is represented in Figure 7.1 and described in Table 7.1. This table indicates the materials and FabLab machines used for manufacturing each part and sub-part. It also indicates in which version of the prototype the design was done. For further details, a bill of material can be found in Appendix E, the manufacturing and assembly protocol is given in Appendix G and all the plans are presented in Appendix H.

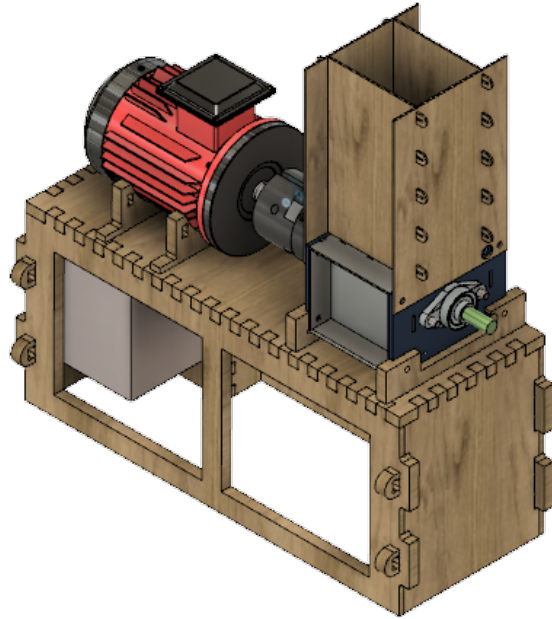


Figure 7.1: Final prototype illustration.

| Part          | Sub part               | Description                                         | FabLab machine                       | Version |
|---------------|------------------------|-----------------------------------------------------|--------------------------------------|---------|
| Hopper        | -                      | 4 sides and pins in wood, cover in plexiglass       | Laser cutter                         | V4      |
| Shredding box | Shaft                  | Hexagonal, in steel                                 | -                                    | V1      |
|               | Blades                 | POM and aluminium claws                             | Laser and water jet cutters          | V5      |
|               | Fixed knives           | POM and aluminium claws, PLA spacers                | Laser cutter, CNC miller, 3D printer | V5      |
|               | Shredding Frame        | 2 sides in POM, 2 sides in wood, sieve in aluminium | Laser cutter, CNC miller             | V5      |
| Frame         | -                      | OSB                                                 | CNC miller                           | V4      |
| Electronics   | Motor                  | 2.2 kW                                              | -                                    | V2      |
|               | Drive controller       | Siemens                                             | -                                    | V2      |
|               | Direct coupling system | In PLA with reinforcement screws                    | 3D printer                           | V2      |

Table 7.1: Final prototype description.

## 7.2 Testings

Two types of testing have been undertaken. The first test consists in the shredding of different plastic types. The performances of the final shredder prototype (Figure 7.1) and the ones of the original shredder (V2) were compared. The second test analyses the final version of the shredder when used for shredding large quantities of take-away PP plastic. Before starting the tests, it was identified that, to work empty, the final prototype needs to rotate at a frequency 0.5 Hz ( $\omega = 30$  rev/min,  $P = 22$  W).

### 7.2.1 Comparison of Final Prototype with Original Shredding Box

The aim of this first test is to compare the performances of the prototype designed and manufactured during this project with the ones of the steel shredding box designed by Precious Plastic. Hence different types of plastic, mainly coming from take-away food containers, were shredded by both shredders. The analysed performance parameters are the needed shredder rotation frequency and the size of the outgoing plastic flakes. Table 7.2 shows the obtained results as well as information about the different plastics' thickness ranges. Pictures illustrating the plastic before shredding, and the obtained flakes for both shredders are presented in Appendix F.

| Plastic type (and thickness) | Motor frequency [Hz]     |                   | Flakes size [mm]         |                   |
|------------------------------|--------------------------|-------------------|--------------------------|-------------------|
|                              | Final shredder prototype | Original shredder | Final shredder prototype | Original shredder |
| PET (0.5-1 mm)               | 8                        | 7-7.5             | 10-20                    | 5-10              |
| PS (0.5-1.5 mm)              | 6.5                      | 7                 | 5-25                     | 5-20              |
| PP (0.5-2 mm)                | 7-9                      | 7-9               | 5-20                     | 5-15              |
| PLA (1-1.5 mm)               | 6.5-8                    | 6-8               | 5-20                     | 5-10              |
| HDPE (1.2-1.5 mm)            | 10.5                     | -                 | 5-10                     | -                 |
| LDPE (0.3 mm)                | 7                        | 7                 | -                        | -                 |

Table 7.2: Experimental results on different plastic types for two different shredding boxes.

The **PET** plastic is a salad bowl cover that was quite difficult to shred due to jamming problems. It was easily folded by the blades that therefore needed to shred several layers of plastic. The **PS** plastics are sushi bowl and coffee cup covers that were well shredded by the steel blades, but transformed into quite big flakes by the POM and aluminium blades. The **PP** plastic is found in a few types of take-away boxes that were more or less hard to shred depending on the box's thickness. The boxes that have flat sides (0.5 mm thickness) are well shredded by both shredders. However, the ones that have ripples (2 mm thickness) require a rotation frequency of 9 Hz ( $\omega = 540$  rev/min,  $P = 395$  W) for both shredders and the shaft often gets stuck. The **PLA** plastic comes from the 3D-printers of the MakiLab and external donations. For both shredders, the range of frequencies is very broad because of the diversity of printed PLA. When cutting filaments, supports and failed parts, the required frequency is around 6.5 Hz ( $\omega = 390$  rev/min,  $P = 286$  W). However, when shredding whole parts that have strong external layers with plastic filaments perpendicular to each other, the shaft gets stuck and only the very small plastic parts can be cut by the POM and aluminium blades. However, the steel shredder has the abilities to shred thicker PLA parts and produce smaller flakes than the POM and aluminium shredder. The **HDPE** does not come from take-away food, but from a shampoo bottle. The final version of the shredder was able to partially shred this plastic but it required too much power and the direct coupling system broke. As the rotation frequencies are similar for both shredders for all the plastic types, it is expected that the steel shredder's frequency should also be above the working limit of the coupling system. Therefore, no test was conducted on HDPE with the original shredder. The **LDPE** plastic does not come from take-away food either, it is a plastic film from packaging. The same results were obtained with both shredding boxes: they are not able to shred it. It is a soft plastic that is only stretched by the blades where it stays stuck. No flakes were small enough to go through the sieve.

For both shredders, it is observed that the required rotation frequency depends on the plastic type to shred. It is a surprising observation because the torque is constant while the frequency stays under 50 Hz (see Section 4.1.5). However, it can be explained

by the fact that the motor is working at a torque of 7 Nm which is way lower than the estimated needed torque of 31.18 Nm (see Section 4). Hence the plastic is shredded through impacts (as done by the hammer mill shredder) instead of being shredded by shear deformation (as done by the blade shredder at low speed and high torque). As a consequence, depending on the resistance of the plastic to impacts, it requires more or less speed and power to be shred.

Overall, it is observed that the needed rotation frequencies (and therefore power) are almost identical for both shredder versions and the divergences can be explained by the better sharpness of the steel blades of the original shredder. However the quality of the obtained plastic flakes is better with the steel shredder than with the POM and aluminium blades. It can be explained by the lack of sharp edges in the POM shredder compared to the steel one. Indeed, despite the use of aluminium for the blades and the small fixed knives, there are still fixed knives that are only made of POM, this has the consequence of folding some plastic instead of cutting it. Moreover the smaller flakes made by the steel blades can be linked to the fact that these steel blades are 1 mm thinner than the POM blades.

For both shredders, it is also observed that, when the plastic is thick or two layers of a thin plastic are taken in the blades at once, the torque is not big enough to shred the plastic and the shaft gets stuck. This is a consequence of the fact that a drive controller is used to reduce the rotation frequency and speed of the motor which therefore does not work at its nominal speed and power. As explained in Section 4.1.5, the relation between the frequency and power is linear. Indeed, if the motor was working at nominal speed with a reduction system (like the pulley and belt system or a gear box) it would be working at nominal power and the torque available would increase while decreasing the speed. The reasons for not working at higher power was explained in Section 4.2.1 (the direct coupling system is not able to go at a frequency higher than 10.5 Hz). In addition, going at nominal speed with a prototype with this little safety measures is dangerous. When the shaft gets stuck, the current solution is to stop the motor and manually make it go backwards to release the blocking plastic piece. In the future, a solution could be to use a programmed signal that automatically makes the motor turn backwards when the shaft is stuck. The drive controller has a program that can enable backward motion, and it may be possible to automate this process using a device like an Arduino.

### **7.2.2 Quantity Testing on Final Prototype**

The aim of this second test is to see the performances of the final shredder prototype when shredding a larger quantity of plastic. As it was easier to collect take-away plastic, this test was conducted on boxes made in PP. Both parts of these boxes can be shredded, the covers are put whole in the shredder and the boxes are cut in half to help the gripping by the blades. The objectives of this test are twofold: firstly, to determine the average time required to shred half a box or a cover made of PP; and secondly, to estimate the average mass flow rate of the final shredder prototype. Additionally, this test investigates

the impact of varying the rotation frequencies of the shredder shaft on the shredding rapidity and examines the degradation of the blades.

When conducting these tests, two timers were used. The first one measured what will be called the "effective shredding time" and was turned on and off for each shredded plastic piece. It measures the actual shredding time and does not take into account the transition time between shredding two plastic pieces, or the times when the motor needs to be stopped to unblock the shaft. The second one measured what will be called the "total shredding time" and was turned on at the same time as the motor, and turned off when all the plastic was shred. It measures the duration of the whole shredding session and includes the transitions times and the moments when the motor had to be stopped to unblock the shaft if stuck.

### Effective Shredding Time

Figure 7.2 shows the effective shredding times needed to shred half boxes and covers for different rotation frequencies corresponding to 7, 8 and 9 Hz ( $w = 420, 480$  and  $540$  rev/min and  $P = 308, 352$  and  $396$  W) that correspond to the identified range in Table 7.2 for PP. These values are obtained from averaging over several samples results. More detailed Figures showing the effective shredding times for all the samples are presented in Appendix F (Figure F.8). It is observed that going from 7 Hz to 8 Hz does not make a noticeable difference in the shredding time. However, when the frequency increases to 9 Hz, the shredding is significantly faster. If an average is taken on all the rotation frequencies, the effective times for shredding half a box and a cover are 31 and 28 seconds respectively.

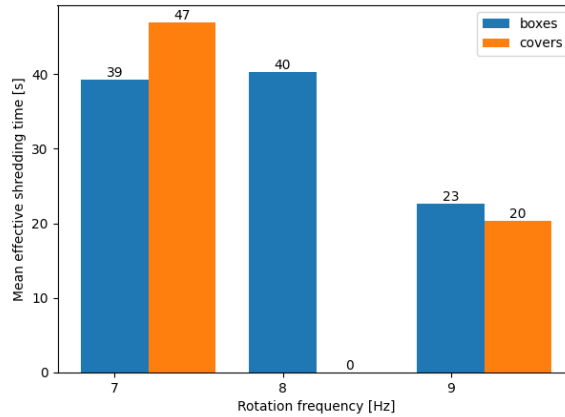


Figure 7.2: Mean effective shredding times for half boxes and covers, for different rotation frequencies.

### Total Shredding Time

To estimate the mass flow rate of the shredder, eight tests were conducted and the results are presented in Table 7.3. Among these tests, five focused on shredding plastic boxes and three on plastic covers. The shaft rotation frequencies was again either 7, 8 or 9 Hz. The test considers that half a box weighs 9 or 12 grams depending on its size, and a cover weighs 11 or 20 grams. The boxes are shown in Appendix F (Figure F.7).

|                        | #  | Rotation frequency [Hz] | Mass [g] | Time [min] | Flow rate [g/h] |
|------------------------|----|-------------------------|----------|------------|-----------------|
| Rectangular half boxes | T1 | 7                       | 132      | 16         | 495             |
|                        | T3 | 7                       | 93       | 22         | 256             |
|                        | T4 | 8                       | 135      | 26         | 312             |
|                        | T5 | 9                       | 138      | 28         | 296             |
| Circular boxes         | T6 | 9                       | 56       | 3          | 1120            |
| Rectangular covers     | T2 | 7                       | 88       | 6          | 845             |
|                        | T7 | 9                       | 185      | 21         | 529             |
| Circular covers        | T8 | 9                       | 12       | 1          | 720             |

Table 7.3: Total shredding time results for different rotation frequencies and plastic shapes.

The first observation is that the mass flow rate is larger for rectangular shredding covers than rectangular half boxes. Indeed, covers have a lower tendency to be folded by the blades and block the shaft than boxes. The circular boxes have a surprisingly high mass flow rate. This is explained by the fact that they did not have the tendency to be folded by the blades and they were well gripped by the blades. The circular boxes were faster shredded than the circular covers which are flat and were not always fast gripped by the blades.

Secondly, the fact that two tests done at the same frequency do not have similar mass flow rates can be explained by two elements. First, at 9 Hz, the huge differences between rectangular and circular boxes (T5 vs T6 and T7 vs T8) are explained by the difference in shapes and the surprising easiness of shredding circular boxes and covers. Secondly, the difference between the two tests at 7 Hz with rectangular half boxes could be explained because they were not conducted on the same day and the shredder had been disassembled and re-assembled, maybe differently between the two tests. Additionally, a plastic pusher was built for T3 to disable the plastic from jumping away from the blades and force it to stay near them, this might have induced jamming problems that were not present during T1. Moreover, T1 was the first long run test ever conducted on the shredding box hence the less satisfying results obtained during T3 may be explained by the wear and degradation of the blades.



In opposition to what was said in the previous section, it is not straightforward to conclude that increasing the rotation frequency increases the flow rate. Indeed, the mass flow rate decreases from T1 to T5 and from T2 to T7. This can again be explained by the fact that the blades were brand new during T1 and T2.

There seems to be a big part of randomness when it comes to the shredding time of a sample (see Figures in Appendix F). Therefore, to estimate the mass flow rate of the manufactured prototype as well as possible, an average was done on all the obtained flow rates and the mean mass flow rate of the shredder is approximately 570 g/h. This is 20 times less than the estimation of the mass flow rate of the Precious Plastic shredder.

### 7.2.3 Other Observations

The major disadvantage of blots is that they unscrew. During the large quantity testing, a blot was unscrewed from its nut, certainly due to the vibrations and got stuck between two blades. It is a problem that can be solved by checking that the blots are well screwed before starting to shred. Other solutions can be found such as using a nut without return or gluing product such as "loctite".

The quality of the blades after shredding varies a lot from a blade to another (Figure 7.3). Indeed, some blades are very worn off, but it is mainly because of some contacts with the heads of the bolts used to attach the aluminium reinforcement to the small fixed knives (Figure 7.3g and 7.3h). This issue could be solved by using longer aluminium reinforcements for the small fixed knives and putting the screws lower on these parts, where the blades go by farther from the stator. On the positive side, the blades that never were in contact with these screws are a little bit worn off, their tips are a bit bent (Figure 7.3a and 7.3b), but it is a minor degradation.

Another observation is that some big fixed knives, that are not protected by aluminium sheets, are quite worn off (Figure 7.4). Indeed, some aluminium claws are not attached tightly enough to the POM blades. They tend to move transversely and dig into these fixed knives. This could be solved by putting aluminium reinforcement on these knives. More importantly, the claws should be made differently so that they would be less able to move in this transversal direction. Indeed, the good alignment of the claws on the blades is essential for the lifespan of the shredding box.

Lastly, it was observed that after a long shredding session, the motor and shredder are warm. This indicates that there are non negligible heat losses and confirms the hypothesis made in Section 4.1.3.

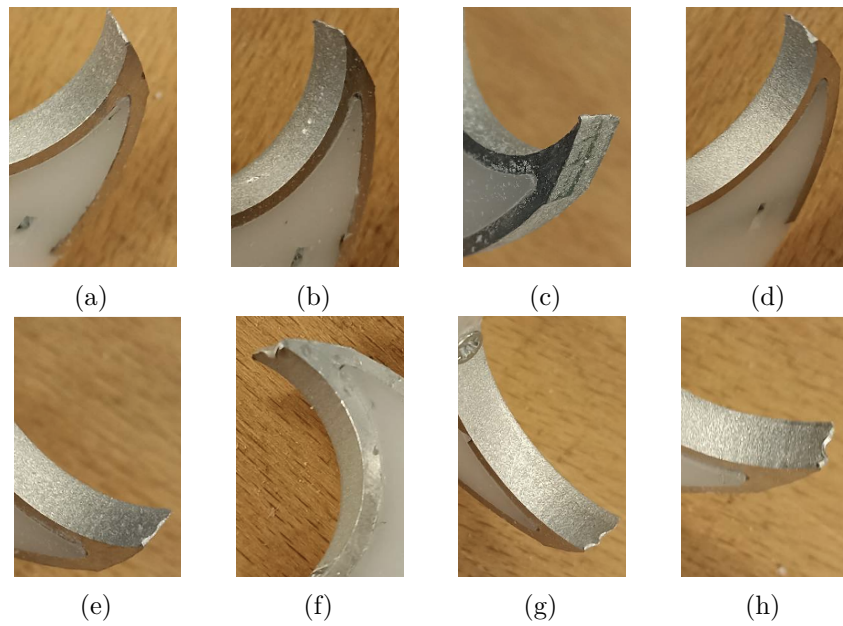


Figure 7.3: Blade quality after shredding large quantities of plastic. Good quality (a and b), top of the tip in contact with the screw (c), small tip deformation (d and e), big tip deformation (f, g and h).



Figure 7.4: Fixed knives quality after shredding large quantities of plastic.

# Part III

## Assessment

## Chapter 8

# Results and Prospects

### 8.1 Results

The objective of this project was to increase the manufacturability of the Precious Plastic shredder in a FabLab. Initially, the shredder was made of 118 objects among which only one (the wooden plate of the frame) could be manufactured in a FabLab. Table 8.1 shows that the machines used to build this Precious Plastic shredder are specific for working with metal and not present in FabLabs. The current design of the shredder is composed of 119 objects among which 110 have been manufactured in the MakiLab. As shown in Table 8.2, all the machines present in the FabLab were used. The parts that are not made in the FabLab are the shaft, the bearings, the bearing spacers, the motor and the drive controller. It is therefore possible to increase the percentage even more by designing a new shaft and different bearing spacers.

|                   | Hopper                        | Frame                              | Power           | Box                                                   | Total       |
|-------------------|-------------------------------|------------------------------------|-----------------|-------------------------------------------------------|-------------|
| Total parts       | 6                             | 28                                 | 4               | 80                                                    | 118         |
| FabLab Parts      | 0                             | 0                                  | 0               | 1                                                     | 1           |
| FabLab percentage | 0%                            | 0%                                 | 0%              | 1.3%                                                  | <b>0.8%</b> |
| Machines          | Metal cutter, grinder, welder | CNC, welder, metal cutter, grinder | Machining lathe | Metal cutter, machining lathe, drill, welder, grinder |             |

Table 8.1: Results initial shredder.

Overall, the shredder went from being 0.8% producible in a FabLab to 92.4%. It is a significant change that needs to be highlighted. Indeed, the objective of increasing the number of parts that can be manufactured in a FabLab has been reached. However, this positive outcome has some functional limitations that will be further developed in Section 8.3.

|                   | Hopper       | Frame | Power      | Box                                                 | <b>Total</b> |
|-------------------|--------------|-------|------------|-----------------------------------------------------|--------------|
| Total parts       | 5            | 14    | 5          | 95                                                  | 119          |
| FabLab Parts      | 5            | 14    | 3          | 88                                                  | 110          |
| FabLab percentage | 100%         | 100%  | 0.6%       | 92.6%                                               | <b>92.4%</b> |
| Machines          | Laser cutter | CNC   | 3D-printer | Laser and water jet cutters, 3D printer, drill, CNC |              |

Table 8.2: Results final prototype.

For these numbers, the bolts, nuts and pins used for the two shredders have not been taken into account because they are not relevant for the percentage of pieces that can be made in a FabLab. Moreover, the 46 3D-printed spacers placed between the blades and blade spacers and between the small and big fixed knives are counted as 2 parts, one for the stator and one for the rotor.

## 8.2 Critical Discussion About the FabLab Machines

After manufacturing this shredder in a FabLab, it is interesting to think about the up and down sides of the FabLab concept and the available machines.

Designing and manufacturing in a FabLab is quite convenient thanks to the opportunity to meet and exchange with new people. Indeed, being able to talk and discuss about the project with external persons was very useful to get some external perspectives and innovative ideas. Moreover, the makers usually have quite a lot of experience with designing and building their own creations, which makes their advice very rich. In addition to the human aspect, working in a FabLab is suitable because the machines are user friendly. Hence one can easily become accommodated with using them. Thanks to this independent environment, manufacturing can be done in a fast and efficient way.

Overall, all the machines are complementary and important. They have different characteristics and purposes which allow for building a large diversity of objects and working with a wide range of materials.

### 8.2.1 Laser Cutter

The laser cutter is by far the machine that was the most used for this project. It is thanks to it that the use of POM was possible. It is very fast, making iterative prototyping rapid and easy. The cutting parameters (speed and power) are very straightforward to find. Tests on a small piece of material can be rapidly conducted to identify the ideal parameters for a new material. Table 8.3 shows the parameters that were used during

this project for the different materials. They correspond to the use of the big laser cutter (100W) hence the parameters for the small laser cutter (80W) might be a bit different.

| Material         | Speed [mm/s] | Power [%] | # of cuts |
|------------------|--------------|-----------|-----------|
| 6 mm POM         | 10           | 70        | 2         |
| 3 mm wood        | 20           | 40        | 1         |
| 4 mm wood        | 20           | 50        | 1         |
| 6 mm wood        | 15           | 60        | 1         |
| 6 mm Plexiglas   | 10           | 60        | 1         |
| 1.5 mm Plexiglas | 20           | 40        | 1         |

Table 8.3: Parameters used for different material for the laser cutter.

### 8.2.2 3D Printers

The 3D printers were used for the crank handle, the coupling system and the spacers inside the shredding box. During the iterative prototyping of the crank handle (explained in Section 4.1.4) it became obvious that 3D printed objects are not very good at sustaining high stresses in all different directions. Indeed, as 3D-printed objects are almost empty, they are not suitable for every applications. The lever arm of the crank handle was first made in laser-cut wood and not in 3D-printed PLA for that reason. Moreover, the connecting system between the shredding shaft and the metal bar lever arm that was built with the 3D printer broke rapidly. However, for the coupling system, the 3D-printed PLA was quite suitable. It was reinforced with bolts and nuts for disabling the plastic layers from going off one from another. Indeed, the transversal direction to the layers (printing z axis) is more easily cracked under load than the longitudinal direction (inside the printing plane). Still, at too high power, the coupling system broke, meaning that there is a limit to the capability of 3D-printed parts to sustain high strengths. This latter observation is an important limitation of the PLA 3D printers. Indeed, it is quite obvious that in the future if the motor needs to go at a higher power, the coupling system will have to change, either be bought or made in another material than PLA.

### 8.2.3 CNC milling

The CNC milling machine was used to manufacture the frame, the sieve, the lever arm of the crank handle and the reinforcements for the small knives. It is also an indispensable machine as it is the only commonly found FabLab machine that can work with metal (aluminium). Moreover, the laser cutter only cuts wood plates up to 6 mm thickness, which makes the CNC machine very useful for cutting wood of 18 mm thickness as was needed for building the frame. In addition, with the CNC machine, it is possible to take out a layer of wood of a specific thickness without going all the way through the material, which is not possible with the laser cutter. The CNC milling machine is, however, the most complicated FabLab machine to get accommodated with. For machining aluminium,

it was at first quite difficult to find the right parameters and some miller cutters were broken when manufacturing the lever arm. Eventually, the right parameters were found (see Table 8.4) and building the sieve and the reinforcements was easier than expected.

| Name                     | Value |
|--------------------------|-------|
| Feed rate [mm/min]       | 127   |
| Plunge rate [mm/min]     | 76.2  |
| Depth per pas [mm]       | 0.1   |
| Rotation speed [rev/min] | 2000  |

Table 8.4: Parameters for machining aluminium with the CNC miller.

### 8.3 Critical Discussion About the Final Prototype

The final prototype is functional and capable of shredding plastic. The main goal of improving the manufacturability of the plastic shredder has been achieved, with a significant increase from 0.8% to 92.4% of the components that can be produced in a FabLab. It should be noted that the aluminum claws were fabricated using a water jet cutter, which, although not officially considered a FabLab machine, is becoming more commonly found in FabLabs. However, the claws could be manufactured with the CNC machine by slightly modifying their design.

While the manufacturability in FabLab has increased, the complexity of certain parts has also increased. The steel blades and small fixed knives, originally cut with a metal laser cutter as a single piece, are now made of two or three parts that are screwed together. Laser-cutting POM is relatively straightforward in a FabLab. Manufacturing the claws, however, requires a good understanding of the CNC machine. Nevertheless, with a prepared G-code and the correct parameters, it can be easily accomplished in a FabLab, although requiring more time. Simplifying the design of the claws could reduce their complexity.

The coupling system used in the final prototype is indeed more complex than the coupling system of Precious Plastic. It is constructed in three parts and requires reinforcement with screws. In contrast, the Precious Plastic coupling system only needs to be tightened with one screw per shaft. However, the advantage of the coupling system of this project is its adaptability to different shaft sizes. Two different tightening systems are employed, and they can be easily adjusted based on the shapes of the available motor and shredder shafts.

The main disadvantage of the prototype is that an insufficient torque is produced. Other disadvantages include the fact that the screws holding the claws on the blades become loose due to vibrations, claws move and damage the large fixed knives, and the screws of the small fixed knives touch some claws, causing significant wear. Proposed solutions to

these problems will be discussed in the following Section (8.4).

Reflecting on the distributed design map, the final design utilizes tools available in a FabLab, which makes them more accessible to a wider range of users compared to industrial CNC tools used in the Precious Plastic project. In terms of materials, steel is more readily available than POM, although other hard plastics suitable for laser-cutting in FabLabs can also be considered. The type of shared information is similar to that of Precious Plastic, where everything is documented and blueprints are shared. In addition to this, the blueprints of certain parts, such as the coupling system and the size and shape of the claws, are adaptable for other shredders. Furthermore, an assembly plan can be found in Appendix G. An amelioration from the Precious Plastic documentation is that the necessary parameters for manufacturing each piece using specific machines are provided to be sure that other people can easily replicate this design.

## 8.4 Future Perspectives

The following section explores future perspectives for the project, outlining potential areas for improvement and development.

### Security

When constructing a plastic shredder, it is imperative to address the safety aspects to ensure the safekeeping of individuals involved. The following considerations should be taken into account in the further development of the shredder.

It is essential to design a system that restricts access to the blades, preventing users from inserting their hands into the machine. This could be achieved by incorporating a sensor system, automatically shutting down the shredder when necessary. Alternatively, the use of a higher hopper could be explored, ensuring that operators cannot reach the shredding area during runtime. Furthermore, in the event of an emergency, an easily accessible emergency stop button is paramount, enabling immediate shutdown of the shredder if needed. Additionally, to enhance safety, the rotating coupling system should be adequately covered. In fact, there are screws sticking out of this component and while turning fast it can be harmful. One end of the shredder shaft is freely turning beyond the frame and a protective housing around it is also necessary.

