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Open Hardware to support Sustainable Development Goals : Case study "Precious Plastics"

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Abstract

This master's thesis is based on the work of Héloïse Nolf and Marine Poudrel in their project "Design for Manufacturing in FabLab of a Plastic Shredder," submitted during the year 2022-2023 at the École Polytechnique de Louvain. Their research approached the problem of plastic waste through redesigning the Precious Plastic shredder for better accessibility and manufacturability in FabLabs. By adapting the design for local fabrication tools, they demonstrated that 92.4% of the shredder's parts could be manufactured using FabLab resources, a major improvement over the original design. Their prototype served as a proof of concept for enabling individuals and small communities to contribute to plastic recycling efforts but left room for further refinements and optimization. This thesis continues that work, focusing on improving the shredder's overall efficiency, safety, and sustainability to expand its usability in local and small-scale recycling initiatives. Key areas of development include optimizing the shredding mechanism, refining the power supply and drive systems, and improving structural components. Enhancing safety is a central goal, with features such as a redesigned hopper for safe loading, emergency stop systems, and protective coverings to minimize risks for community users. A technology assessment of the final shredder will be conducted using the principles outlined in Michael F. Ashby's Materials and Sustainable Development. This assessment will consider some aspects like the ecological footprint or the life cycle of the shredder to try to determine how effectively the shredder meets the trend of sustainability and helps reduce plastic waste. We will also document methodologies and results of the improvements made to create a comprehensive reference for further research or application within the community. In summary, the thesis will focus on developing an overall efficiency and safety of the plastic shredder, within strong overtones of sustainability, guided by Ashby's work.

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 : technology that uses computer programming to control the movements of machines for precise manufacturing.
FabLab	Fabrication Laboratory
GHG	Greenhouse Gases
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
OSB	Oriented Strand Board
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid (used for 3D printing)
PMD	Plastic packaging, Metal packaging, and Drink cartons
POM	Polyoxymethylene
PP	Polypropylene
Prototyping	The process of creating a preliminary or working model of a product, system, or design concept.
PS	Polystyrene
PVC	Polyvinyl chloride
V1	First version of the shredder (2022-2023)
V2	Improved version of the shredder (2024-2025)

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Introduction

Introduction

Plastic pollution has become one of the biggest environmental challenges of the 21st century, with over 9 billion tonnes of plastic produced since the 1950s and less than 10% actually recycled [1]. The majority of this plastic goes to landfills, incinerators, or the natural environment, where it remains for centuries, polluting ecosystems and threatening biodiversity. Besides the immediate environmental impact, plastic production is also a serious contributor to greenhouse gas emissions and the climate crisis. Growing plastic use in the next decades highlights the urgent need for innovative solutions to combat this problem and reduce its environmental, economic, and social consequences.

The Precious Plastic project is one solution to this problem. The project supports and offer open-source, small-scale recycling machines that allow people to use and recycle their own plastic waste. These machines are designed to be manufacturable by people and society in general, enabling the transformation of plastic waste into new materials and products, within a circular economy perspective. However, there are still challenges with this small-scale solution. The designs often require significant technical expertise and access to advanced tools, which has greatly limited their use.

This thesis builds upon and continues the work of Héloïse Nolf and Marine Poudrel, whose master's thesis addressed these challenges by redesigning the Precious Plastic shredder to improve manufacturability in FabLabs. Their shredder, which we will call the "V1 shredder," demonstrated that more than 90% of the shredder's parts could be fabricated locally, making the machine more accessible. While their design proved that the machine could be made locally, there was still significant room for improvement in efficiency, safety, and long-term durability. This thesis takes their work further, developing a new version of the shredder, the "V2 shredder": a stronger and more sustainable version that aims to address the limitations of the V1 prototype. The V2 shredder intends to strike a balance between functionality and accessibility by redesigning key components with enhanced subsystems while still being manufacturable in a FabLab environment. The project also evaluates the shredder's technology and its alignment with sustainability principles, guided by Michael F. Ashby's framework for sustainable development, ensuring responsible innovation.

The thesis is structured into four parts, each addressing a particular aspect of the project:

Part I: Background and Context

This section introduces the global plastic pollution crisis, identifying recycling as one of the solutions. It explains the Precious Plastic initiative and its vision for decentralized recycling through open-source designs. This section also reviews the achievements and limitations of the V1 shredder, laying the foundation for the improvements discussed in this work.

Part II: Subsystem Optimization on V1

This section focuses on the redesign process, breaking the shredder into subsystems in order to try to improve them. Each subsystem, such as the blades, hopper, motor integration, and safety systems, will be redesigned to correct the defaults found on V1. It will be done in a structural manner, where each of these components will go through a full risk analysis and so called "triple constraint method" to assess whether it makes sense to redesign and improve the subsystem.

Part III: Results and Assessment

This section discusses and summarizes how the V2 shredder was improved compared to the first version. It visually presents how each subsystem has been modified and enhanced. It also compares the two versions in terms of cost, shredding results, safety, and manufacturability. The section concludes with a technology assessment using Ashby's sustainability framework, evaluating how the shredder's design and functionality can effectively support local recycling initiatives while promoting sustainable practices.