By addressing these safety measures, the risk of accidents and injuries associated with operating the plastic shredder can be significantly reduced.

### Automation

In the pursuit of enhancing the functionality and efficiency of a plastic shredder, automation plays a vital role. By integrating automated features, such as the ability to reverse automatically when the shredder is stuck, the overall performance and user experience



can be significantly improved. The current drive controller provides the capability for backward motion. To facilitate automation, the drive controller can be connected to a device such as an Arduino, which serves as a programmable controller. Through this connection, the Arduino can monitor the shredder's operation, detect obstructions, and trigger the necessary actions for reversing the shredder's rotation. Furthermore, such a device can also monitor the shredder's performance, including parameters such as motor speed, torque, and temperature, to ensure optimal operation and prevent any potential issues or overheating.

Automation does not only improve the efficiency of the plastic shredder but also enhances safety. By automatically reversing when a blockage occurs, the risk of damage to the shredder's components and potential operator injuries are significantly reduced.

### **Parametric Shredder**

The ultimate objective is to achieve a parametric design for the shredder, where the design is adapted to the specific plastic being shredded. The type of plastic and its thickness significantly influence the required torque for effective shredding. This, in turn, impacts the design of the blades, fixed knives, motor, and reduction system. Rather than aiming for a "one-size-fits-all" shredder, the goal would be to design a shredder tailored to specific use cases. By following the presented methodology in designing this shredder, it becomes possible to extend and apply the same approach to different use cases, ensuring optimal performance and efficiency.

### **Reduction System**

In order to effectively shred thicker plastics and prevent blockage issues, the shredder motor should possess a higher torque and a lower rotation speed. This can be achieved through the implementation of a reduction system, which serves to decrease the angular speed while simultaneously increasing the torque.

As mentioned in the section on the reduction system (Section 4.2.2), improvements need to be made to the actual design in order to obtain a functional reduction system. One possible solution involves manufacturing aluminum pulleys in multiple layers using CNC technology. These layers can then be assembled in a manner similar to the actual wooden pulleys. Another option is to purchase a gearbox that matches the motor specifications (see Appendix C).

The shredder of this project has been specifically designed for being manufactured in FabLabs, where PLA waste is generated from 3D printers. It is important to note that PLA is currently not recycled by any recycling centers. By increasing the torque of the motor with a reduction system, PLA can be effectively shredded.

### **Coupling System**

As indicated in Section 4.2.1, the current coupling system experienced a failure when operating at a speed equivalent to a frequency of 10.5 Hz. To facilitate the shredding of plastic, a higher torque than the actual torque is required. The developed coupling system may not be able to withstand a higher torque. It would be beneficial to examine the weak parts of the system and reinforce them accordingly. Alternatively, exploring the use of different materials for this device is advisable. As previously mentioned, 3D printing has its limitations, and even with reinforcement, it may not be able to endure significant stress levels.

### **Shaft**

Currently, the shaft is made of steel and has a unique design with a combination of round and hexagonal sections, making it almost impossible to be manufactured in a FabLab. Aluminum is the only metal that can be manufactured in a FabLab, but manufacturing it in 3-dimensions using a CNC machine poses significant complexity. As discussed in the section addressing the shaft (Section 6.2), one potential solution could be to use a standard circular shaft and modify the blade fixation mechanism accordingly. Further investigations are needed to explore different design options and find a feasible solution for manufacturing the shaft within the constraints of a FabLab.

### **Blades and Fixed Knives**

As mentioned before, one crucial aspect is to ensure that the bolts used to fasten the blades and fixed knives remain securely in place during runtime. The vibrations and mechanical forces involved in shredding can cause the bolts to become loose over time, compromising the shredder's effectiveness. An adhesive product such as Loctite could be used to prevent the bolts from unscrewing.

To reduce friction and optimize the performance of the shredder, it is recommended to position the fixed knives bolts lower. By adjusting the positioning, friction between rotating and fixed blades can be minimized, resulting in smoother operation and improved efficiency.

Furthermore, reinforcing the large fixed knives is essential to enhance their strength and durability. Using a similar reinforcement as the small fixed knives or exploring alternative designs that can withstand the forces and stresses exerted during shredding operations is recommended. Additionally, the alignment of the claws on the blades is crucial to ensure efficient shredding and prevent potential damage to the large fixed knives. Regular inspections should be conducted to check the alignment and make necessary adjustments if misalignment is detected.

Lastly, by simplifying the shape of the claws (by having more straight surfaces), they can be more easily manufactured using the CNC machine, eliminating the need for a laser jet

cutter. A simpler shape not only facilitates the manufacturing process but also reduces the overall production time.

### **Closing the Recycling Loop**

Shredding is just one aspect of the recycling loop. Once plastic waste is shredded into flakes, these flakes can be used by other Precious Plastic machines, such as the extrusion, injection, and compression machines, to transform the shredded plastic into new plastic objects.

Before shredding, waste must be sorted, collected, cleaned, and potentially pre-cut. Inefficient sorting and cleaning can lead to two common issues when using other Precious Plastic machines. Firstly, contamination or dirt in the plastic can cause nozzle clogging and difficulties in extrusion. Secondly, different types of plastics may be mixed together, resulting in uneven melting and poorly produced objects, obstructing the smooth flow of plastic through the extrusion nozzle. To mitigate these issues, proper sorting and cleaning of waste are necessary, but it is also needed to ensure that the shredder is cleaned when transitioning between different types of plastics. The quality of the output flakes primarily depends on the quality of the input waste and the cleanliness of the shredder itself.

However, even with thorough sorting and cleaning, it is important to note that most recycled plastic objects undergo downcycling. Through the recycling process, their properties and quality degrade compared to the original material, making it in most cases challenging to recreate the exact same object as the initial one.

### **Future Prospects of This Shredder**

It has been demonstrated that the shredder is capable of effectively shredding plastics. Therefore, the shredder can be utilized to shred plastics with suitable properties and dimensions. Additionally, it is important to highlight that this shredder serves as a testing platform, allowing for experimentation. The current design can be further tested and refined, and potential areas of improvement can be explored. Consequently, this shredder primarily serves as an experimental test bench, enabling the exploration of various possibilities and enhancements.

## Chapter 9

# Conclusion

This master thesis aims at increasing the manufacturability of a plastic shredder in a FabLab environment. Through the redesign of the Precious Plastic shredder, the goal is to enhance the percentage of components that could be produced in a FabLab.

The results of this project are significant, with a remarkable increase in the manufacturability of the shredder. The initial Precious Plastic shredder consisted of 118 parts, of which only one could be manufactured in a FabLab. This corresponded to a meager 0.8% of the shredder's components. However, through the redesign and manufacturing process, the final prototype is composed of 119 parts, with 110 of them being produced in the FabLab. This results in a substantial improvement, with a manufacturability percentage of 92.4% achieved for the final prototype.

This paper provides a comprehensive background on global and Belgian plastic waste contexts, the Precious Plastic project, and FabLabs. It includes a state-of-the-art analysis of plastic shredders, recycled plastics' properties, and engineering design and prototyping methods. The design and prototyping of the shredder are meticulously presented, with alternative solutions investigated for each part. Through iterative testing and refinement, a final concept for the shredder was developed, validated and tested.

The key concept of the project is the exploration of various designs through several prototyping iterations. The ultimate version of the shredder incorporates the following nine described elements. The most critical parts are the blades which are made of POM with aluminum tips. They are mounted onto a hexagonal steel shaft designed by Precious Plastic. The fixed knives are also cut from POM, and the small ones are reinforced with aluminum. The shredding frame is a combination of POM and wood. The hopper, responsible for guiding the waste towards the blades, is laser-cut from wood, while the frame is CNC-cut from wood as well. The current motor of this prototype has a power output of 2.2 kW and its rotation frequency and speed can be controlled using a drive controller. A coupling system has been specifically designed and 3D-printed to connect the motor and shredder box together.

This functional prototype primarily serves as a test bench, demonstrating the possibility of adapting parts for being manufactured in FabLabs. In addition, it successfully shreds plastic, although producing slightly larger flakes compared to a steel shredder, and having more wear. Tests with larger plastic quantities have been conducted, demonstrating that the shredder is capable to process approximately 570g/h of plastic waste.

While the shredder is not yet optimal for recycling plastic, it has the potential for significant positive impact on plastic waste sorting and recycling, particularly in Louvain-la-Neuve. Furthermore, its adaptability for manufacturing in various locations worldwide makes it a valuable solution for countries with inadequate or nonexistent plastic recycling systems.

In conclusion, this master thesis has successfully increased the manufacturability of a plastic shredder in a FabLab environment. The project also highlights the strengths and limitations of FabLab machines, emphasizing their usability and potential for diverse manufacturing applications. By enhancing the manufacturability of the plastic shredder, this project contributes to the broader objective of promoting sustainable waste management practices. The ability to produce shredder components locally in FabLabs can facilitate the establishment of recycling initiatives in various communities, enabling the processing of plastic waste at a smaller scale.

Moving forward, further improvements and optimizations can be achieved on the shredder design to enhance its performance and efficiency. This well-documented project sets the foundation for future research and development, contributing to the Precious Plastic initiative by enhancing the accessibility and reproducibility of the plastic shredder. Researchers and enthusiasts interested in reproducing this shredder prototype can find all the necessary information at the following link: <https://openhub.fab-manager.com/#!/>.

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# Part IV

## Appendix

## Appendix A

### Use case survey

This section presents the results obtained from a survey conducted among the students of Louvain-la-Neuve to determine their willingness to collect and deposit plastic take-away food containers in designated trash cans within the city. The survey had 74 responses.

From the first question, it is found that 24% of the students consume take-away food once or several times per week, while 74% do so at least once a month.

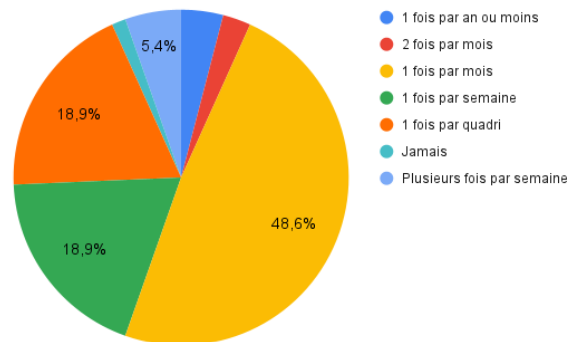


Figure A.1: At what frequency do you eat take-away food.

Based on the survey results, it can be concluded that the student living in Louvain-la-Neuve are willing to collect specific plastic containers to contribute positively to the environment. Therefore, one or more specific trash cans could be placed in the city center. Additionally, it was identified that not everyone is able or willing to clean the waste before disposal. Hence, a cleaning step must be implemented before shredding the waste in the shredder.

Regarding the second question, the survey revealed that 12.3% of the students dispose of the plastic containers in the nearest trash can without seeking out a suitable PMC trash can. However, 64.4% of the students already dispose of them in the right PMC trash can.

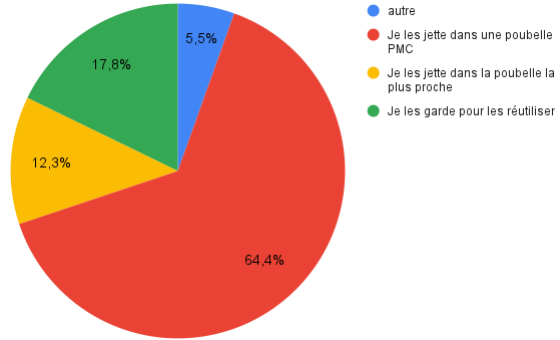


Figure A.2: What do you do with the containers?

The third question highlights that 97.2% of the Louvain-la-Neuve students are willing to change their habits and collect the plastic containers separately from the PMC waste.

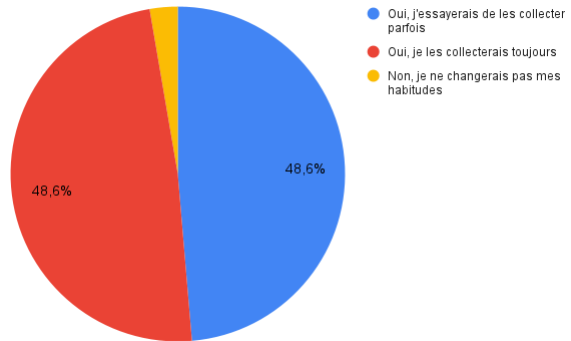


Figure A.3: Would you change your habits and collect the plastic containers?

Furthermore, 86.5% of the students are willing to bring these containers to a specific trash can. However, 18.9% would do it on the condition that the trash can is conveniently located, either along their regular route or near their accommodation.

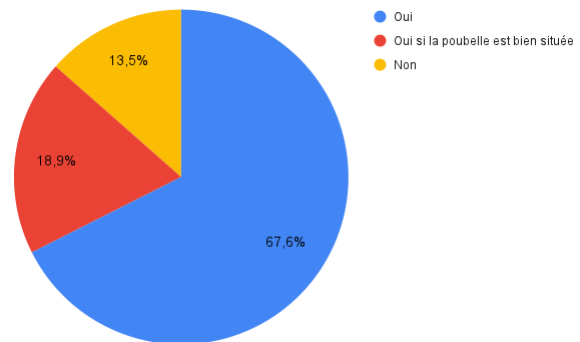


Figure A.4: Would you bring the plastic containers to a specific trash can?

Finally, slightly over 50% of the student would willingly clean the plastic containers. In addition to the other half who are not always willing to clean their plastic containers, considering the goal of collecting containers from individuals who consume food outside their homes, it is expected that not all the plastic collected will be cleaned.

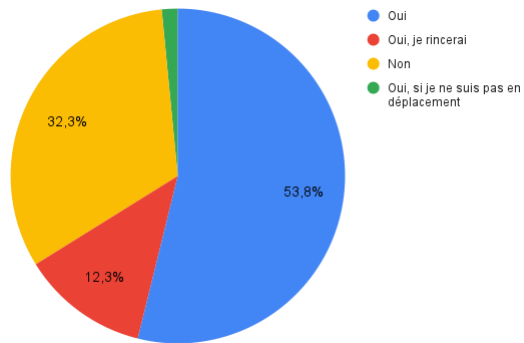


Figure A.5: Would you clean the plastic containers before bringing them?



# Appendix B

## Drive Controller Data Sheet

# SIEMENS

Data sheet for SINAMICS V20

Article No. : 6SL3210-5BB22-2UV1

Client order no. :  
Order no. :  
Offer no. :  
Remarks :

Item no. :  
Consignment no. :  
Project :



Figure similar

| Rated data |  |  |
|------------|--|--|
|------------|--|--|

|                  |                           |  |
|------------------|---------------------------|--|
| Input            |                           |  |
| Number of phases | 1 AC                      |  |
| Line voltage     | 200 ... 240 V -15 % +10 % |  |
| Line frequency   | 47 ... 63 Hz              |  |

|                    |              |                        |
|--------------------|--------------|------------------------|
| Output             |              |                        |
| Number of phases   | 3 AC         |                        |
| Rated voltage      | 230V IEC     | 240V NEC <sup>1)</sup> |
| Rated power (LO)   | 2.20 kW      | 3.00 hp                |
| Rated power (HO)   | 2.20 kW      | 3.00 hp                |
| Rated current (LO) | 11.00 A      | 11.00 A                |
| Rated current (HO) | 11.00 A      | 11.00 A                |
| Rated current (IN) | 11.00 A      |                        |
| Pulse frequency    | 8.00 kHz     |                        |
| Output frequency   | 0 ... 550 Hz |                        |

|                                                       |  |
|-------------------------------------------------------|--|
| Overload capability                                   |  |
| Low Overload (LO)                                     |  |
| 110 % rated output current for 60 s, cycle time 300 s |  |
| High Overload (HO)                                    |  |
| 150 % rated output current for 60 s, cycle time 300 s |  |

| General tech. specifications |  |
|------------------------------|--|
|------------------------------|--|

|                           |            |
|---------------------------|------------|
| Power factor $\lambda$    | 0.72       |
| Offset factor $\cos \phi$ | 0.95       |
| Efficiency $\eta$         | 0.98       |
| Filter class (integrated) | Unfiltered |

| Communication |  |
|---------------|--|
|---------------|--|

|               |                 |
|---------------|-----------------|
| Communication | USS, Modbus RTU |
|---------------|-----------------|

| Inputs / outputs |  |
|------------------|--|
|------------------|--|

|                                    |                                             |
|------------------------------------|---------------------------------------------|
| Standard digital inputs            |                                             |
| Number                             | 4                                           |
| Digital outputs                    |                                             |
| Number as relay changeover contact | 1                                           |
| Number as transistor               | 1                                           |
| Analog inputs                      |                                             |
| Number                             | 2 (Can be used as additional digital input) |
| Analog outputs                     |                                             |
| Number                             | 1                                           |

| Ambient conditions |  |
|--------------------|--|
|--------------------|--|

|                         |                                |
|-------------------------|--------------------------------|
| Cooling                 | External fan                   |
| Installation altitude   | 1,000 m (3,280.84 ft)          |
| Ambient temperature     |                                |
| Operation <sup>2)</sup> | -10 ... 60 °C (14 ... 140 °F)  |
| Storage                 | -40 ... 70 °C (-40 ... 158 °F) |
| Relative humidity       |                                |
| Max. operation          | 95 %                           |

| Connections |  |
|-------------|--|
|-------------|--|

|                         |                  |
|-------------------------|------------------|
| Max. motor cable length |                  |
| Shielded                | 25 m (82.02 ft)  |
| Unshielded              | 50 m (164.04 ft) |

| Mechanical data |  |
|-----------------|--|
|-----------------|--|

|                      |                                       |
|----------------------|---------------------------------------|
| Mounting position    | Wall mounting / side-by-side mounting |
| Degree of protection | IP20                                  |
| Frame size           | FSAD                                  |
| Net weight           | 1.90 kg (4.19 lb)                     |
| Dimensions           |                                       |
| Width                | 136.6 mm (5.38 in)                    |
| Height               | 176.5 mm (6.95 in)                    |
| Depth                | 158.8 mm (6.25 in)                    |

| Standards |  |
|-----------|--|
|-----------|--|

|                           |                                         |
|---------------------------|-----------------------------------------|
| Compliance with standards | CE, cULus, C-Tick (RCM)                 |
| CE marking                | EN 61800-5-1 /EN 60204-1 and EN 61800-3 |

<sup>1)</sup>The output current and HP ratings are valid for the voltage range 220V-240V

<sup>2)</sup>Please observe derating at temperatures of 40 °C or above

## Appendix C

### Gearbox

The gearbox shown in Figure C.1, with its power corresponding to 3 hp, is suitable for the motor that has a power about 3 hp. The size of the input shaft (24mm) matches the motor's shaft, making it a suitable choice. However, the output shaft of the gearbox does not match the shredder, necessitating the addition of an extra shaft and a coupling system, as described in Section 4.2.1, to connect it to the shredding box.



**RÉDUCTEUR À VIS SANS FIN  
DIMENSION 75 BRIDE PAM 200/24 -  
MOTEUR CARCASSE 90 B5**

**181,16 € TTC**  
149,72 € HT

Avec arbre de sortie creux de Ø28mm, et bride d'entrée PAM 200/24 (Ø Ext 200mm et Ø arbre d'entrée 24mm) type B5, adapté aux moteurs avec taille du carcasse 90.

rapports de réduction disponibles : 7,5-10-15-20-25-30-40.

Les puissances des moteurs habituels à 1500 tr/min sont :

- 1,5CV Max. red. i=40.
- 2CV Max. red. i=30.
- 3CV Carcasse réduite. Max. red. i=15.

Taux de réduction

|     |    |    |    |    |    |    |
|-----|----|----|----|----|----|----|
| 7.5 | 10 | 15 | 20 | 25 | 30 | 40 |
|-----|----|----|----|----|----|----|

Figure C.1: Gearbox [86]

## Appendix D

### PLA Spacers

As the blades, blade spacers, small and big fixed knives all have the same thickness, it was necessary to add some spacers to avoid the friction between the blades and the big fixed knives. This Appendix explains how the thickness of these spacers has been computed to enable anyone to redo this computation with other thicknesses.

As the Precious Plastic shaft is used to hold all the blades together, the dimensions from Precious Plastic have been taken. All the fixed knives assembled together should have a thickness of 149 mm, and the blades and blade spacers should be 148 mm thick to all fit on the shaft.

The POM sheet that was used to manufacture all the elements is 6.1mm thick. It was therefore decided to use 12 blades, 11 blade spacers, 12 small fixed knives and 11 big fixed knives. The equation to solve to find the thickness of the additional spacers is, for the fixed knives side :

$$11 * 6.1 + 12 * (6.1 + x) = 149 \quad (D.1)$$

Giving  $x = 0.725$  mm. However, instead of have only one spacer per big fixed knife, it was decided that it would be better to have two spacers of half the thickness (0.3625 mm).

For the blades side, this leads to a total thickness of 148.275 mm instead of 148. The two side blades will therefore not be entirely on the shaft.

$$11 * (6.1 + x) + 12 * 6.1 = 148.275 \quad (D.2)$$

## Appendix E

# Bill of Material

| Machine part   | Description        | Material  | Details                             | Quantity                                | Where to get   | Price [€]     |
|----------------|--------------------|-----------|-------------------------------------|-----------------------------------------|----------------|---------------|
| Shredding box  | 6 mm sheet         | POM       | Cutted                              | 0.4 m <sup>2</sup>                      | Eriks [87]     | 100           |
|                | 6 mm sheet         | Aluminium | Cutted                              | 0.02 m <sup>2</sup>                     | Metal shop     | 18            |
|                | 0.5 mm sheet       | Aluminium | Cutted                              | 0.03 m <sup>2</sup>                     | Metal shop     | 3             |
|                | 3 mm sheet         | Wood      | Cutted                              | 40 mm x 60 mm                           | FabLab         | 4             |
|                | Filament           | PLA       | Basic<br>2.85 mm diameter           | 20g                                     | FabLab         | 2             |
|                | Hexagonal bar      | Steel     | Hexagon: 27 mm<br>Shaft: 20 mm diam | 32 cm                                   | Bazar [18]     | 25            |
|                | Bearings           | Bearings  | 20 mm UCFL204                       | 2x                                      | Bazar          | 18            |
|                | 3 mm ring          | Steel     | 20 mm inner diam                    | 2x                                      | Bazar          | 5             |
|                | 6 mm ring          | Steel     | 20 mm inner diam                    | 2x                                      | Bazar          | 5             |
|                |                    |           | Steel                               | M10                                     | 2 x 200 mm     | DIY shop [88] |
| Bolts and nuts |                    | Steel     | M8                                  | 2 x 200 mm                              | DIY shop       |               |
|                |                    | Steel     | M10                                 | 4 x 25 mm<br>(countersunk head)         | Amazon [89]    | 30            |
|                |                    | Steel     | M8                                  | 4 x 30 mm                               | DIY shop       |               |
|                |                    | Steel     | M2.5                                | 48 x 20 mm<br>+ 24 x 10 mm              | DIY shop       |               |
|                |                    |           |                                     |                                         |                |               |
| Hopper         | 3 mm sheet         | Wood      | Cutted                              | 40 mm x 60 mm                           | FabLab, Shop   | 4             |
| Frame          | Bolts and nuts     | Steel     | M6                                  | 1 x 400 mm                              | DIY shop       | 5             |
|                | 18 mm sheet        | OSB wood  | Cutted                              | 2x(600x2400) mm <sup>2</sup>            | DIY shop       | 16            |
| Electronics    | Three-phased motor | -         | 2.2 kW                              | 1x                                      | Amazon [90]    | 170           |
|                | Driver             | -         | -                                   | 1x                                      | Siemens [87]   | 400           |
|                | Cables             | -         | Mono-phased                         | 1 m                                     | Old households | 0             |
|                |                    | -         | Three-phased                        | 0.7 m                                   | Old households |               |
|                | Bolts and nuts     | Steel     | M7                                  | 4 x 60 mm                               | DIY shop       | 5             |
| Coupling       | Filament           | PLA       | Basic<br>2.85 mm diameter           | 350g(à vérifier)                        | FabLab         | 35            |
|                | Bolts and nuts     | Steel     | M6                                  | 4 x 20 mm<br>+ 7 x 50 mm<br>+ 2 x 60 mm | DIY shop       | 5             |
| Laser cutter   | Machine use        | -         | 5€ / 30 min                         | 4 x 30 min                              | FabLab         | 20            |
| TOTAL          |                    |           |                                     |                                         |                | 870           |

Table E.1: BOM

## Appendix F

### Shredding results



(a) Initial plastic



(b) POM flakes



(c) Steel flakes

Figure F.1: PET



(a) Initial plastic



(b) POM flakes



(c) Steel flakes

Figure F.2: PS



(a) Initial plastic

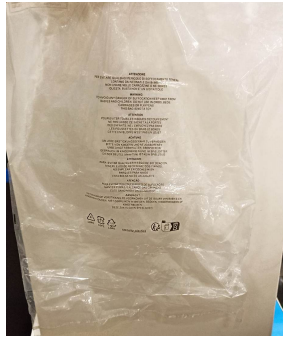


(b) POM flakes



(c) Final result

Figure F.3: HDPE



(a) Initial plastic

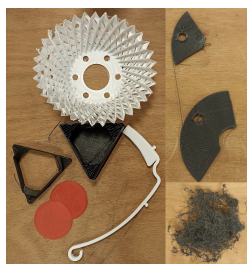


(b) POM jam



(c) Steel jam

Figure F.4: LDPE



(a) Initial plastic



(b) POM flakes



(c) Steel flakes

Figure F.5: PLA



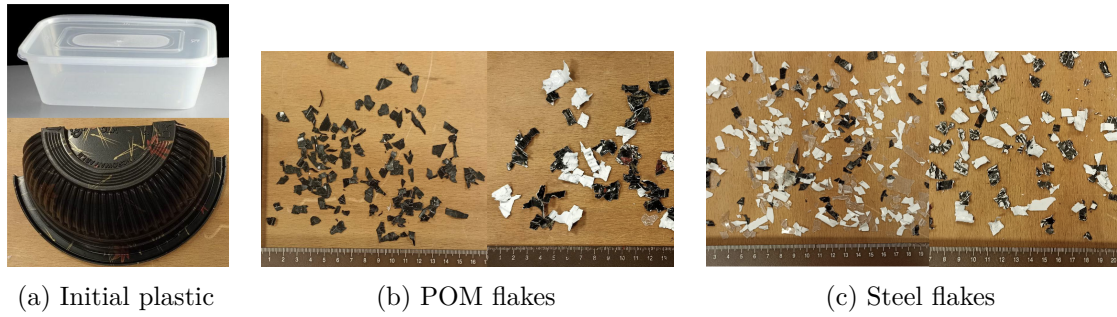


Figure F.6: PP

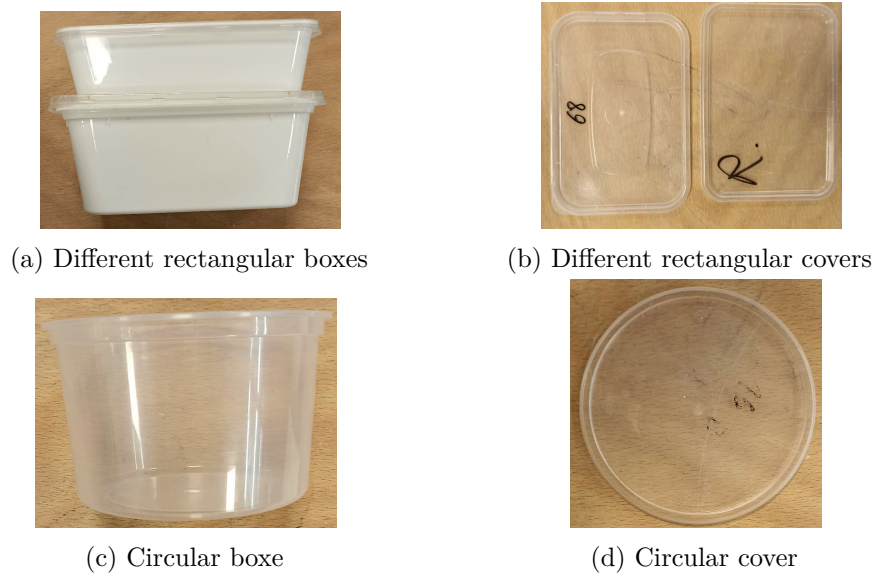
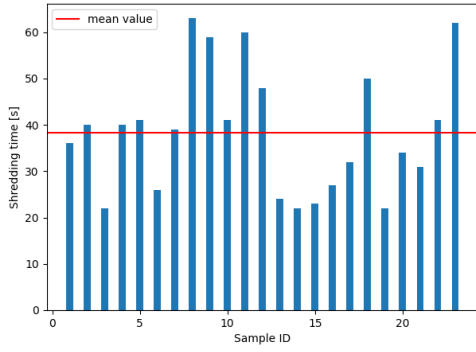
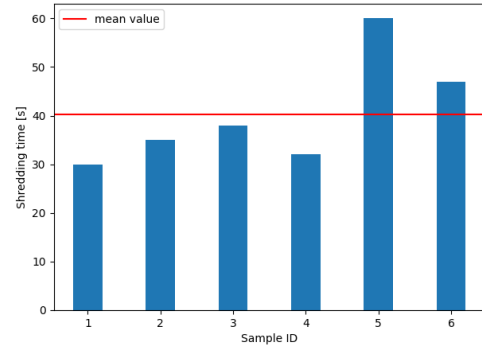
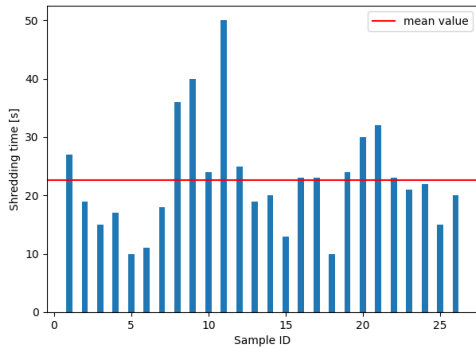
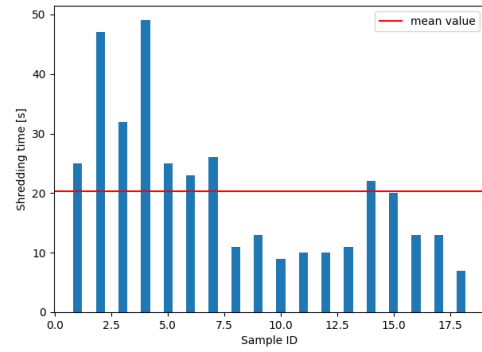
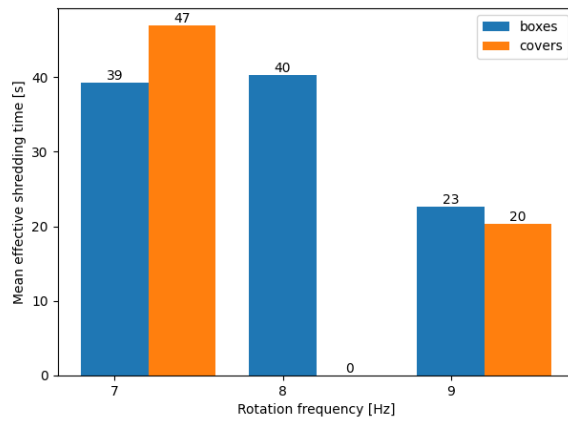


Figure F.7: PP boxes and covers, rectangular and circular.




 (a) Boxes,  $f = 7$  Hz

 (b) Boxes,  $f = 8$  Hz

 (c) Boxes,  $f = 9$  Hz

 (d) Covers,  $f = 9$  Hz


(e) Comparison

Figure F.8: Effective shredding times, for different rotation speeds, for each sample and average.

## Appendix G

# Fabrication and Assembly Plan

Table G.1 gives the parameters for laser cutting for the different materials

| Material         | Speed [mm/s] | Power [%] | # of cuts |
|------------------|--------------|-----------|-----------|
| 6 mm POM         | 10           | 70        | 2         |
| 3 mm wood        | 20           | 40        | 1         |
| 4 mm wood        | 20           | 50        | 1         |
| 6 mm wood        | 15           | 60        | 1         |
| 6 mm Plexiglas   | 10           | 60        | 1         |
| 1.5 mm Plexiglas | 20           | 40        | 1         |

Table G.1: Parameters used for different material for the laser cutter.

### Shredding Box

#### Parts Manufacturing

##### Laser Cut

| Part                                         | Quantity | Document name         | Material  |
|----------------------------------------------|----------|-----------------------|-----------|
| Blade 1                                      | 4        | Blade1                | POM 6 mm  |
| Blade 2                                      | 4        | Blade2                | POM 6 mm  |
| Blade 3                                      | 4        | Blade3                | POM 6 mm  |
| Blade spacer                                 | 11       | BladeSpacer           | POM 6 mm  |
| Small fixed knife                            | 12       | SmallFixedKnife       | POM 6 mm  |
| Big fixed knife                              | 11       | LargeFixedKnife       | POM 6 mm  |
| Sieve holder                                 | 2        | SieveHolder           | Wood 3 mm |
| Shredding frame (stator side) middle         | 1        | FixedKivesMiddle      | Wood 3mm  |
| Shredding frame (stator side) side           | 2        | FixedKivesSide        | Wood 3mm  |
| Shredding frame (rotor side) middle          | 1        | FreeMiddle            | Wood 3mm  |
| Shredding frame (rotor side) side 1          | 2        | FreeSide3mm           | Wood 3mm  |
| Shredding frame (rotor side) side 2          | 3        | FreeSide6mm           | Wood 6mm  |
| Shredding frame (rotor side) reinforcement 1 | 2        | FreeReinforcement37mm | Wood 3mm  |
| Shredding frame (rotor side) reinforcement 2 | 2        | FreeReinforcement38mm | Wood 3mm  |
| Large shredding frame plate 1                | 1        | POMSide1              | POM 6 mm  |
| Large shredding frame plate 2                | 1        | POMSide1              | POM 6 mm  |

Table G.2: Shredding box, parts manufacturing, laser cut.

**3D Printed**

Machine parameters: infill 30%

| Part              | Quantity | Document name   | Material |
|-------------------|----------|-----------------|----------|
| PLA blades spacer | 22       | PLABladesSpacer | PLA      |
| PLA knives spacer | 24       | PLAKnivesSpacer | PLA      |

Table G.3: Shredding box, parts manufacturing, 3D-printed

**CNC-Cut**

Table G.4 gives the parameters for manufacturing aluminium with the CNC-milling machine. Table G.5 gives the needed information to build the parts of the shredding box with this machine.

| Name                     | Value |
|--------------------------|-------|
| Feed rate [mm/min]       | 127   |
| Plunge rate [mm/min]     | 76.2  |
| Depth per pas [mm]       | 0.1   |
| Rotation speed [rev/min] | 2000  |

Table G.4: Parameters for machining aluminium with the CNC miller.

| Part                       | Quantity | Document name           | Material        |
|----------------------------|----------|-------------------------|-----------------|
| Sieve                      | 1        | Sieve                   | Aluminium 0.5mm |
| Fixed knives reinforcement | 12       | FixedKnifeReinforcement | Aluminium 0.5mm |
| Blade claw <sup>a</sup>    | 24       | Claw                    | Aluminium 6mm   |

Table G.5: Shredding box, parts manufacturing, CNC-cut

<sup>a</sup>Can also be manufactured with a water jet cutter.

**Parts to Buy or Manufacture Outside a FabLab**

| Part                  | Quantity | Document name    |
|-----------------------|----------|------------------|
| Shaft                 | 1        | Shaft            |
| Bearings              | 2        | /                |
| Small bearing spacers | 2        | BearingSpacer3mm |
| Big bearing spacers   | 2        | BearingSpacer6mm |

Table G.6: Shredding box, parts to manufacture outside a FabLab

**Bolts:**

- 2 M10 x 200 mm (fixed knives)
- 2 M8 x 200 mm (rotor side)
- 4 M10 x 25 mm milled head (bearings)
- 4 M8 x 30 mm (fix shredding box on frame)

- 48 M2.5 x 20 mm (fix claws on blades)
- 24 M2.5 x 10 mm (fix reinforcement on knives)

## Assembly

1. Assemble the small fixed knives with their aluminium reinforcements:
  - Drill two holes with a 3 mm bit in both parts.
  - Insert the nuts in the POM knife and fix the the aluminum plate with the bolts. First insert one bolt, then fold the aluminium plate and insert the other bolt.
2. Place the following parts next to each other and aligned: 1 3D-printed fixed knife spacer - 1 assembled small fixed knife - 1 3D-printed fixed knife spacer - 1 large fixed knife. Repeat this until no parts remain. Lock the assembly with the two M10 x 200 mm threaded shafts.
3. Assemble the shredding frame stator side using the two sides and the middle part.
4. Place the assembled fixed knives on this shredding frame side.
5. Assemble the blades with their aluminium claws:
  - Drill two holes with a 3 mm bit in both parts
  - Insert the nuts in the POM blade and fix the the aluminum claw with the bolts
6. Place the following parts on the hexagonal part of the shaft: 1 3D-printed blade spacer - 1 assembled blade - 1 3D-printed blade spacer - 1 blade spacer. Repeat this until no parts remain.
7. Place the two large bearing spacers on each side of the shaft. Place the two small bearing spacers on each side of the shaft. Place the assemble shaft on the assembled fixed knives
8. Fix the two bearings on the POM sides of the shredding frame.
9. Fix the two sieve holders on each POM side of the shredding frame.
10. Insert one POM side on the two threaded shafts.
11. If you have nuts that are hard to unscrew, remove one threaded shaft and insert it back the other way around. Do the same with the other threaded shaft. Insert the other POM side on the two threaded shafts. Be careful to insert also the wooden middle side inside the two POM sides.
12. Give a curved shape to the sieve and insert it along the holders.

13. Insert the rotor side of the shredding frame. First the middle part inside the two holes in the POM sides. Then the side parts and the reinforcements.
14. Insert the two other threaded shafts (M8 x 200 mm).
15. Tighten everything with the threaded shafts.

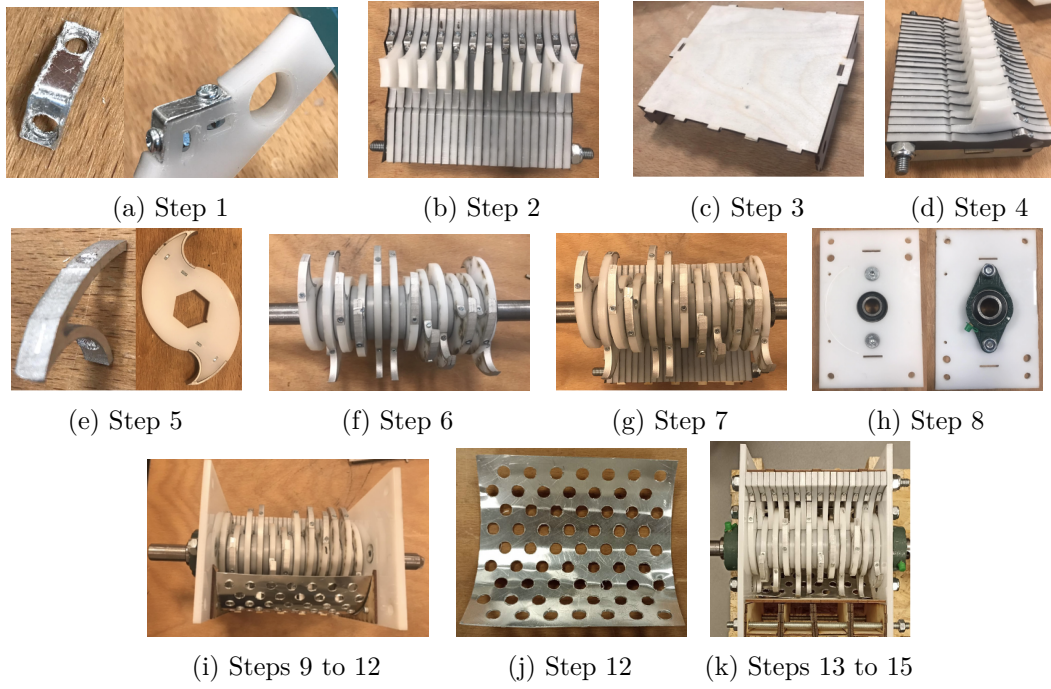


Figure G.1: Assembly of the shredding box steps

## Hopper

### Parts Manufacturing

#### Laser Cut

| Part   | Quantity | Document name | Material       |
|--------|----------|---------------|----------------|
| Side 1 | 2        | HopperSide1   | Wood 3 mm      |
| Side 2 | 2        | HopperSide2   | Wood 3 mm      |
| Pin    | 20       | HopperPin     | Wood 3 mm      |
| Cover  | 1        | HopperCover   | Plexiglas 6 mm |

Table G.7: Hopper, parts manufacturing, laser cut.

#### Bolts:

- M6 threaded shaft 400 mm (cover)

#### Assembly

1. Assemble the four sides of the hopper together without using the pins yet.
2. Assemble the hopper and shredding box with two M8 bolts for the fixed knives side of the shredding box and the upper M8 threaded shaft for the free side of the shredding box.
3. Place the pins.
4. Attach the long threaded shaft to the cover with two nuts.



(a) Steps 1 to 3



(b) Step 4



(c) Assembled Hopper

Figure G.2: Assembly of the hopper steps

## Actuation and Power Transmission

### Parts Manufacturing

#### 3D Printed

Machine parameters: 30% infill

| Part                  | Quantity | Document name       | Material |
|-----------------------|----------|---------------------|----------|
| Coupler motor side    | 1        | CouplerMotorSide    | PLA      |
| Coupler shredder part | 1        | CouplerShredderSide | PLA      |
| Coupler middle part   | 1        | CouplerMiddle       | PLA      |

Table G.8: Actuation and power transmission, parts manufacturing, 3D-printed

### Parts to Buy or Manufacture Outside a FabLab

| Part             | Quantity | Document name |
|------------------|----------|---------------|
| Motor            | 1        | /             |
| Drive controller | 1        | /             |
| Cables           | 2        | /             |

Table G.9: Power Supply, parts to buy outside a FabLab

#### Bolts:

- 4 M7 x 60 mm (fix motor on frame)
- 4 M6 x 20 mm (coupler middle part)
- 7 M6 x 50 mm (coupler shredder and motor parts)
- 2 M6 x 60 mm (coupler motor part)
- Electrical terminals

### Assembly

1. Put the nuts and bolts in the three parts of the coupler, tighten.
2. Mount the motor part on the motor shaft, as well as the middle part and tighten the perpendicular screw.
3. Mount the shredder part on the shredding box shaft, tighten the four bolts.
4. Assemble the shredder part and the middle part.



5. Connect the drive controller to the plug and the motor, with electrical terminals when needed.

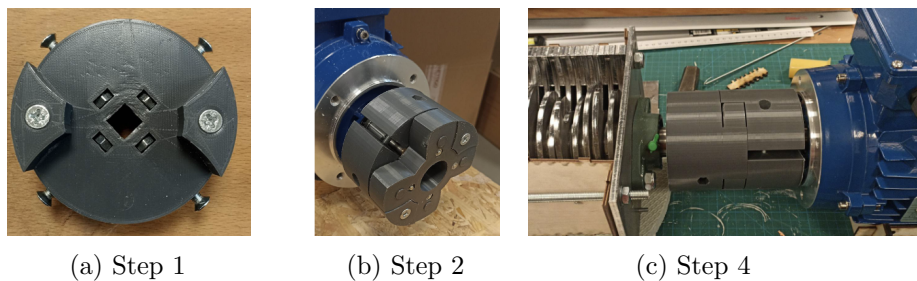


Figure G.3: Assembly of the Coupler Steps

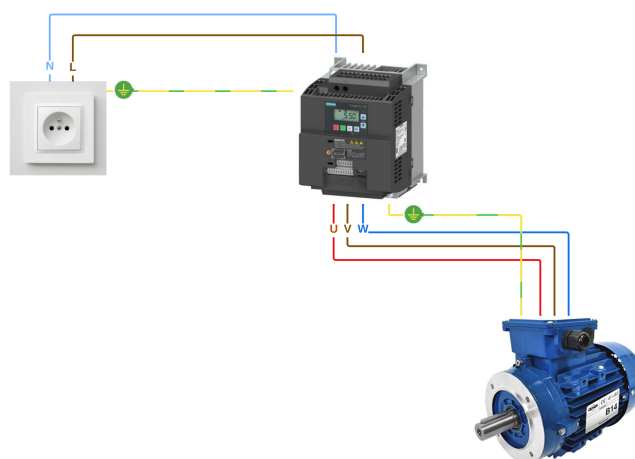


Figure G.4: Step 5: Cables connection

## Frame

### Parts Manufacturing

#### Laser Cut

| Part         | Quantity | Document name | Material  |
|--------------|----------|---------------|-----------|
| Motor holder | 2        | MotorHolder   | Wood 6 mm |

Table G.10: Frame, parts manufacturing, laser cut.

**CNC-Cut**

| Name                     | Value |
|--------------------------|-------|
| Feed rate [mm/min]       |       |
| Plunge rate [mm/min]     |       |
| Depth per pas [mm]       |       |
| Rotation speed [rev/min] |       |

Table G.11: Parameters for machining OSB with the CNC miller.

| Part                       | Quantity | Document name                 | Material  |
|----------------------------|----------|-------------------------------|-----------|
| Frame Front                | 1        | FrameFront.dxf                | OSB 18 mm |
| Frame Back                 | 1        | FrameBack.dxf                 | OSB 18 mm |
| Frame Top                  | 1        | FrameTop.dxf                  | OSB 18 mm |
| Right side                 | 1        | FrameRightSide.dxf            | OSB 18 mm |
| Left side                  | 1        | FrameLeftSide.dxf             | OSB 18 mm |
| Shredding box support 1    | 1        | FrameSupportShredderLong1.dxf | OSB 18 mm |
| Shredding box support 2    | 1        | FrameSupportShredderLong2.dxf | OSB 18 mm |
| Shredding box support 3    | 2        | FrameSupportShredderShort.dxf | OSB 18 mm |
| Motor support              | 2        | FrameSupportMotor1.dxf        | OSB 18 mm |
| Motor holder               | 2        | FrameSupportMotor2.dxf        | OSB 18 mm |
| Drive controller support 1 | 1        | FrameDriverSupport1           | OSB 18 mm |
| Drive controller support 2 | 1        | FrameDriverSupport2           | OSB 18 mm |
| Large pin                  | 12       | FramePinBig.dxf               | OSB 18 mm |
| Small pin                  | 20       | FramePinSmall.dxf             | OSB 18 mm |

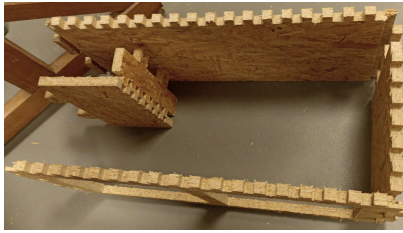
Table G.12: Frame, parts manufacturing, CNC-cut

**Assembly**

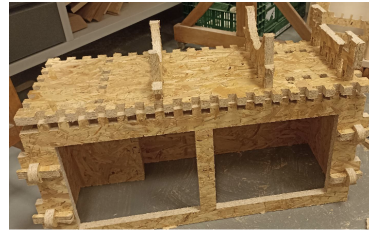
Warning: it may be needed to use a hammer and to sand the holes if they are too tight. OSB breaks easily so be careful to not use the hammer too strongly.

1. Assemble the drive Controller holder to the left side.
2. Assemble the four sides together (front, back, left, right).
3. Mount the supports (shredding box and motor) on the top part.
4. Mount the top part on the assembled four sides.
5. Add the pins.
6. Fix the motor on the motor holders with the M7 bolts.

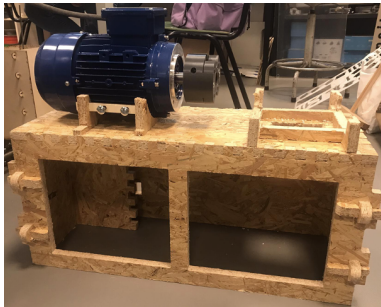
7. Fix the shredding box on the adapted supports with the M8 bolts.



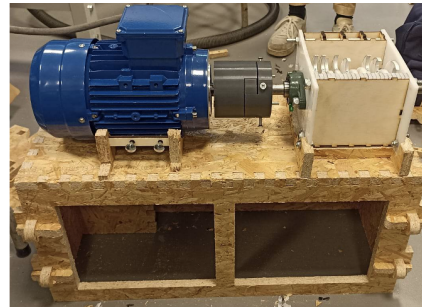
(a) Step 2



(b) Step 5



(c) Step 6



(d) Step 7

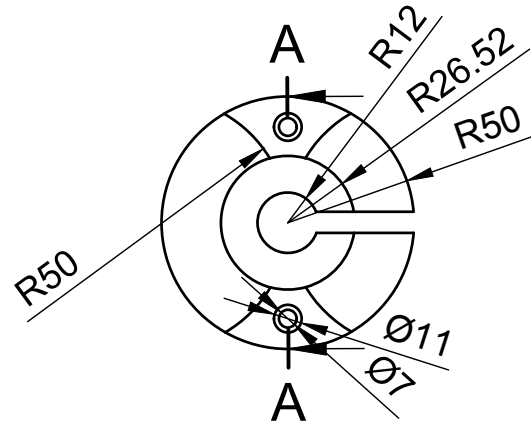
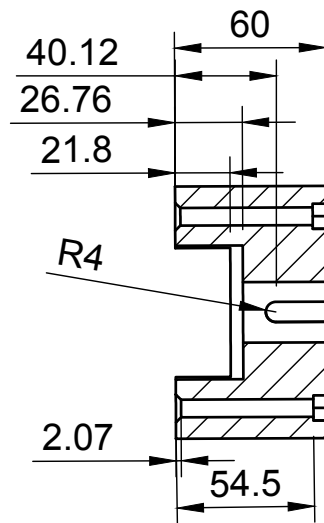
Figure G.5: Assembly of the Frame Steps

# Appendix H

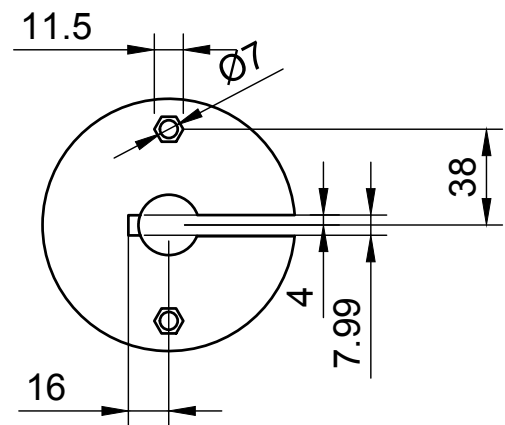
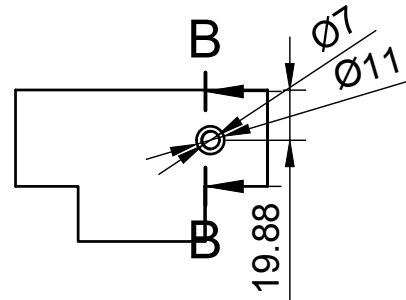
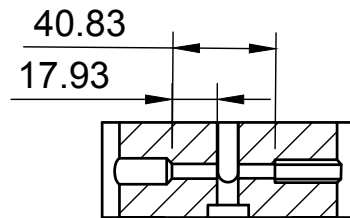
## Plans

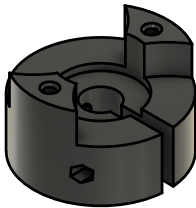


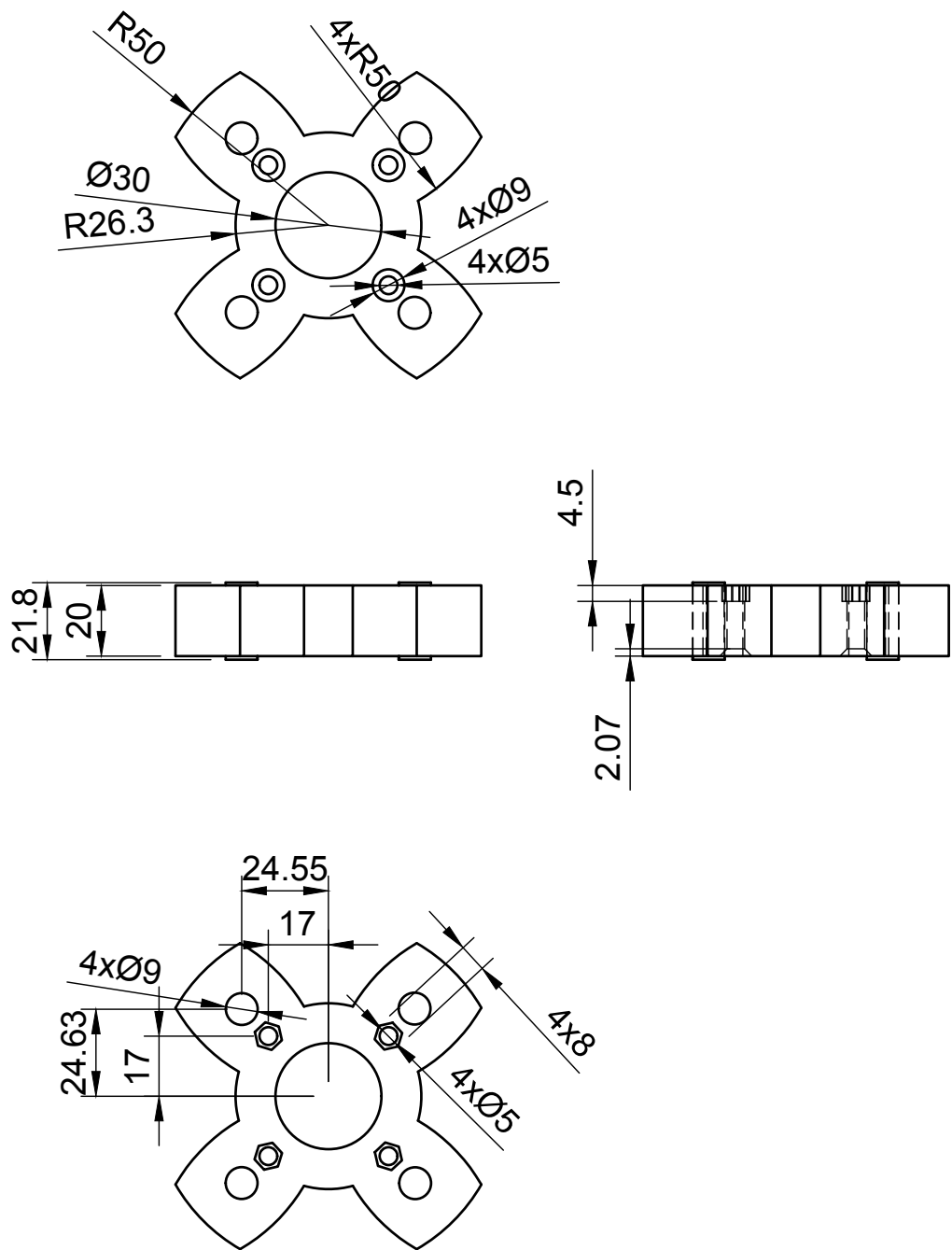
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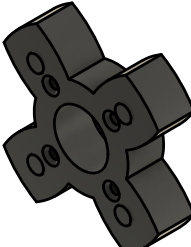


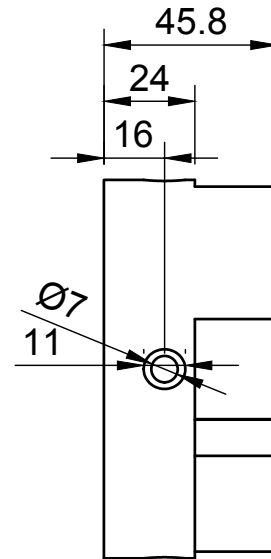
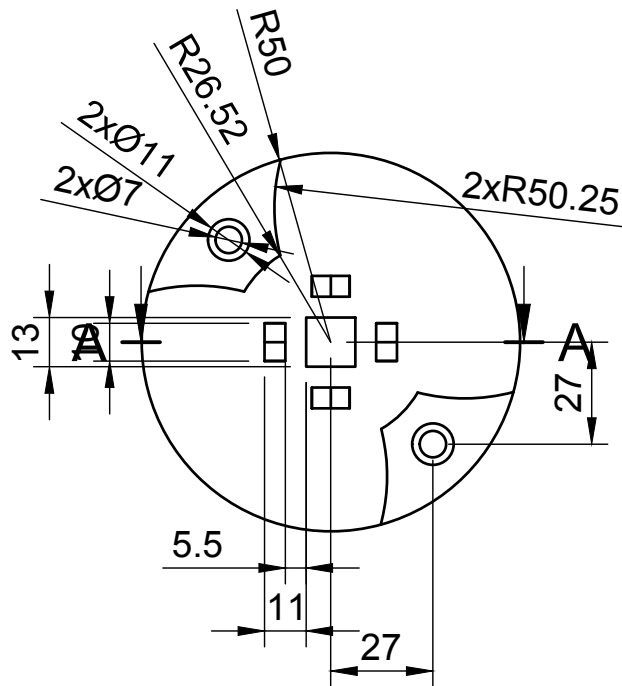
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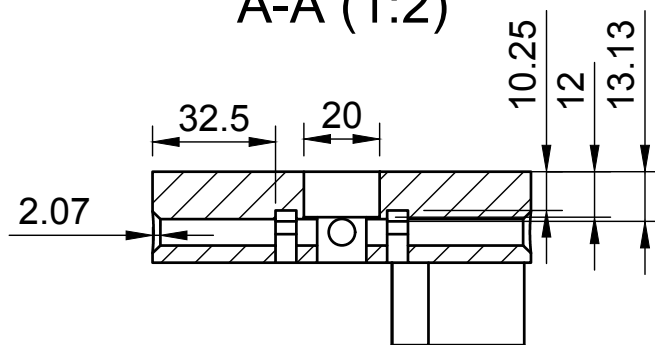
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|  |                                                | Document type<br><b>Size in mm</b>  | Document status<br><b>Scale 1:3</b> |                     |
|                                                                                     |                                                | Title<br><b>Coupler Motor Side</b>  | DWG No.<br><b>V1</b>                |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b>  | Sheet<br><b>1/1</b> |

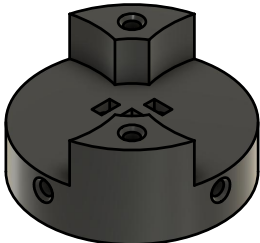


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| Dept.<br><b>Coupler</b>                                                             | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel 28/05/23</b> | Approved by                         |                                    |                     |
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|                                                                                     |                                                |                                              | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

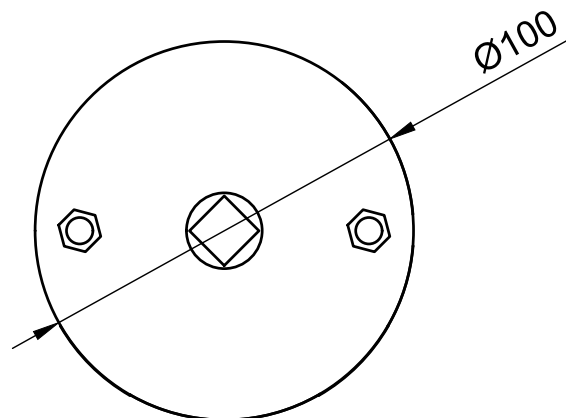
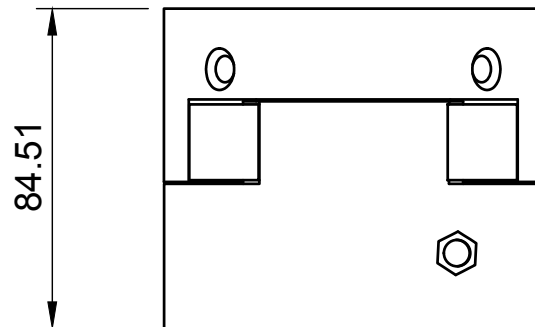


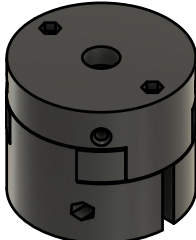
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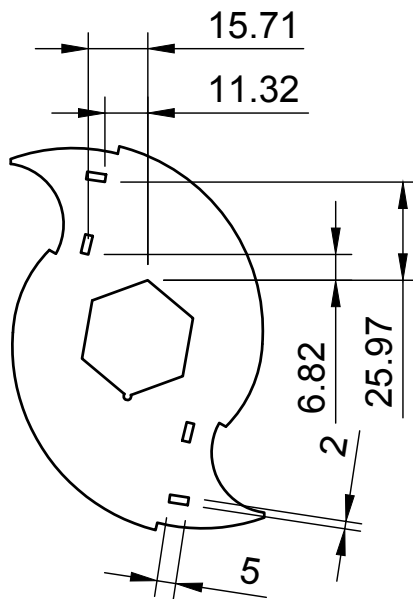
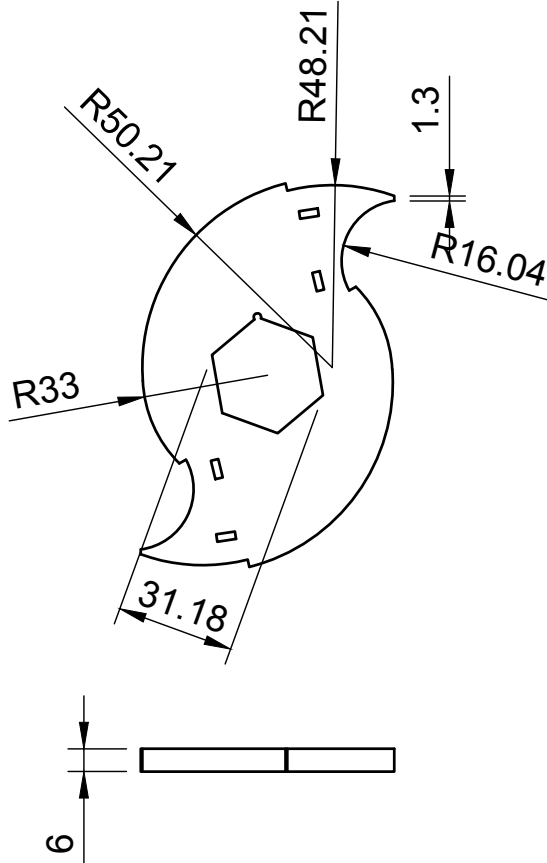


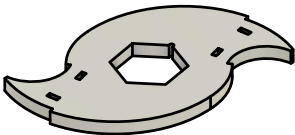
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|  |                                                | Document type<br><b>Size in mm</b>           | Document status<br><b>Scale 1:2</b> |
|                                                                                     |                                                | Title<br><b>Coupler Shredder Part</b>        | DWG No.<br><b>V1</b>                |
|                                                                                     |                                                | Rev.<br><b>A4</b>                            | Date of issue<br><b>05/06/2023</b>  |
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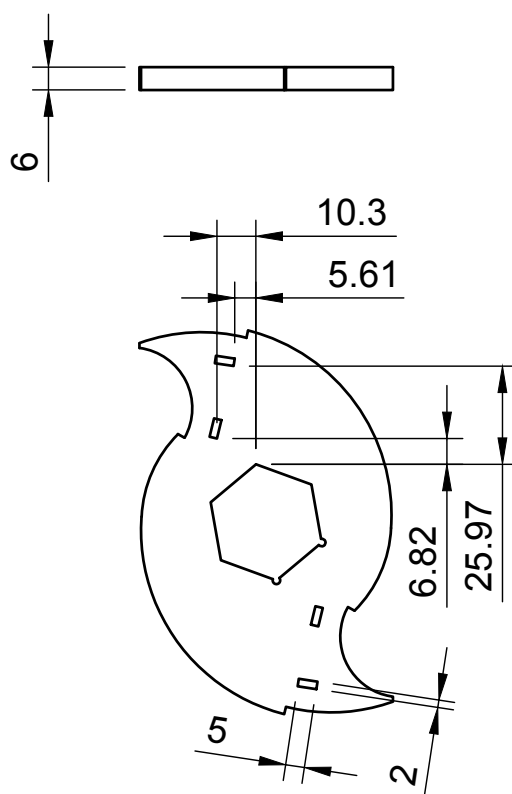
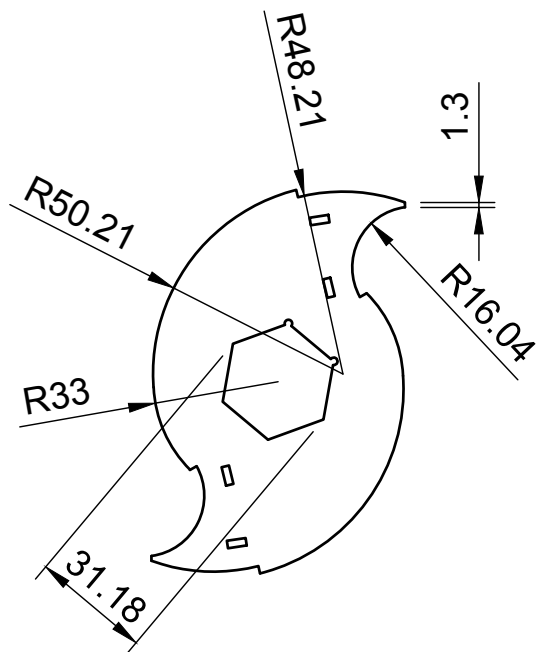


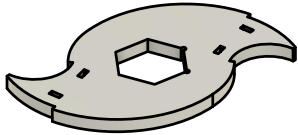


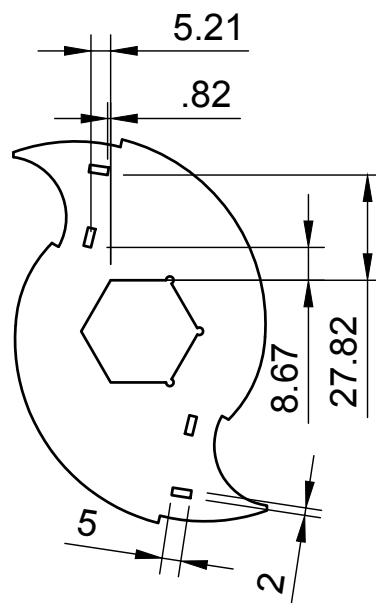
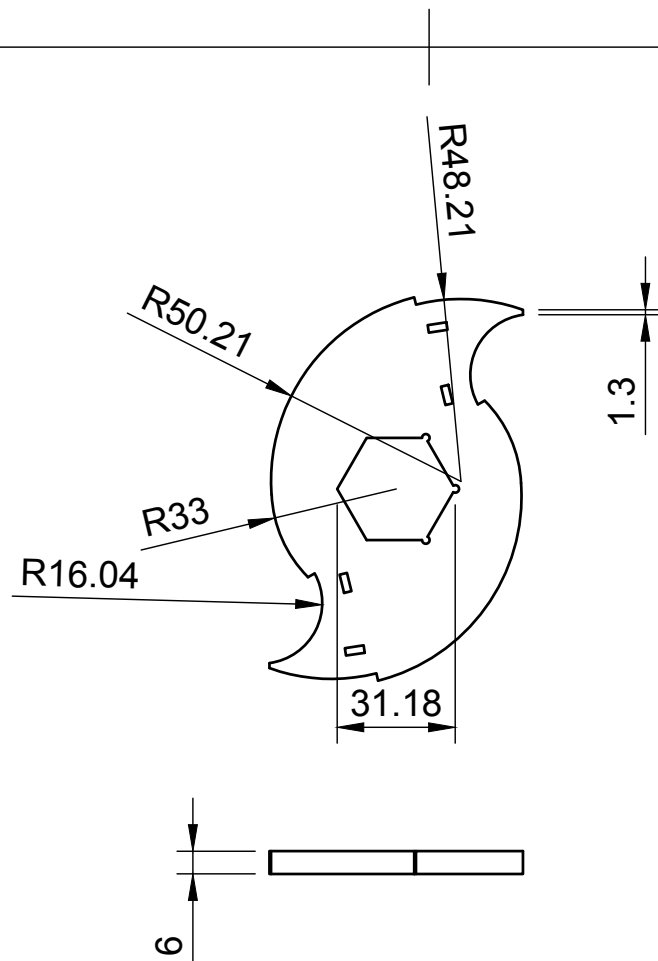
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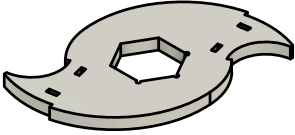


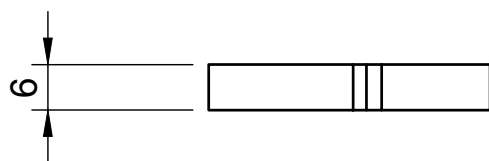
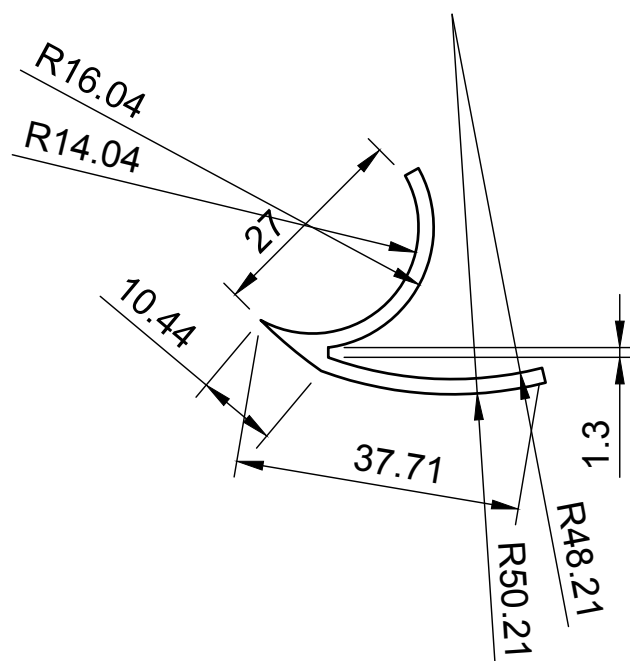
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| Dept.<br><b>Blades</b>                                                              | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel</b> | 30/05/23                            |                                    | Approved by         |
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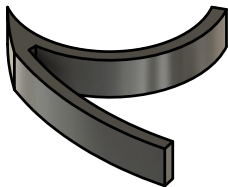


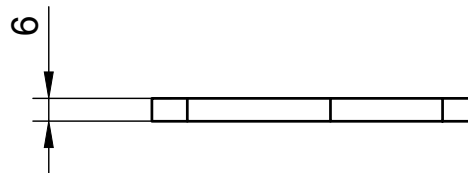
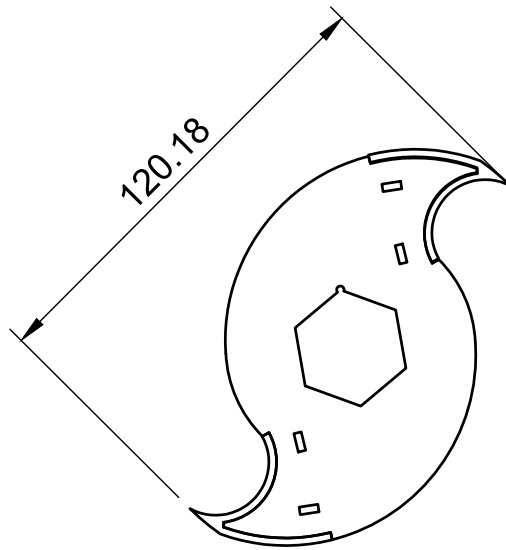
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|                                                                                     |                                                |                                     | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> |
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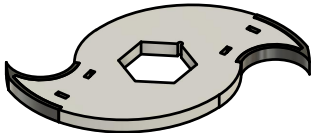


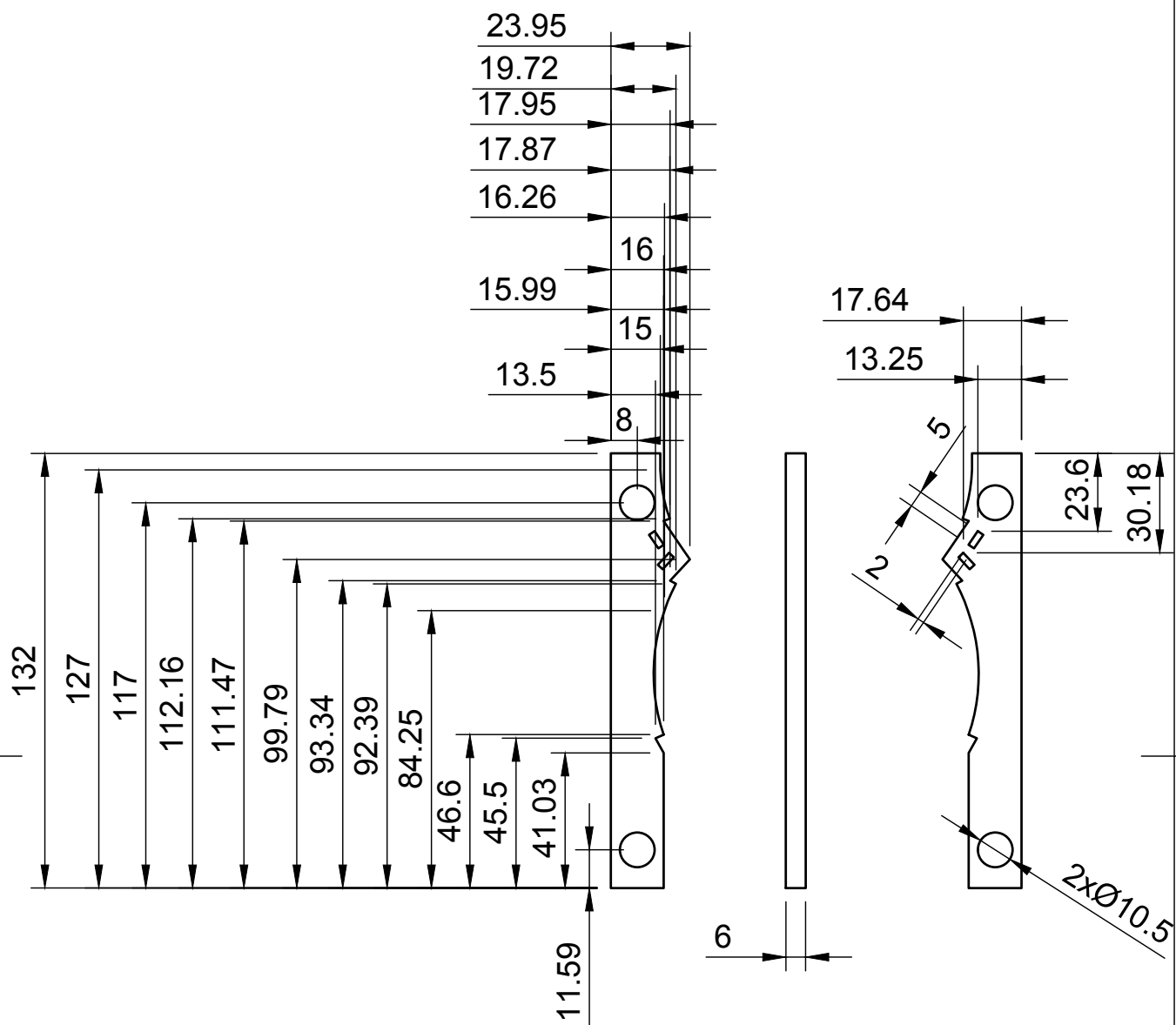
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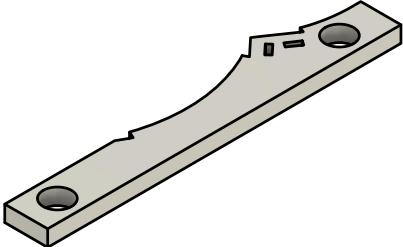


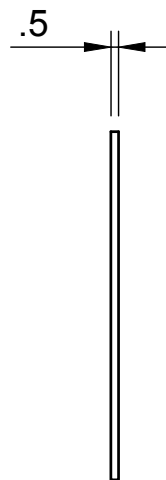
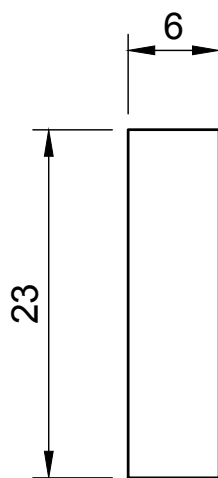
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|                                                                                     |                                                | Title<br><b>Blade Claw</b>          | DWG No.<br><b>V1</b>                |                                    |                     |
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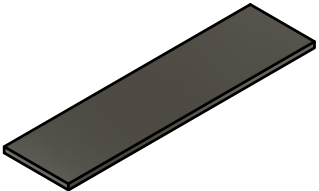


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|                                                                                     |                                                |                                              | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

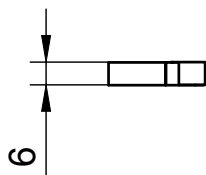
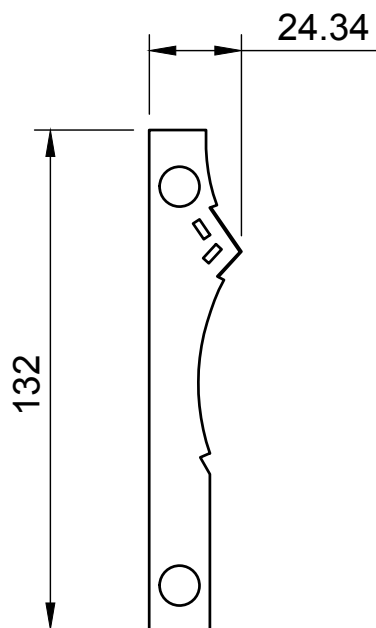


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| Dept.<br>Fixed Knives                                                               | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 31/05/23 | Approved by                  |
|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |
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|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |

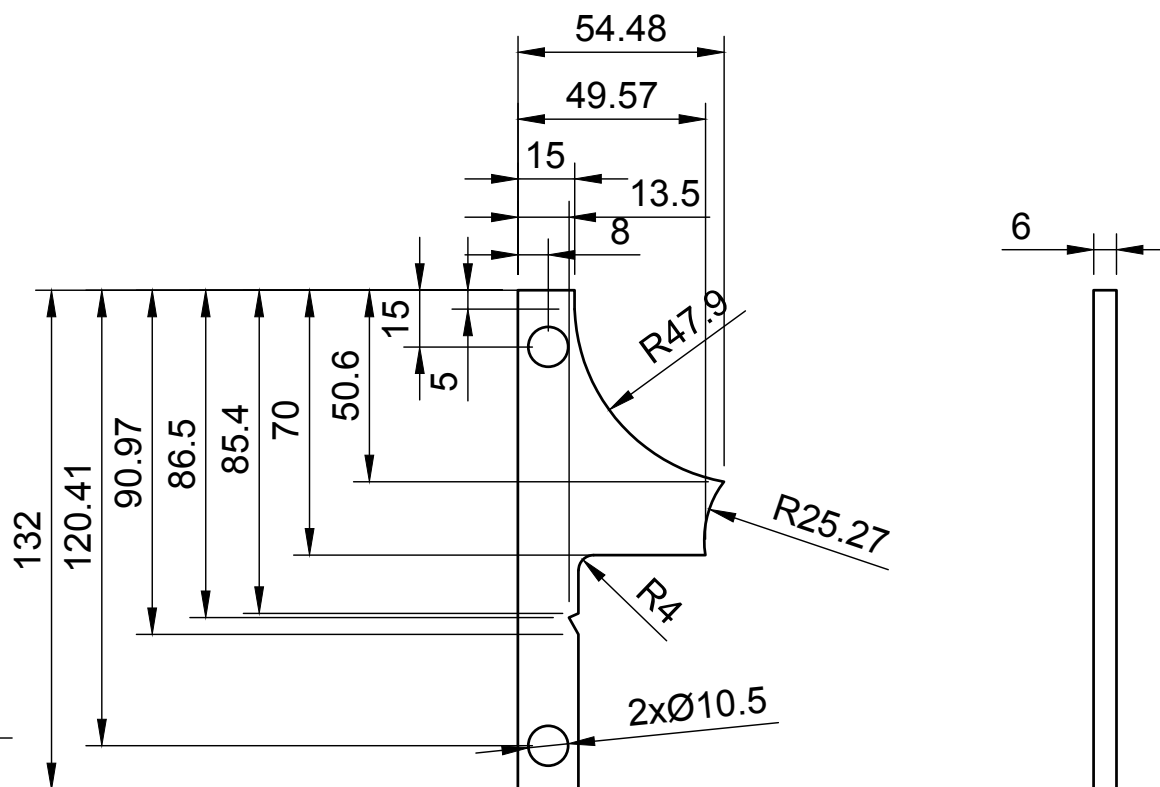


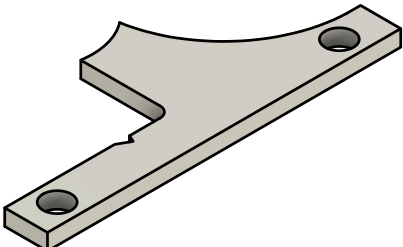
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|                                                                                     |                                         | Title<br>Fixed Knife Reinforcement    | DWG No.<br>V1                |                             |
|                                                                                     |                                         |                                       | Rev.<br>A4                   | Date of issue<br>05/06/2023 |
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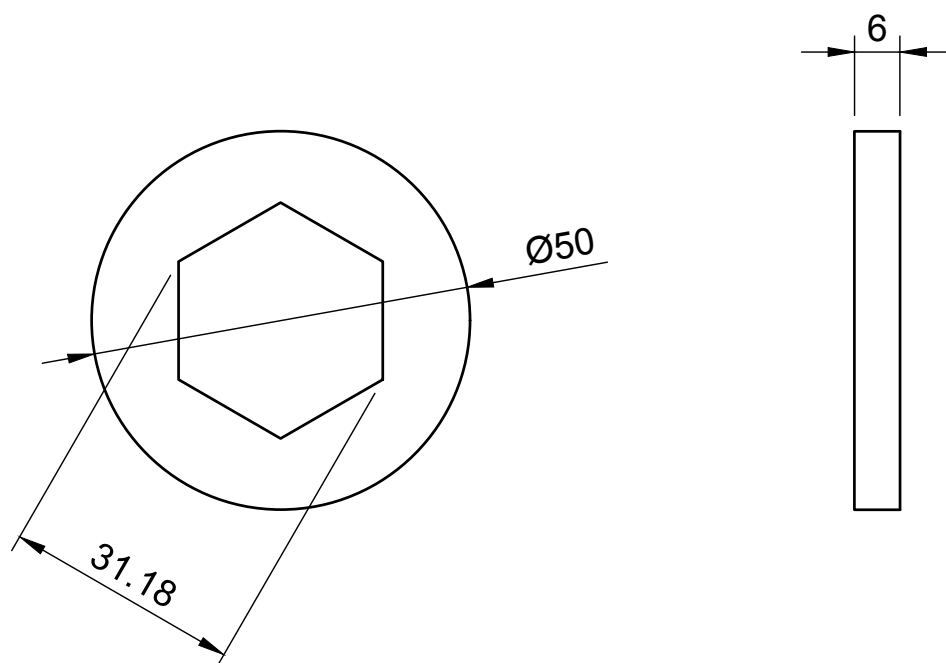


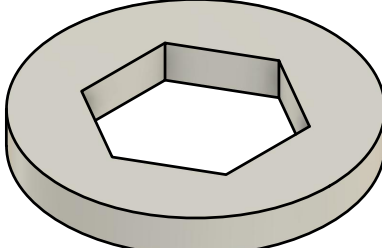


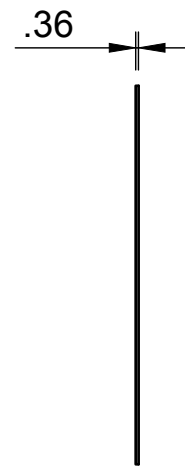
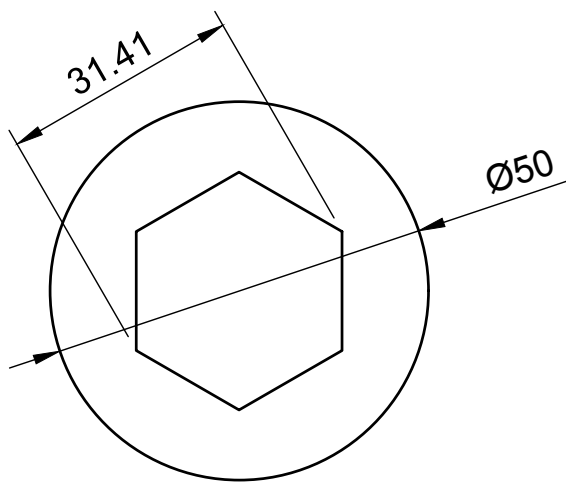
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|                                                                                     |                                         | Title<br>Fixed Knife Assembly         | DWG No.<br><br>V1            |                             |              |
|                                                                                     |                                         |                                       | Rev.<br>A4                   | Date of issue<br>05/06/2023 | Sheet<br>1/1 |

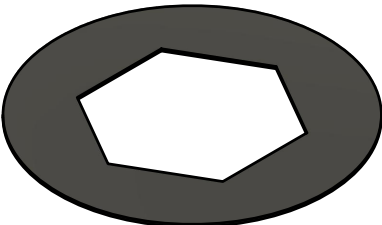


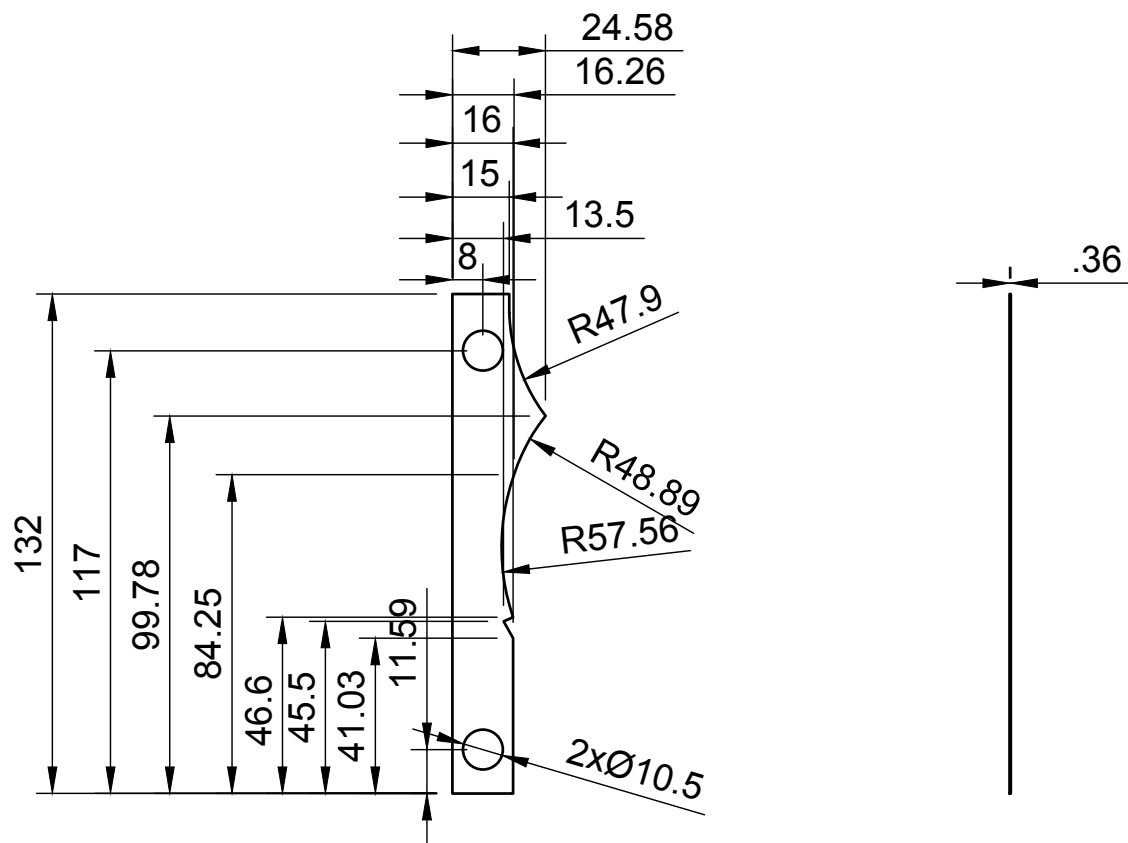
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|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |

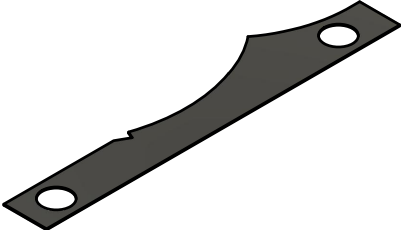


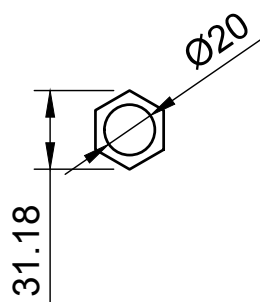
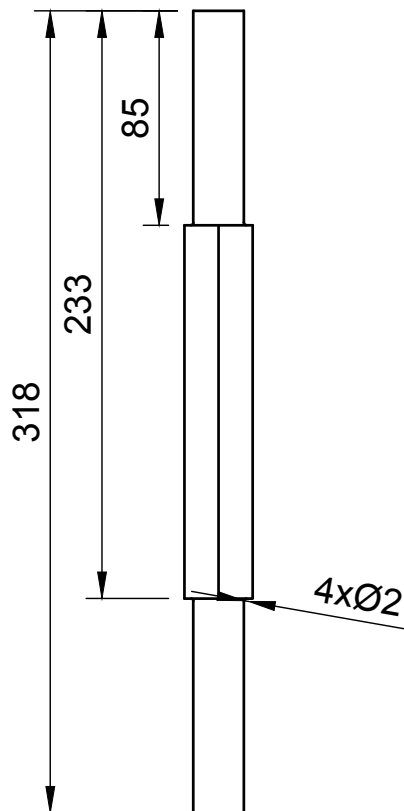
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|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:1 |  |
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|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

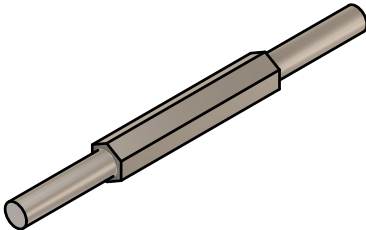


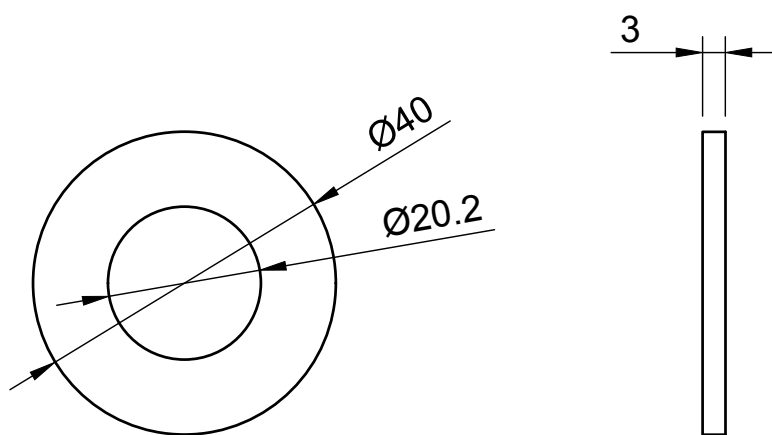
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|                                                                                     |                                         | Rev.<br>A4                            | Date of issue<br>05/06/2023  | Sheet<br>1/1 |

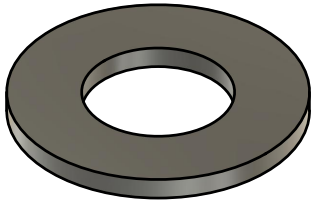


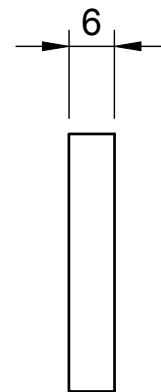
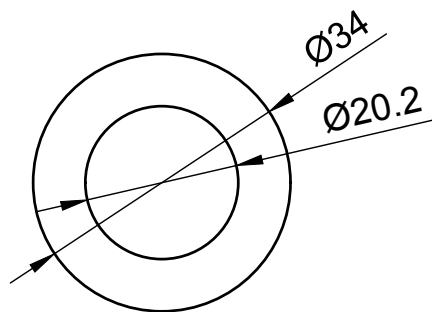
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|                                                                                     |                                         | Title<br>PLA Knives Spacers           | DWG No.<br>V1                |              |
|                                                                                     |                                         | Rev.<br>A4                            | Date of issue<br>05/06/2023  | Sheet<br>1/1 |

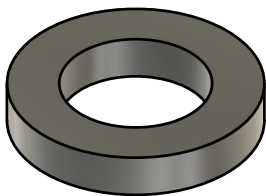


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| Dept.<br><b>Shaft</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel 30/05/23</b> | Approved by                         |                                    |
|  |                                                | Document type<br><b>Size in mm</b>           | Document status<br><b>Scale 1:3</b> |                                    |
|                                                                                     |                                                | Title<br><b>Shaft</b>                        | DWG No.<br><b>V1</b>                |                                    |
|                                                                                     |                                                |                                              | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> |
|                                                                                     |                                                |                                              |                                     | Sheet<br><b>1/1</b>                |

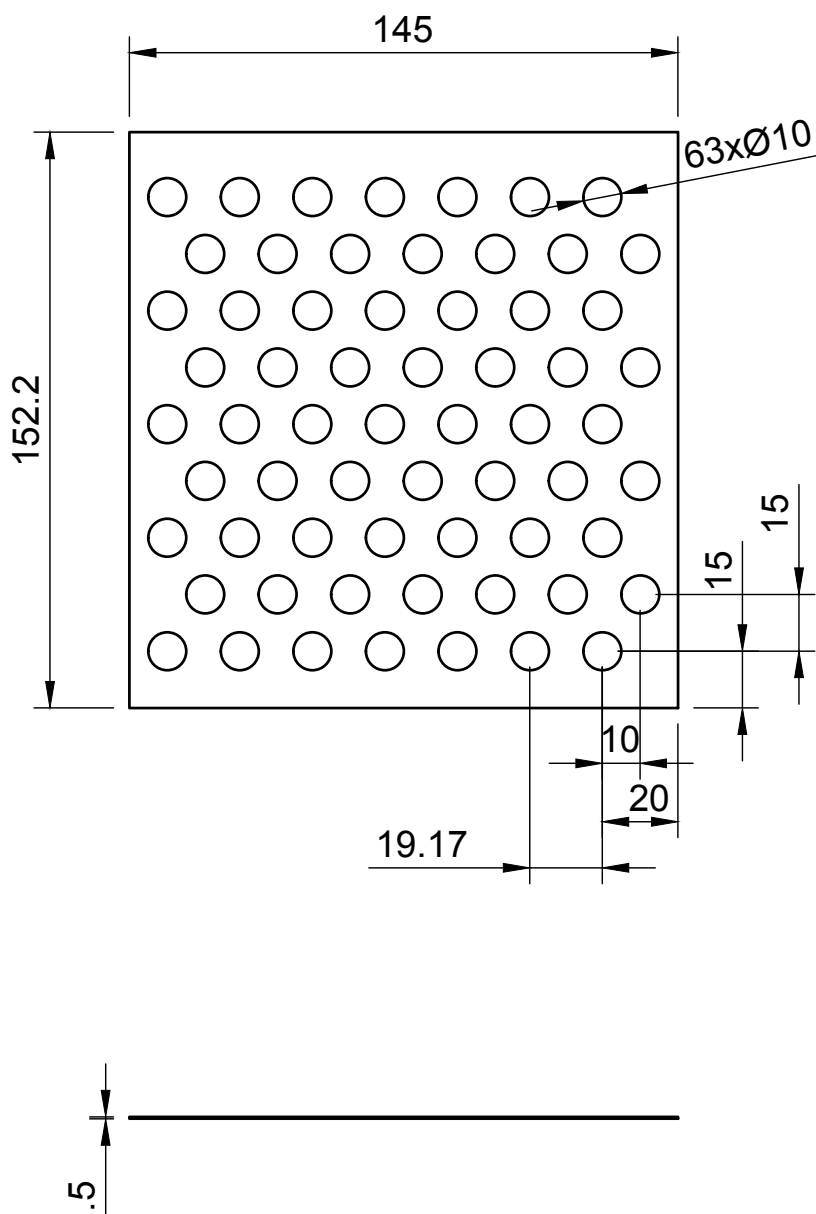


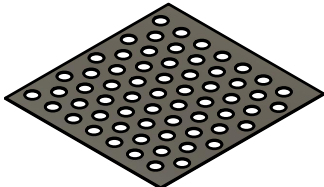
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| Dept.<br><b>Shaft</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel 30/05/23</b> | Approved by                         |  |
|  | Document type<br><b>Size in mm</b>             |                                              | Document status<br><b>Scale 1:1</b> |  |
|                                                                                     | Title<br><b>Bearing Spacer 3mm</b>             |                                              | DWG No.<br><b>V1</b>                |  |
|                                                                                     | Rev.<br><b>A4</b>                              | Date of issue<br><b>05/06/2023</b>           | Sheet<br><b>1/1</b>                 |  |

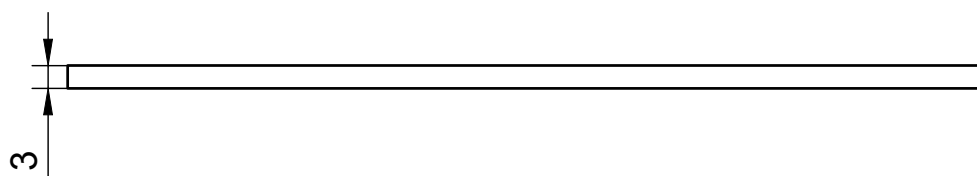
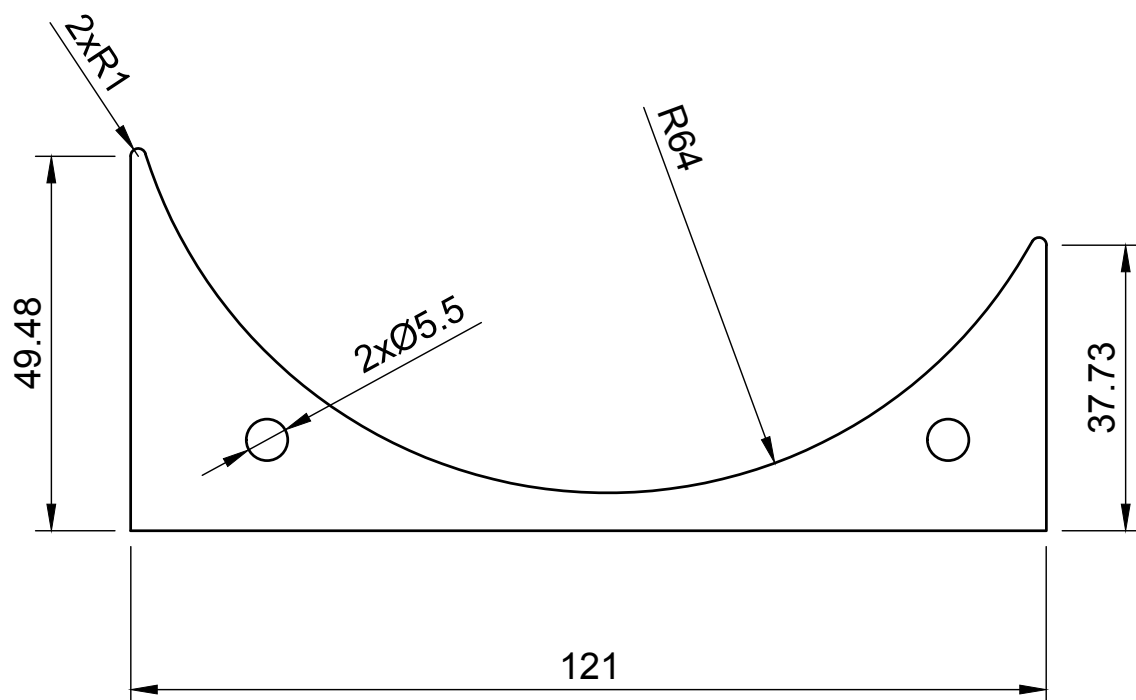


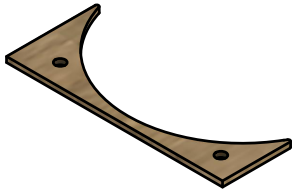
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|  |                                                | Document type                       | Document status<br><b>Scale 1:1</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Bearing Spacer 6mm</b>  | <b>V1</b>                           |                                    |                     |
|                                                                                     |                                                |                                     | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

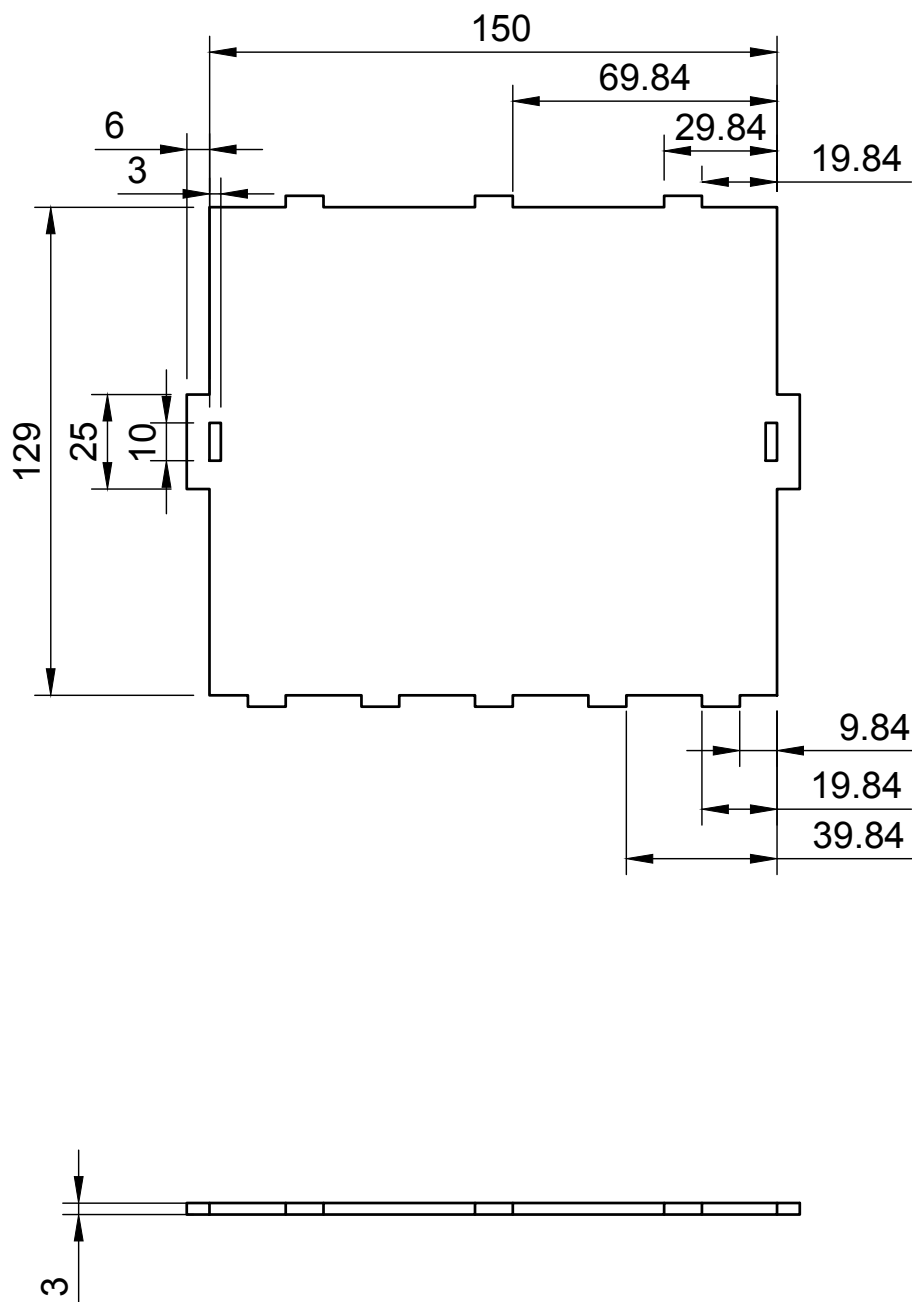




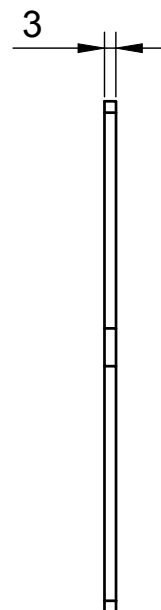
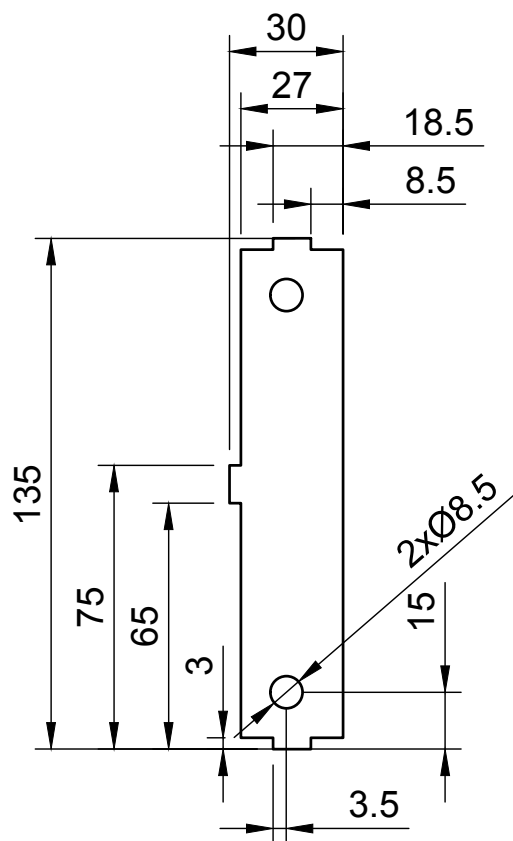
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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                  |  |
|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |  |
|                                                                                     | Title<br>Sieve                          |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

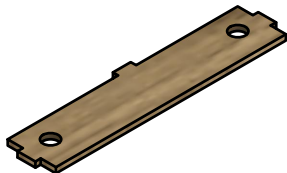


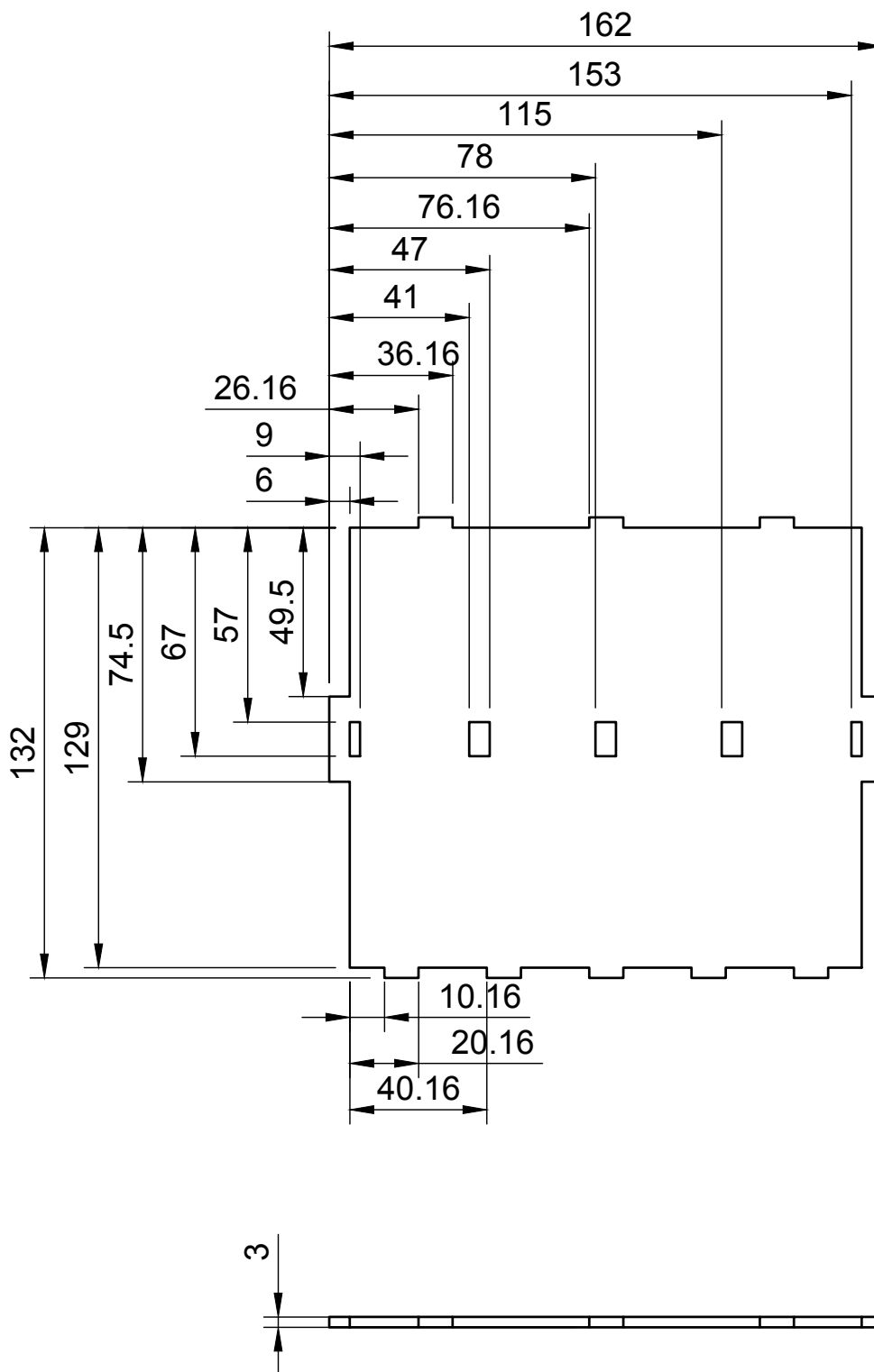
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|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:1 |  |
|                                                                                     | Title<br>Sieve Holder                   |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

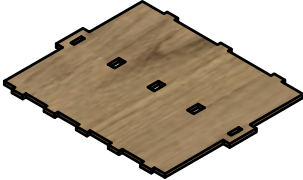


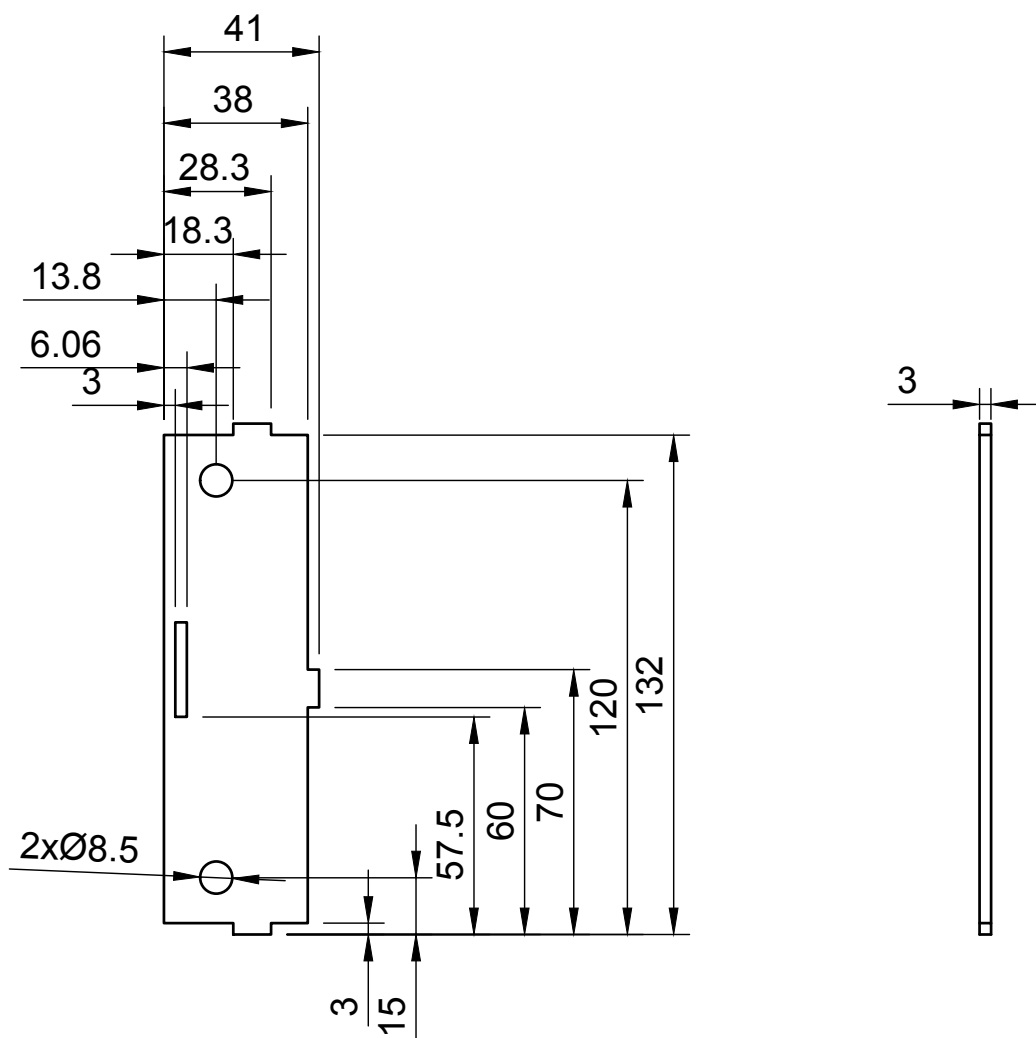
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|  |                                         | Document type<br>Size in mm                | Document status<br>Scale 1:2 |                             |              |
|                                                                                     |                                         | Title<br>Fixed Knives Middle               | DWG No.<br><br>V1            |                             |              |
|                                                                                     |                                         |                                            | Rev.<br>A4                   | Date of issue<br>30/05/2023 | Sheet<br>1/1 |



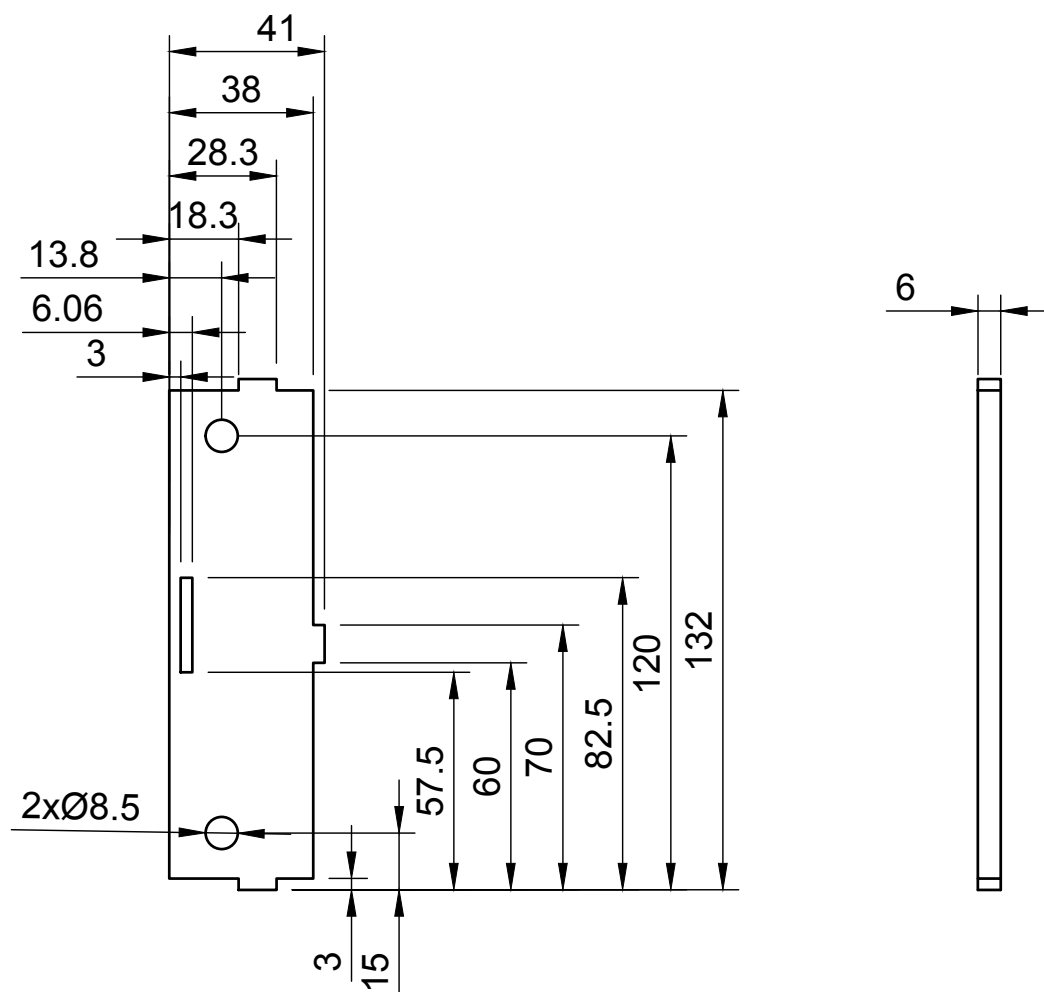
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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                  |                             |              |
|  |                                         | Document type<br>Size in mm           | Document status<br>Scale 1:2 |                             |              |
|                                                                                     |                                         | Title<br>Fixed Knives Side            | DWG No.<br><br>V1            |                             |              |
|                                                                                     |                                         |                                       | Rev.<br>A4                   | Date of issue<br>05/06/2023 | Sheet<br>1/1 |



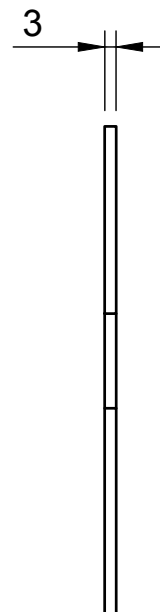
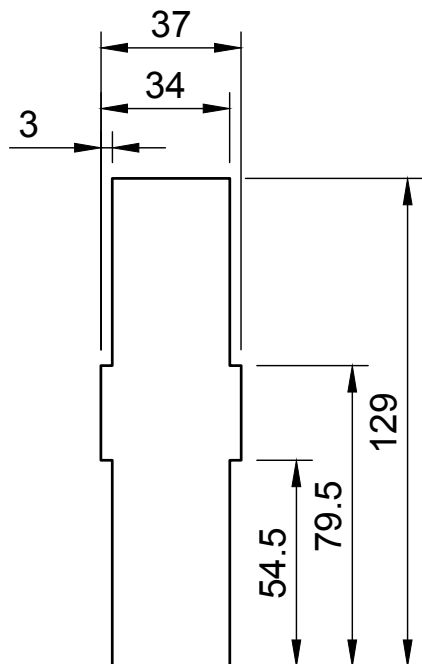
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|  |                                         | Document type<br>Size in mm           | Document status<br>Scale 1:2 |              |
|                                                                                     |                                         | Title<br>Free Middle                  | DWG No.<br>V1                |              |
|                                                                                     |                                         | Rev.<br>A4                            | Date of issue<br>30/05/2023  | Sheet<br>1/1 |



|                                                                                     |                                         |                                       |                              |  |
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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                  |  |
|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |  |
|                                                                                     | Title<br>Free Side 3mm                  |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

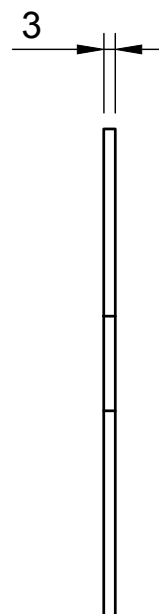
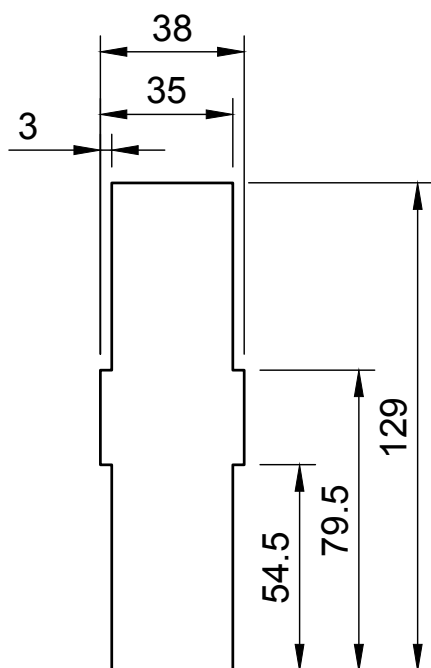


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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                  |  |
|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |  |
|                                                                                     | Title<br>Free Side 6mm                  |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |



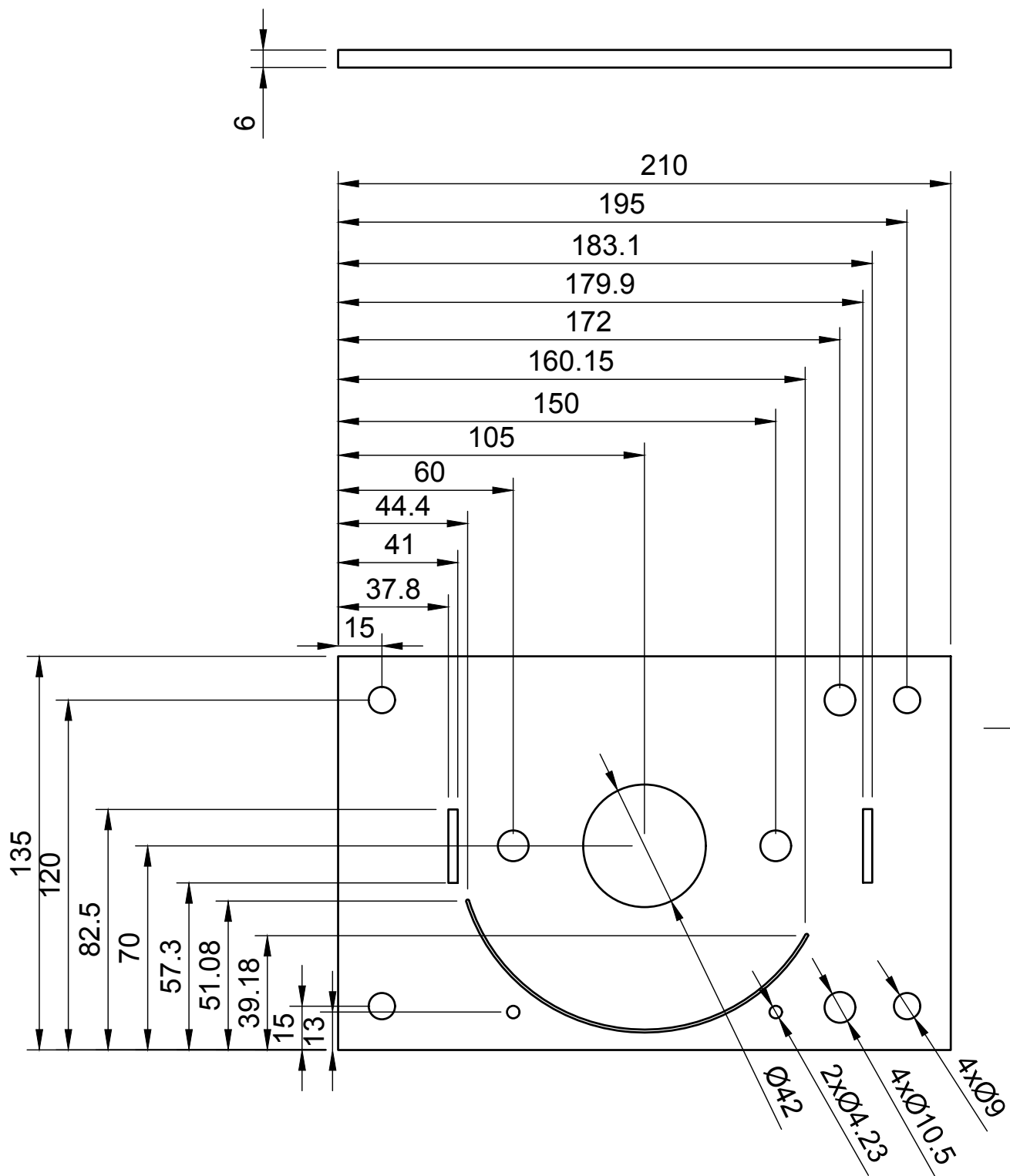
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|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |  |
|                                                                                     | Title<br>Free Reinforcement 37 mm       |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

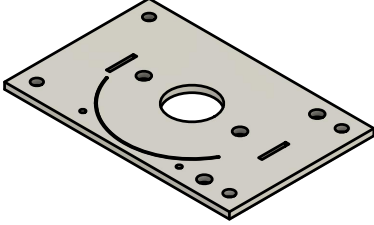


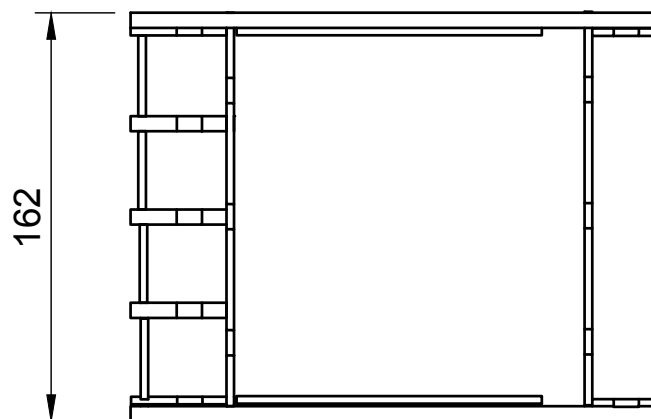
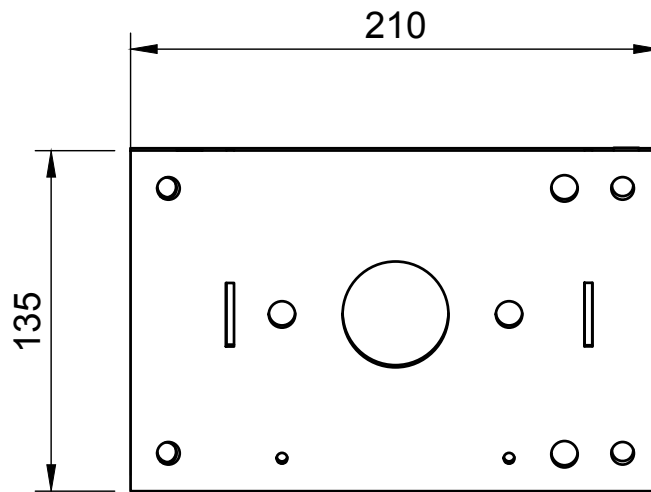


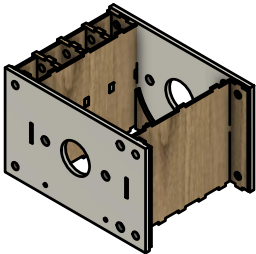
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|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:2 |  |
|                                                                                     | Title<br>Free Reinforcement 38mm        |                                       | DWG No.<br>V1                |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

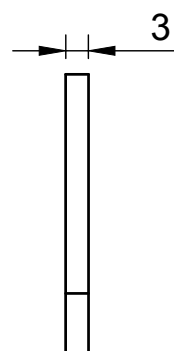
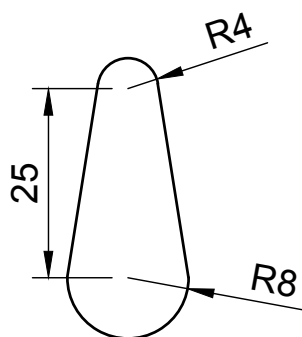




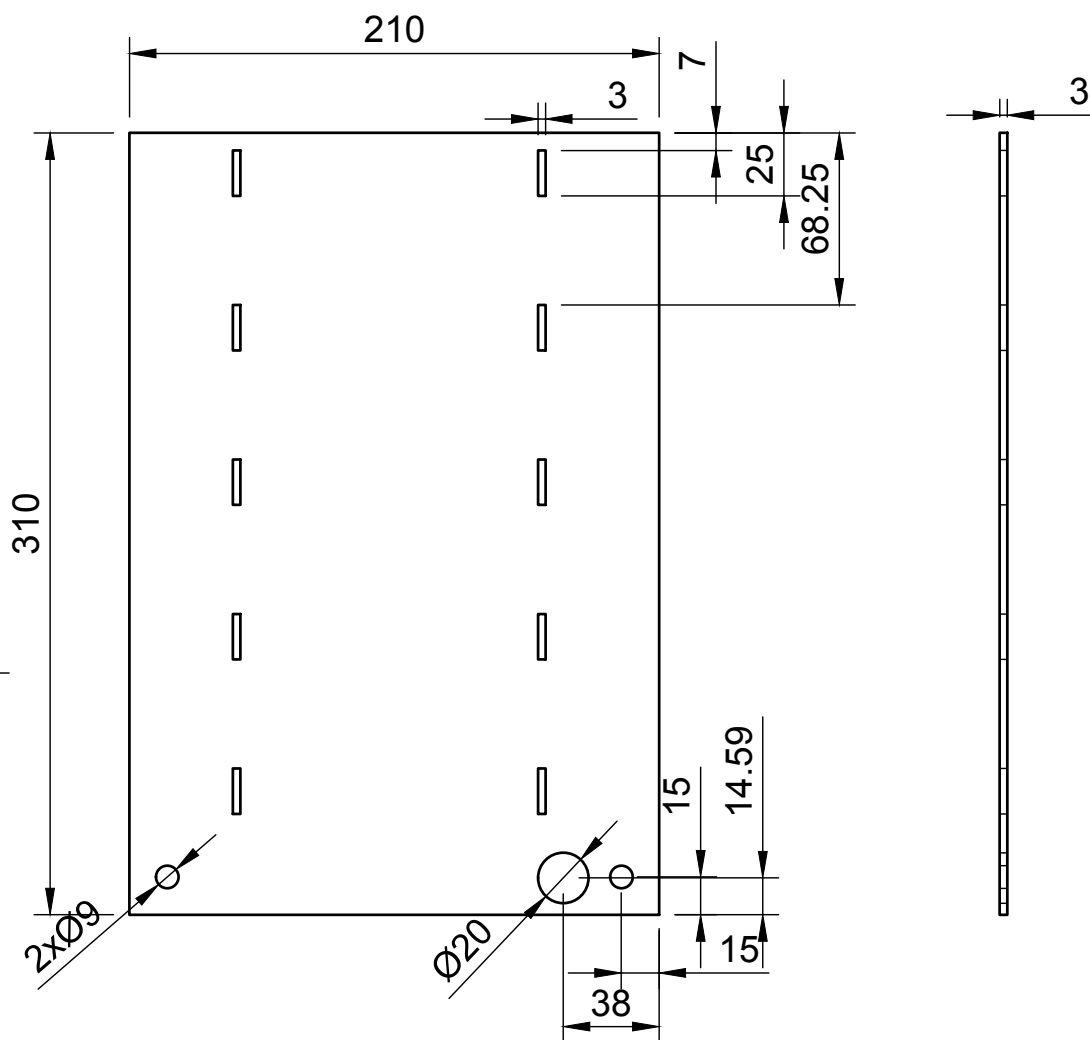
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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                 |
|  | Document type<br>Size in mm             | Document status<br>Scale 1:2          |                             |
|                                                                                     | Title<br>POM Side 2                     | DWG No.<br>V1                         |                             |
|                                                                                     |                                         | Rev.<br>A4                            | Date of issue<br>06/05/2023 |
|                                                                                     |                                         | Sheet<br>1/1                          |                             |

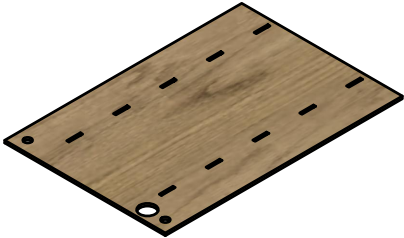


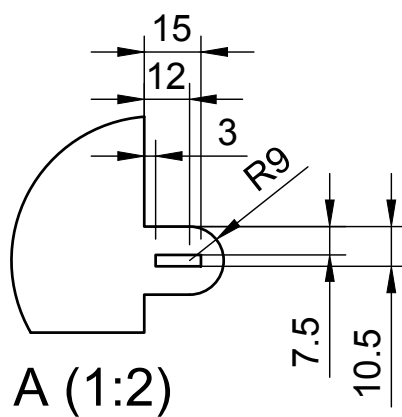
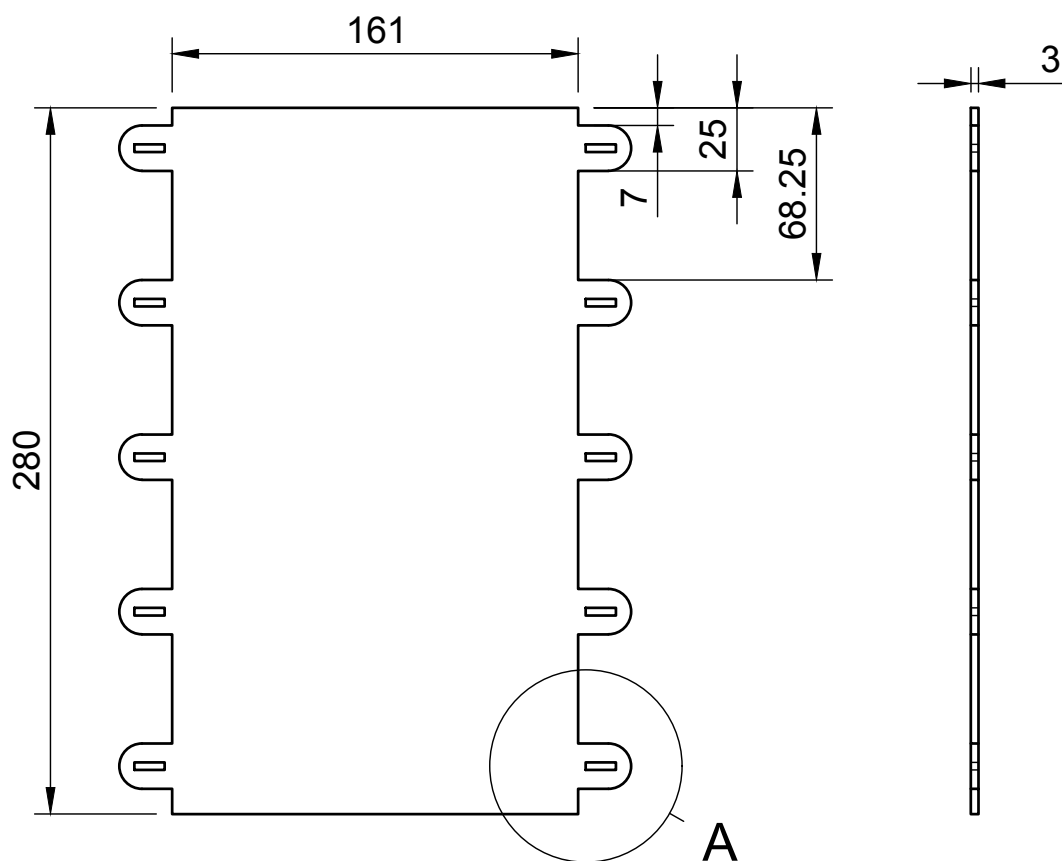
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| Dept.<br>Shredding Frame                                                            | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 30/05/23 | Approved by                  |  |
|  | Document type<br>Size in mm             |                                       | Document status<br>Scale 1:3 |  |
|                                                                                     | Title<br>Shredding Frame                |                                       | DWG No.<br><br>V1            |  |
|                                                                                     | Rev.<br>A4                              | Date of issue<br>05/06/2023           | Sheet<br>1/1                 |  |

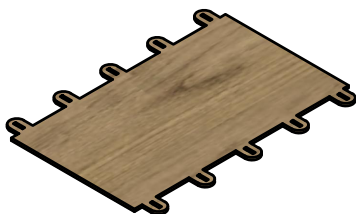


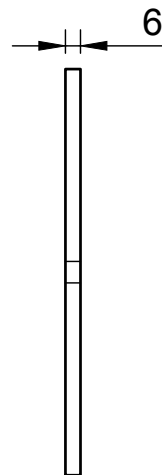
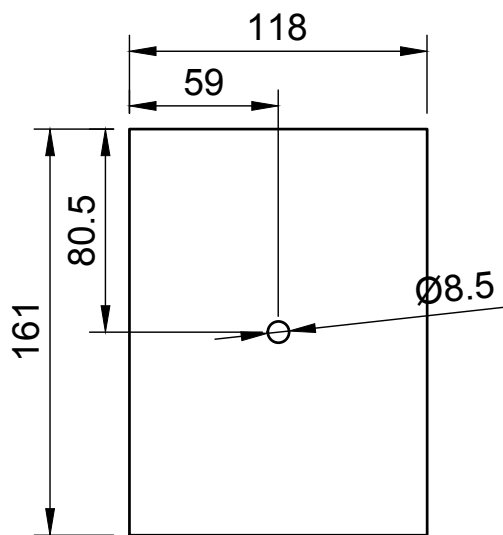
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| Dept.<br><b>Hopper</b>                                                              | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel</b> | <b>17/05/23</b>                     |                                    | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b>  | Document status<br><b>Scale 1:1</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Hopper Pin</b>          | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                |                                     | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

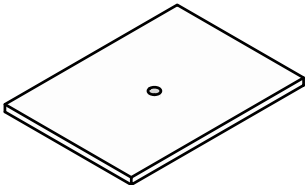


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| Dept.<br><b>Hopper</b>                                                              | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel</b> | 18/05/23                            | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b>  | Document status<br><b>Scale 1:3</b> |                     |
|                                                                                     |                                                | Title<br><b>HopperFace1</b>         | DWG No.<br><b>V1</b>                |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b>  | Sheet<br><b>1/1</b> |

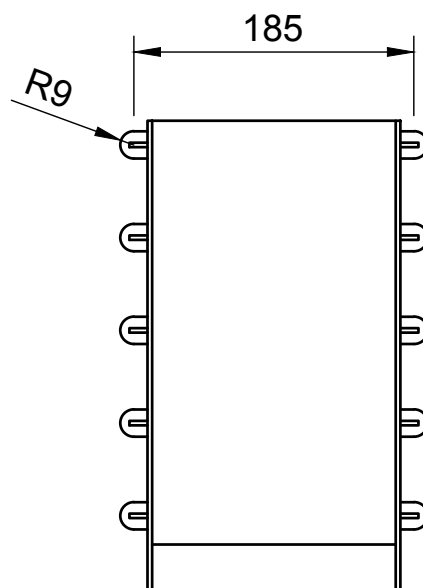
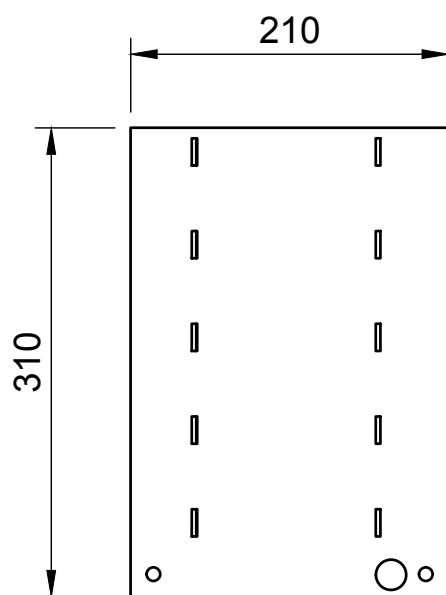


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| Dept.<br>Hopper                                                                     | Technical reference<br>Precious Plastic | Created by<br>marine poudrel 18/05/23 | Approved by                  |              |
|  |                                         | Document type<br>Size in mm           | Document status<br>Scale 1:3 |              |
|                                                                                     |                                         | Title<br>Hopper Face 2                | DWG No.<br>V1                |              |
|                                                                                     |                                         | Rev.<br>A4                            | Date of issue<br>05/06/2023  | Sheet<br>1/1 |



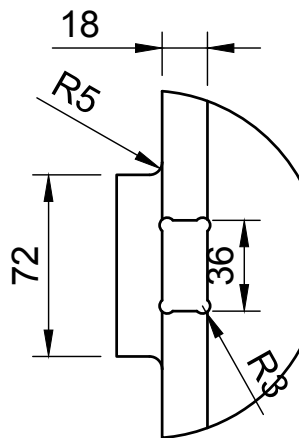
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| Dept.<br><b>Hopper</b>                                                              | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel 28/05/23</b> | Approved by                         |                     |
|  |                                                | Document type<br><b>Size in mm</b>           | Document status<br><b>Scale 1:3</b> |                     |
|                                                                                     |                                                | Title<br><b>Hopper Cover</b>                 | DWG No.<br><b>V1</b>                |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                            | Date of issue<br><b>05/06/2023</b>  | Sheet<br><b>1/1</b> |



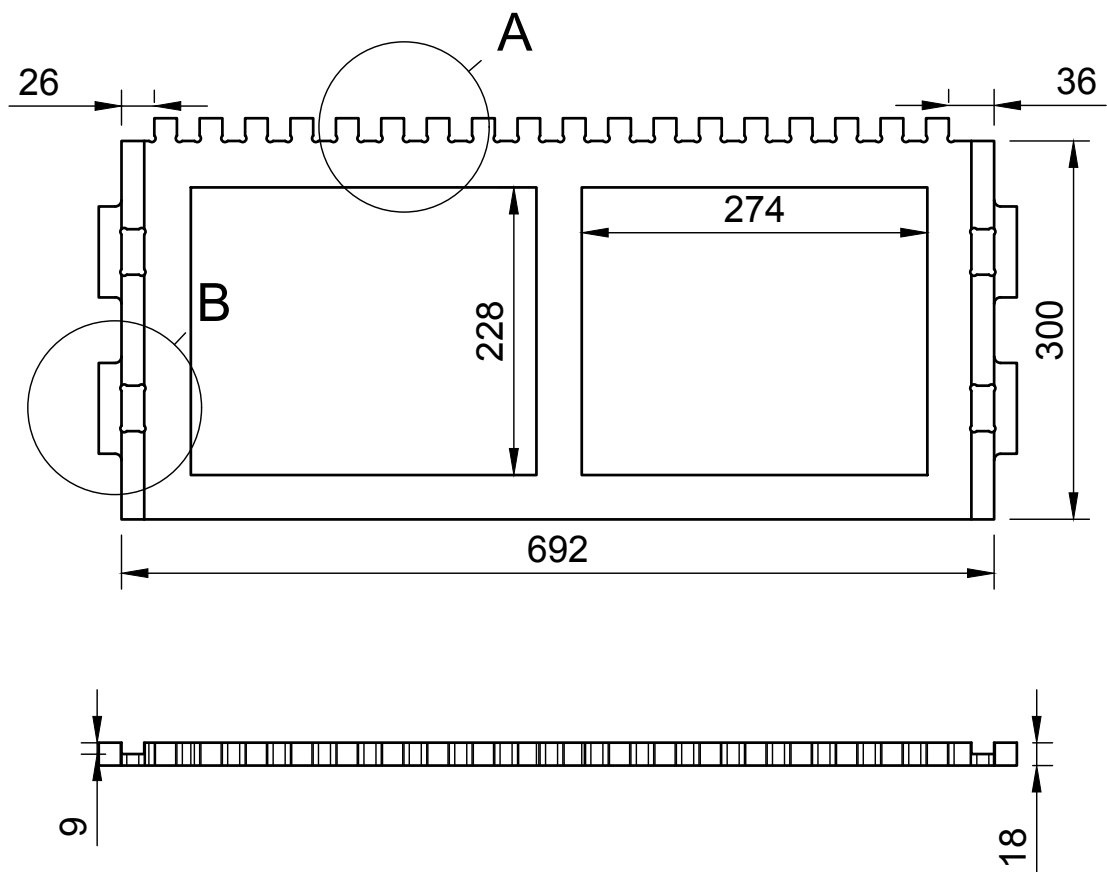
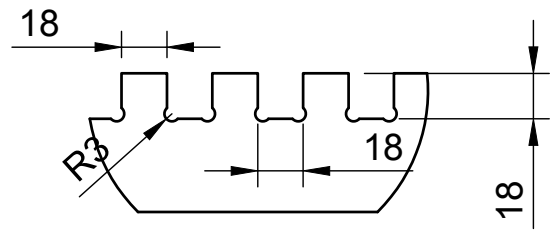


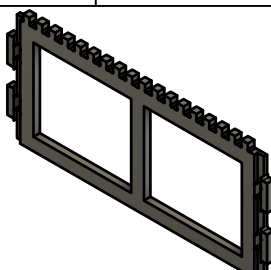
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| Dept.<br><b>Hopper</b>                                                              | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel 28/05/23</b> | Approved by                         |                                    |                     |
|  |                                                | Document type<br><b>Size in mm</b>           | Document status<br><b>Scale 1:5</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Hopper Assembly</b>              | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                |                                              | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

B (1:3)

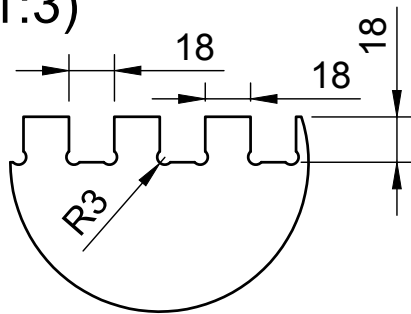


A (1:3)



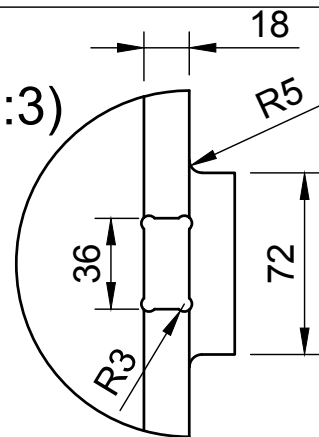
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| Dept.<br>Frame                                                                      | Technical reference<br>Precious Plastic | Created by<br>Héloïse Nolf  | 17/05/23                     | Approved by  |
|  |                                         | Document type<br>Size in mm | Document status<br>Scale 1:6 |              |
|                                                                                     |                                         | Title<br>Frame Front        | DWG No.<br>V1                |              |
|                                                                                     |                                         | Rev.<br>A4                  | Date of issue<br>05/06/2023  | Sheet<br>1/1 |

A (1:3)



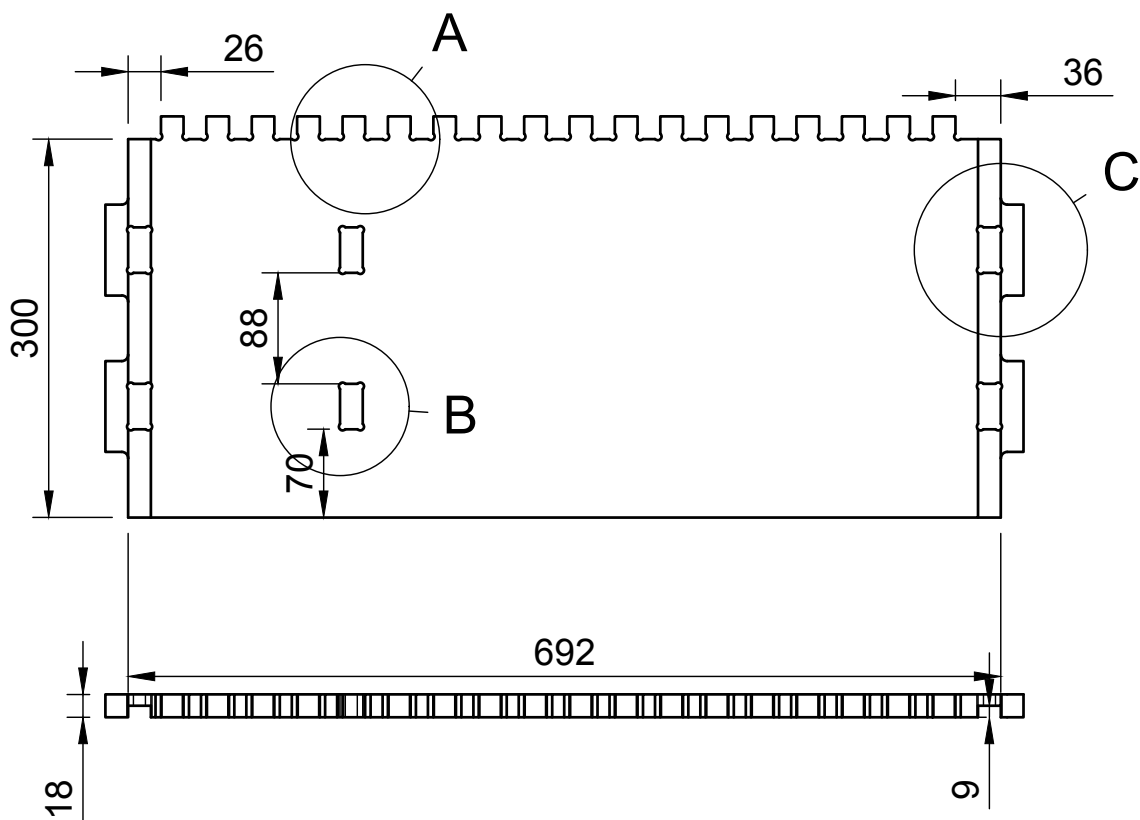
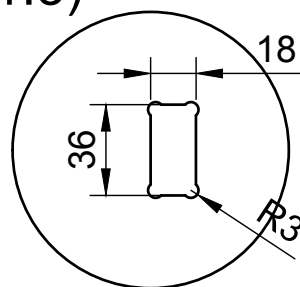
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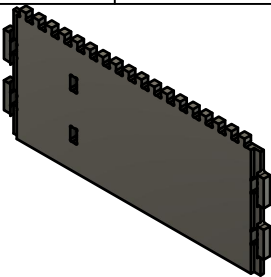
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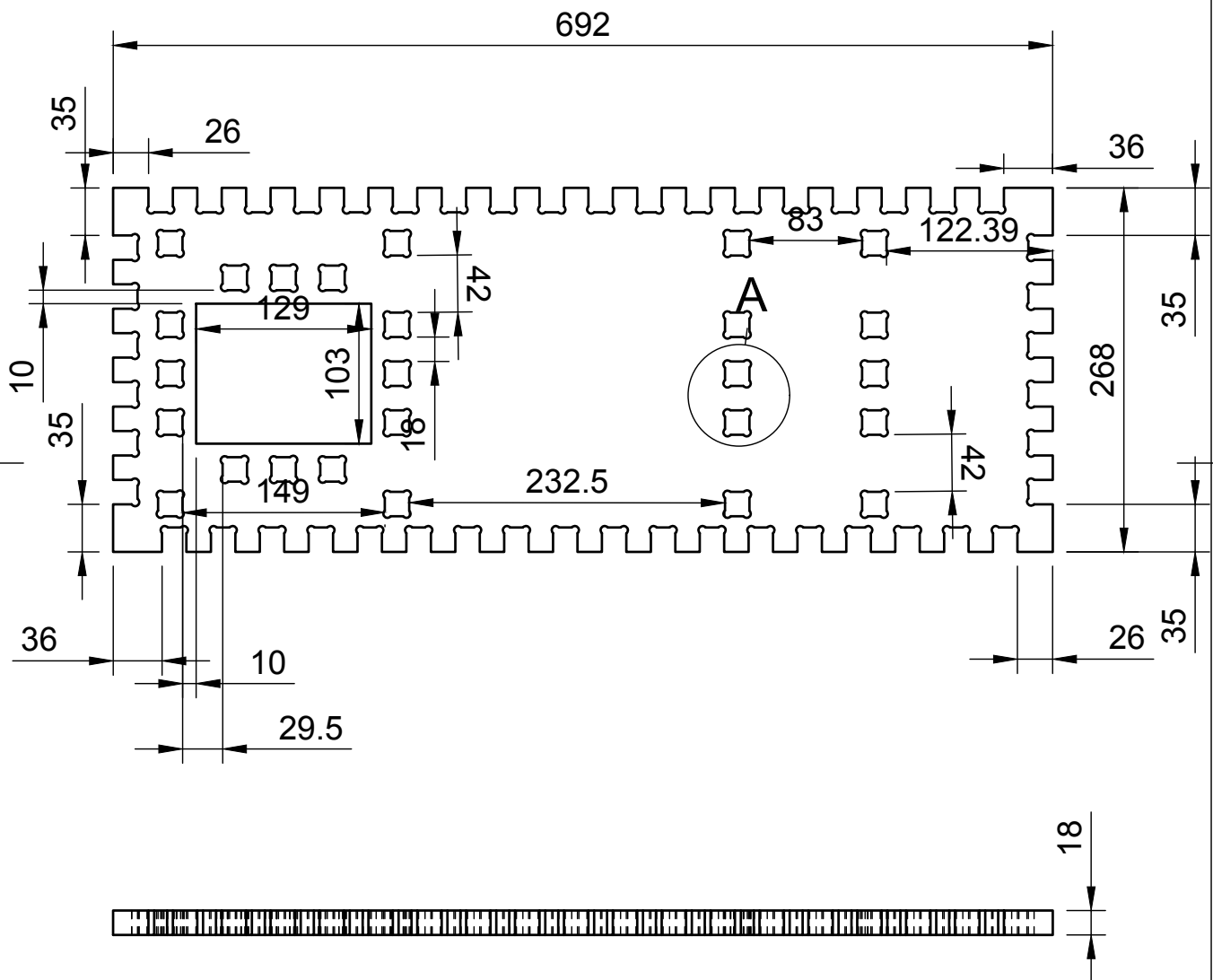
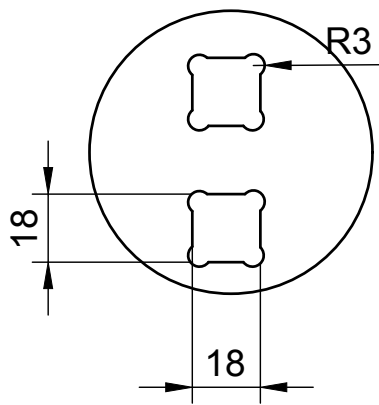
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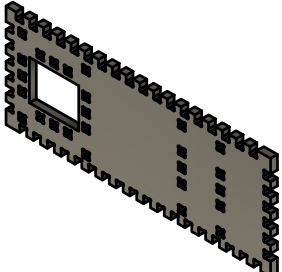
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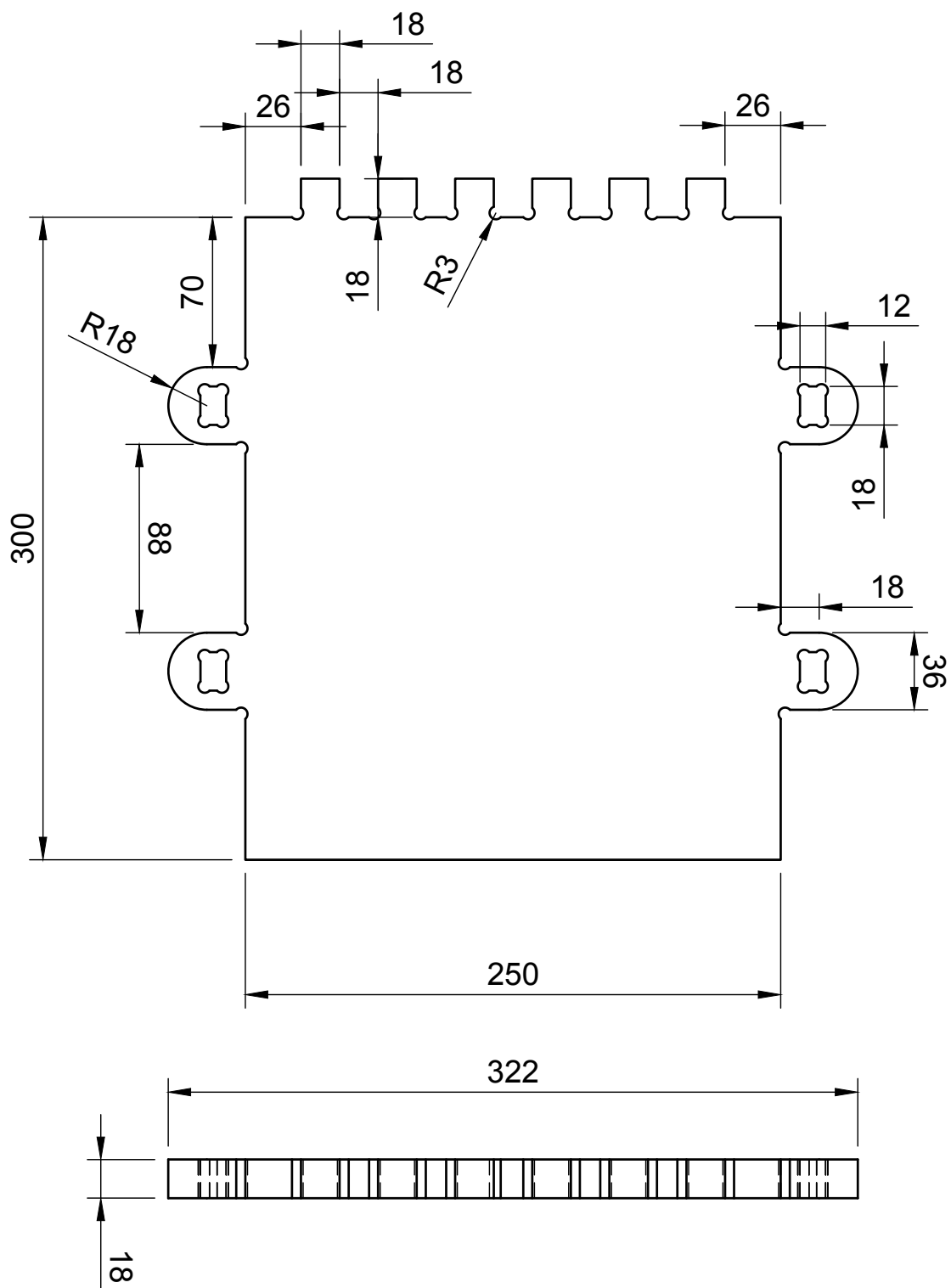


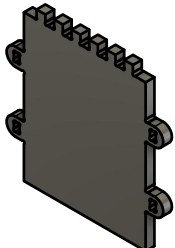
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| Dept.<br>Frame                                                                      | Technical reference<br>Precious Plastic | Created by<br>Héloïse Nolf  | 17/05/23                         | Approved by  |
|  |                                         | Document type<br>Size in mm | Document status<br>Scale 1:6/1:3 |              |
|                                                                                     |                                         | Title<br>Frame Back         | DWG No.<br>V1                    |              |
|                                                                                     |                                         | Rev.<br>A4                  | Date of issue<br>05/06/2023      | Sheet<br>1/1 |

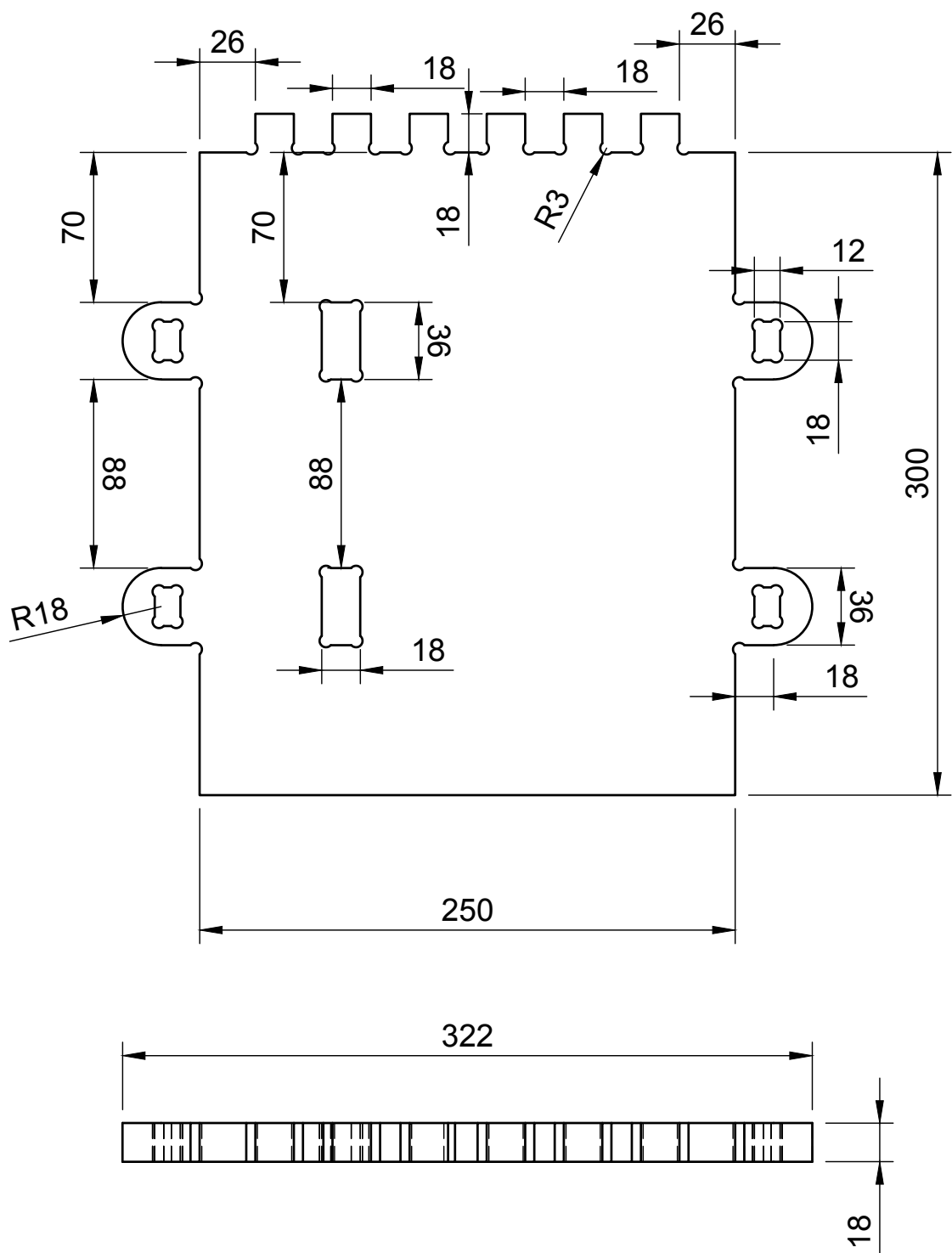
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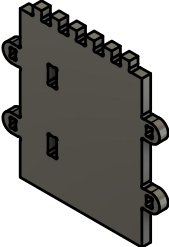


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| Dept.<br>Frame                                                                      | Technical reference<br>Precious Plastic | Created by<br>Héloïse Nolf  | 30/05/23                     | Approved by  |
|  |                                         | Document type<br>Size in mm | Document status<br>Scale 1:5 |              |
|                                                                                     |                                         | Title<br>Frame Top          | DWG No.<br>V1                |              |
|                                                                                     |                                         | Rev.<br>A4                  | Date of issue<br>05/06/2023  | Sheet<br>1/1 |

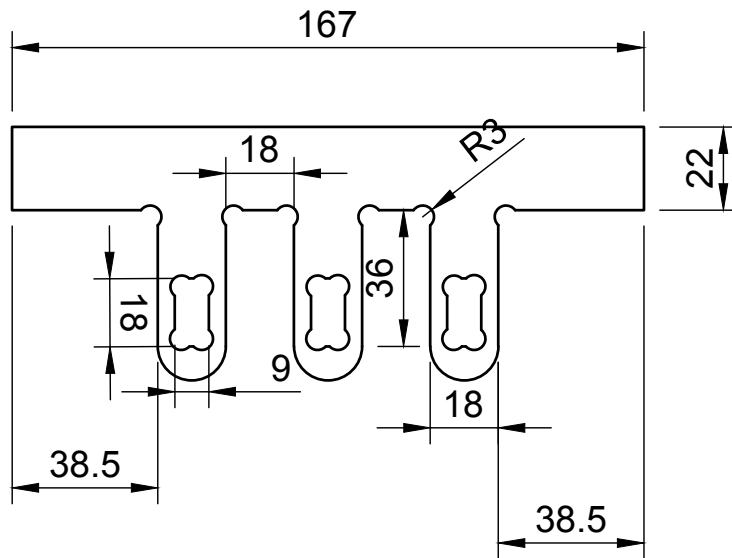
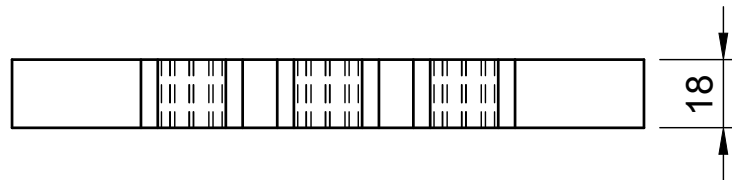


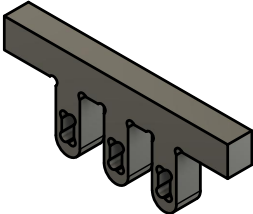
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | <b>1/06/23</b>                      | Approved by |
|  | Document type<br><b>Size in mm</b>             |                                    | Document status<br><b>Scale 1:3</b> |             |
|                                                                                     | Title<br><b>Right side</b>                     |                                    | DWG No.<br><b>V1</b>                |             |
|                                                                                     | Rev.<br><b>A4</b>                              | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b>                 |             |



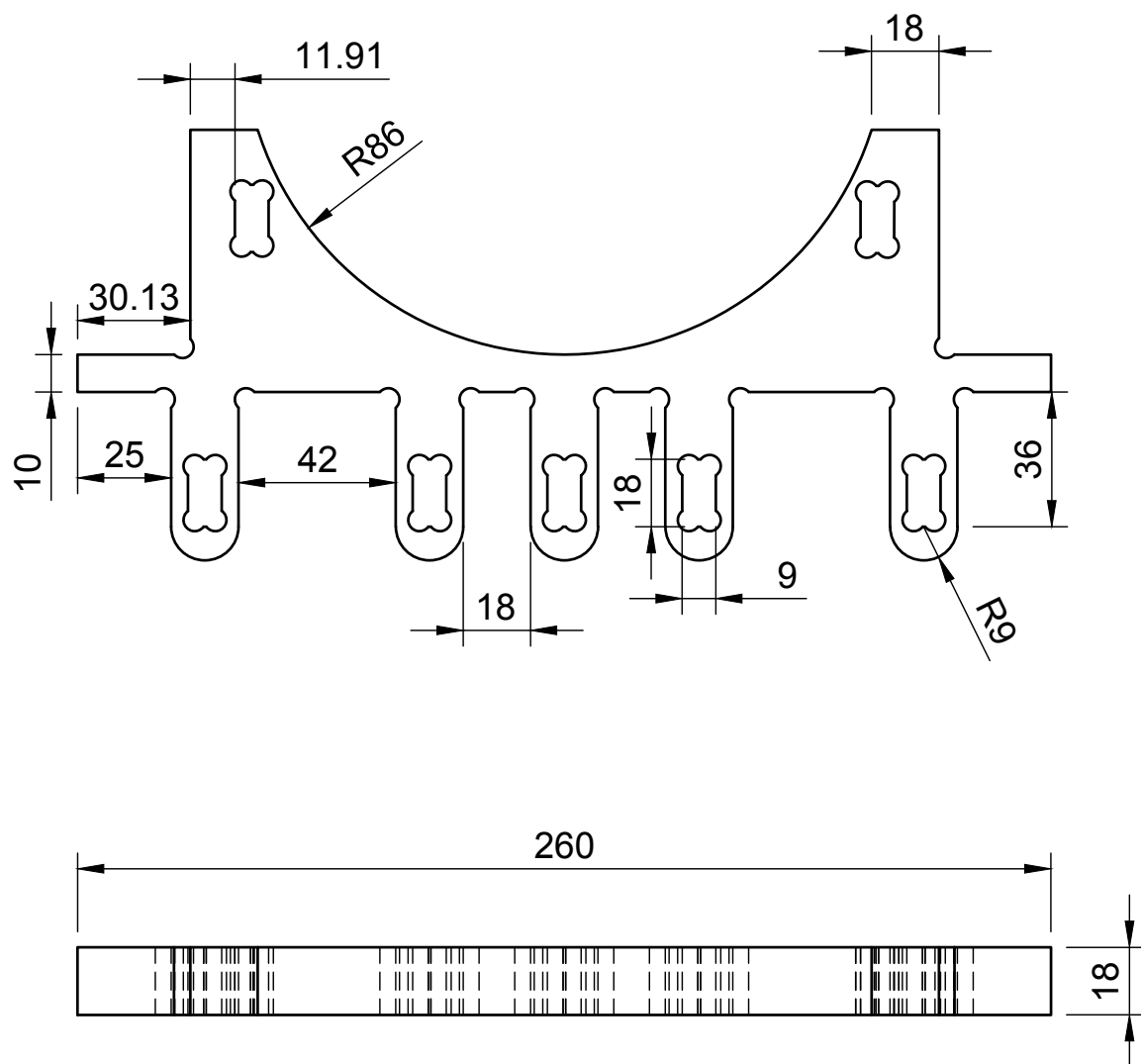
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | 1/06/23                             |                                    | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b> | Document status<br><b>Scale 1:3</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Left side</b>          | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                |                                    | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

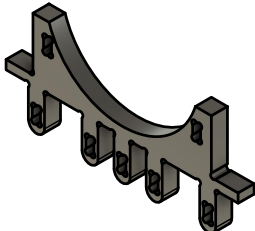


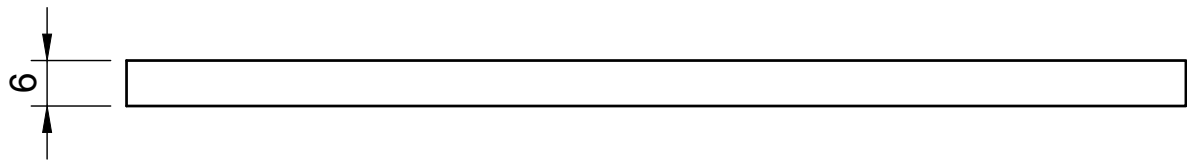
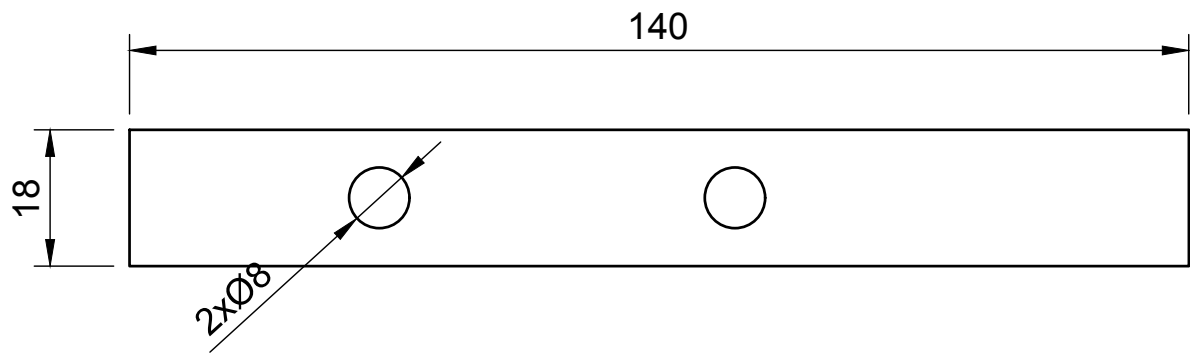


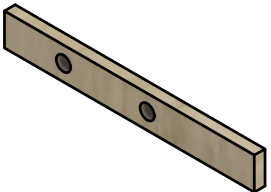
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>      | 1/06/23                             | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b>     | Document status<br><b>Scale 1:2</b> |                     |
|                                                                                     |                                                | Title<br><b>Shredder support small</b> | DWG No.<br><b>V1</b>                |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                      | Date of issue<br><b>05/06/2023</b>  | Sheet<br><b>1/1</b> |

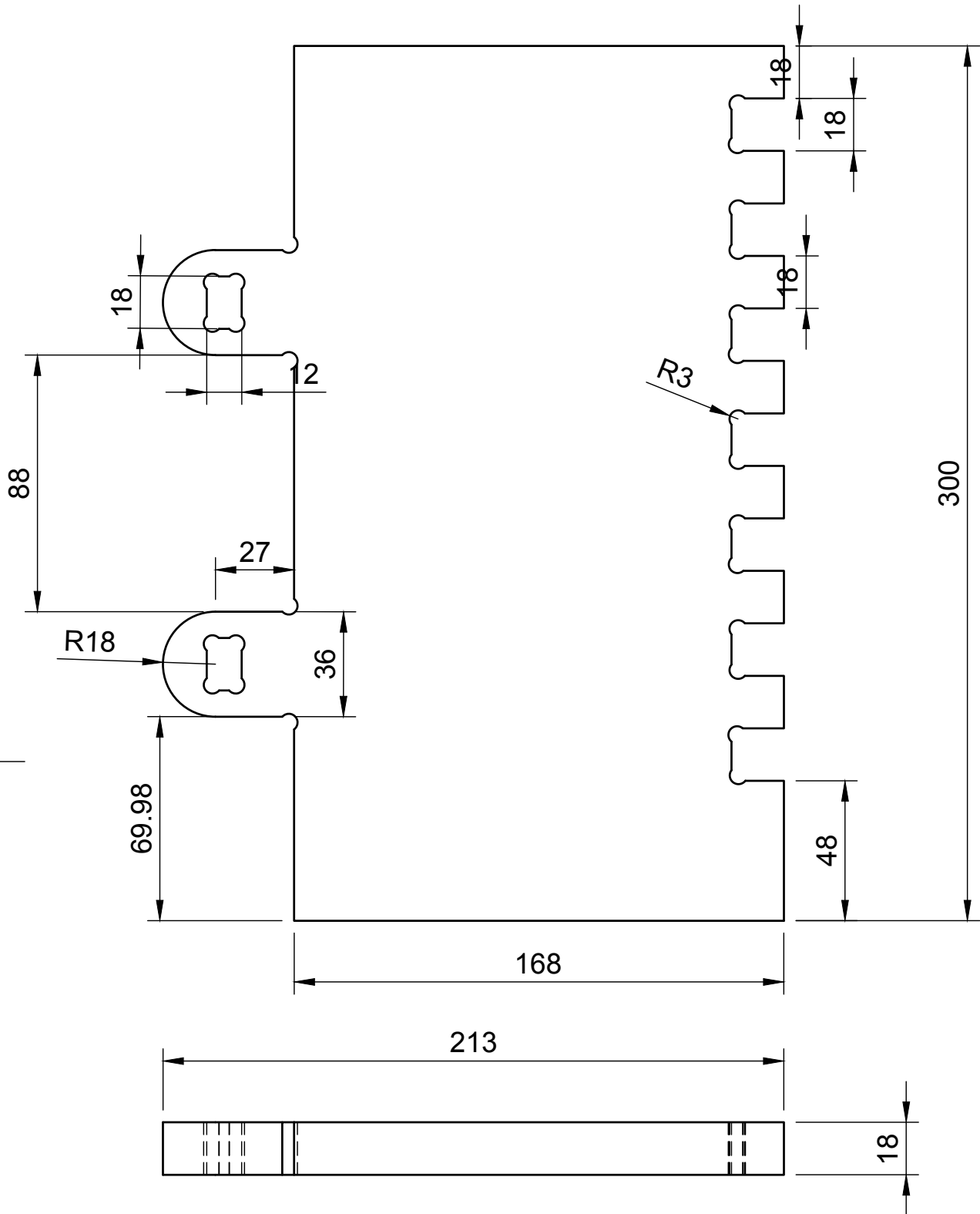


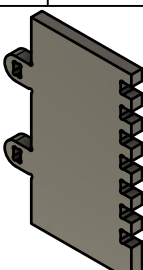


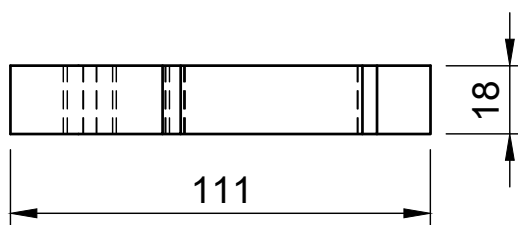
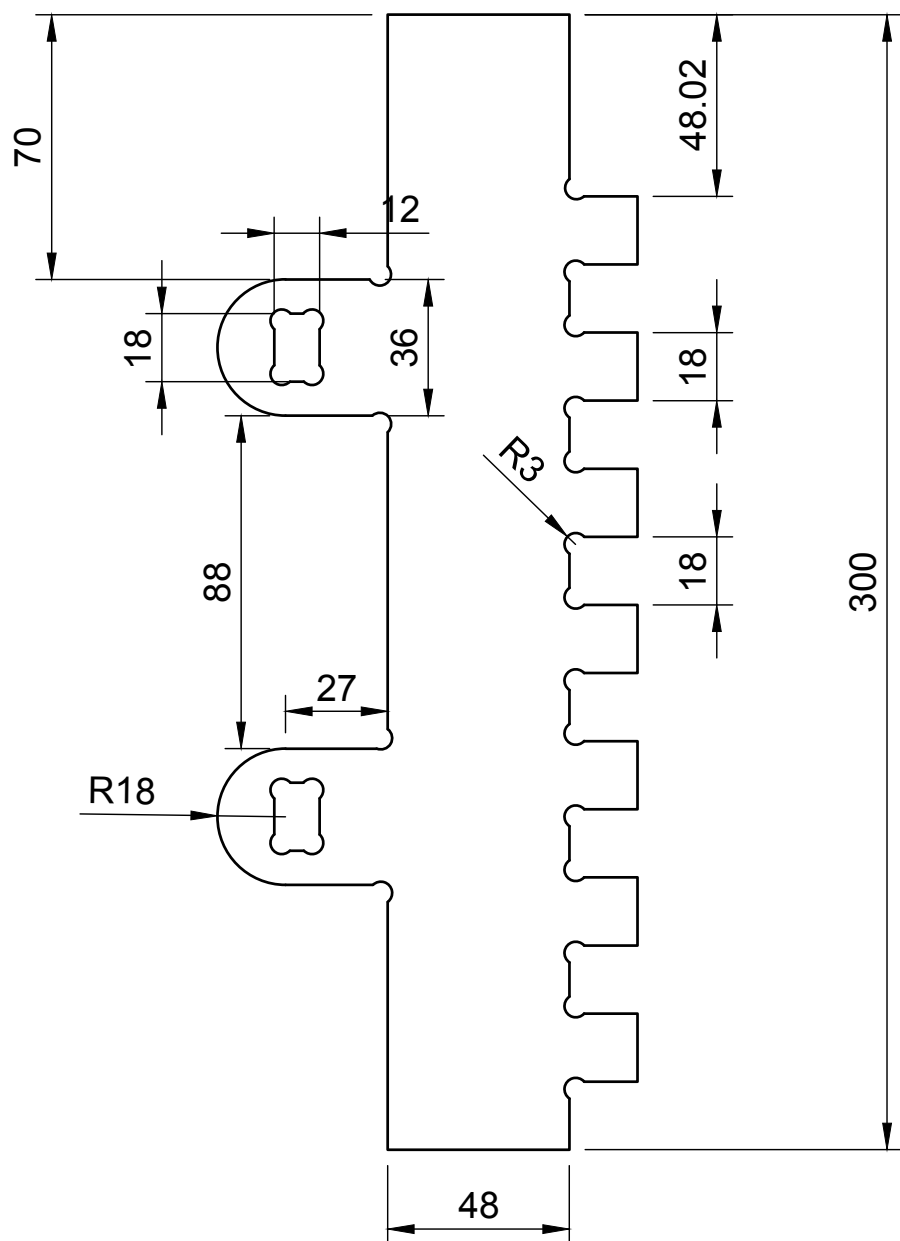
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | 1/06/23                             | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b> | Document status<br><b>Scale 1:2</b> |                     |
|                                                                                     |                                                | Title<br><b>Motor support</b>      | DWG No.<br><b>V1</b>                |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                  | Date of issue<br><b>05/06/2023</b>  | Sheet<br><b>1/1</b> |

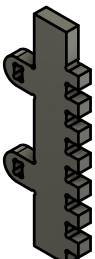


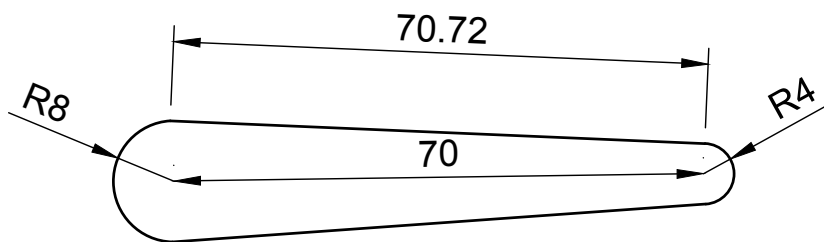
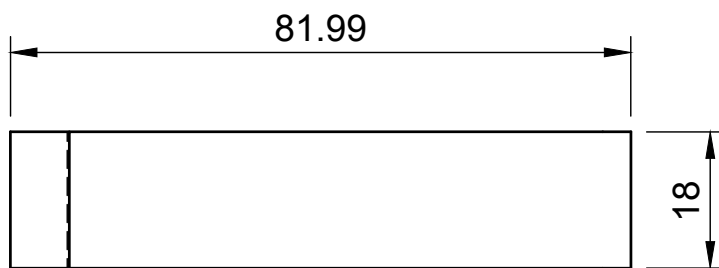
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>marine poudrel</b> | 1/06/23                             |                                    | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b>  | Document status<br><b>Scale 1:1</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Motor Holder</b>        | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                |                                     | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

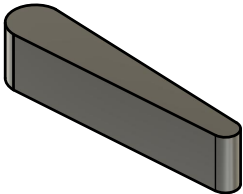


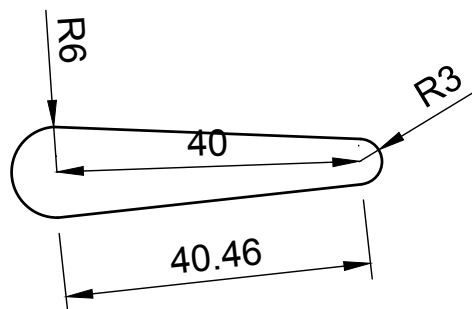
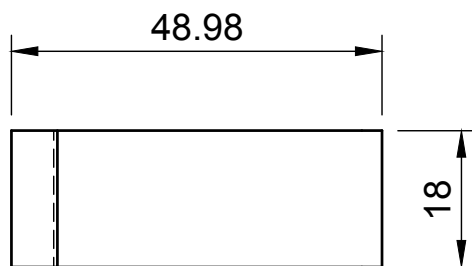
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>   | <b>1/06/23</b>                     | Approved by         |
|  | Document type<br><b>Size in mm</b>             | Document status<br><b>Scale 1:2</b> |                                    |                     |
|                                                                                     | Title<br><b>Driver support 1</b>               | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |

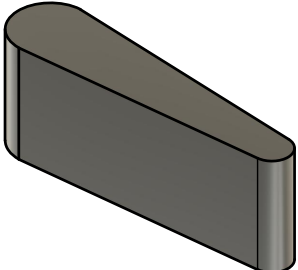


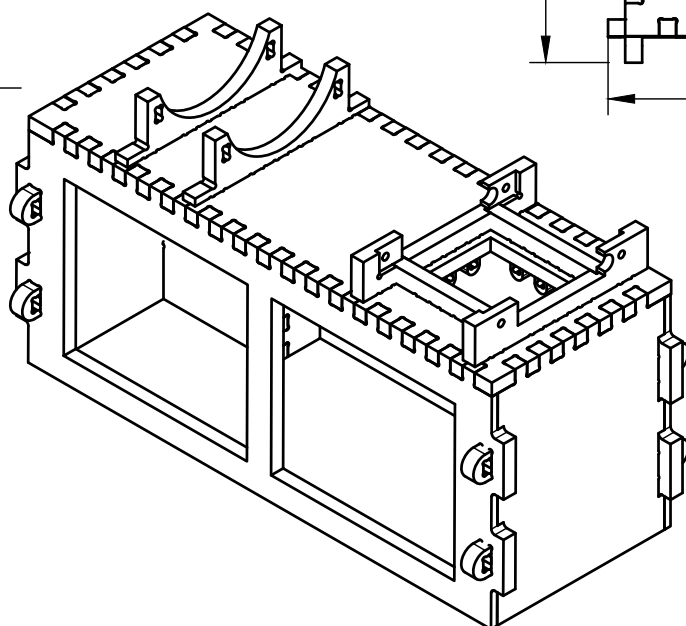
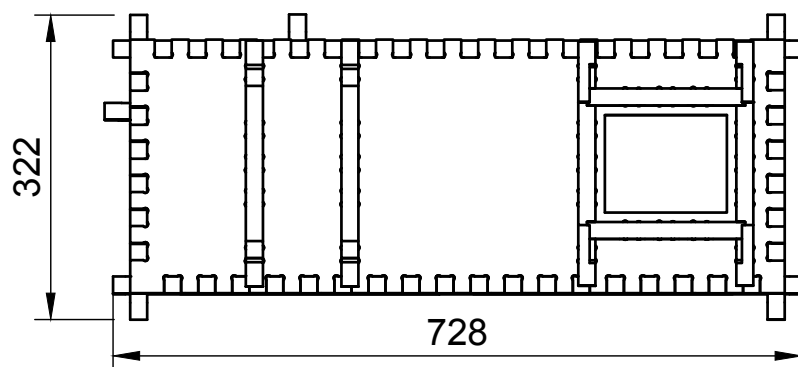
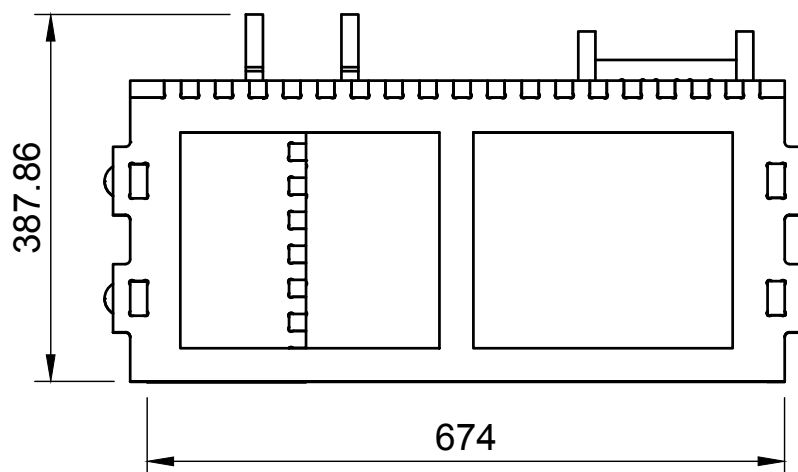
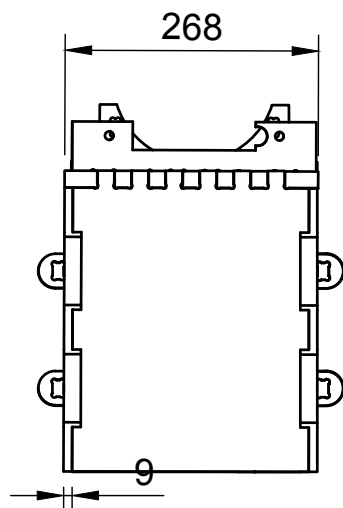
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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | 1/06/23                             | Approved by |
|  | Document type<br><b>Size in mm</b>             |                                    | Document status<br><b>Scale 1:2</b> |             |
|                                                                                     | Title<br><b>Driver support 2</b>               |                                    | DWG No.<br><b>V1</b>                |             |
|                                                                                     | Rev.<br><b>A4</b>                              | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b>                 |             |

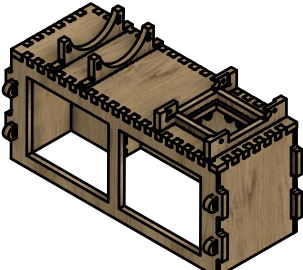


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| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | <b>1/06/23</b>                      |                                    | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b> | Document status<br><b>Scale 1:1</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Large pin</b>          | <b>V1</b>                           |                                    |                     |
|                                                                                     |                                                |                                    | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |



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|-------------------------------------------------------------------------------------|------------------------------------------------|------------------------------------|-------------------------------------|------------------------------------|---------------------|
| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | <b>1/06/23</b>                      |                                    | Approved by         |
|  |                                                | Document type<br><b>Size in mm</b> | Document status<br><b>Scale 1:1</b> |                                    |                     |
|                                                                                     |                                                | Title<br><b>Small pin</b>          | DWG No.<br><b>V1</b>                |                                    |                     |
|                                                                                     |                                                |                                    | Rev.<br><b>A4</b>                   | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b> |



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|-------------------------------------------------------------------------------------|------------------------------------------------|------------------------------------|-------------------------------------|--|-------------|
| Dept.<br><b>Frame</b>                                                               | Technical reference<br><b>Precious Plastic</b> | Created by<br><b>Héloïse Nolf</b>  | 1/06/23                             |  | Approved by |
|  | Document type<br><b>Size in mm</b>             |                                    | Document status<br><b>Scale 1:8</b> |  |             |
|                                                                                     | Title<br><b>Frame Assembly</b>                 |                                    | DWG No.<br><b>V1</b>                |  |             |
|                                                                                     | Rev.<br><b>A4</b>                              | Date of issue<br><b>05/06/2023</b> | Sheet<br><b>1/1</b>                 |  |             |

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