Part IV: Appendices

This part provides a comprehensive reference for the technical aspects of the project, including detailed designs, fabrication plans, and shredding results. These appendices aim to serve as a resource for future iterations of the shredder or similar projects.

Special note: All the project documentation, including files for laser cutting, 3D printing, and CNC manufacturing, were created with the software Fusion360 and will be in a USB key, available for any Makilab/Fablab users. The website Canva 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 use, production and recycling

Between 1950 and 2015, an impressive 9.2 billion tonnes of plastic were produced [2]. This is equivalent to more than one tonne per person that is living on Earth right now. A big portion of this plastic consists of single-use products and packaging, which are directly thrown away after being used.

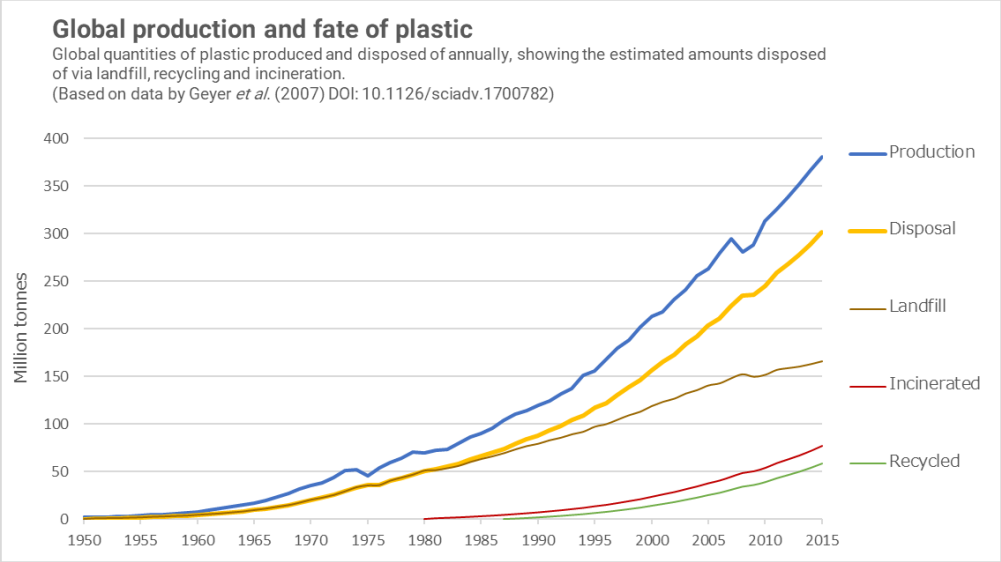


Figure 1.1: Global production and fate of plastic [1]

Figure 1.1 illustrates the trends in plastic production and disposal over time. Plastic production increased exponentially, from a negligible amount in 1950 to almost 400 million tonnes per year by 2015. What happens after plastic is used is concerning too. Land filling remains the dominant fate for plastic waste, followed by incineration, while recycling stays far behind.

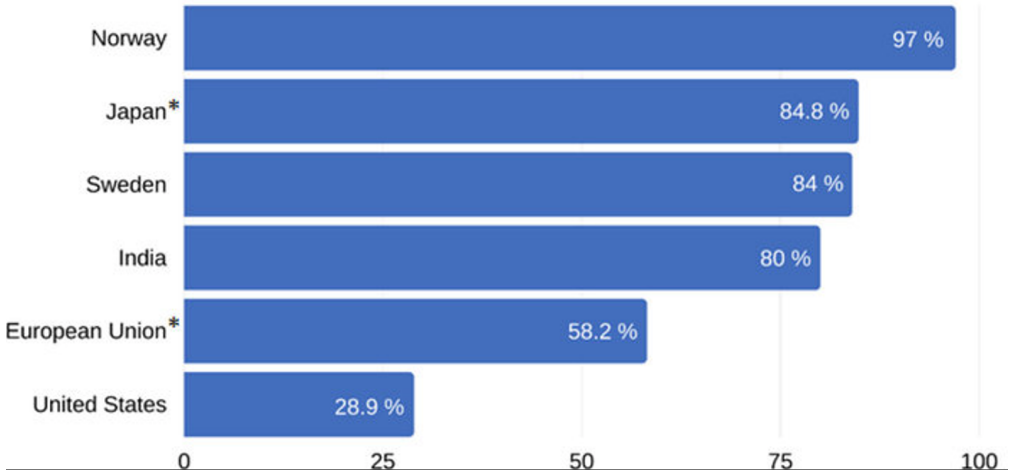


Figure 1.2: Recycling rates worldwide [3]

Recycling rates differ significantly across countries as one can see on Figure 1.2, with, for example, Norway leading at 97%, followed by Japan and Sweden at 84%. In contrast, the European Union averages 58%, and the United States lags behind at 28.9%. Belgium performs better than most EU countries, with a 62% recycling rate for plastic packaging in 2022.[4]
The gap between plastic production and recycling shows how important it is to take action. Countries like Norway and Japan have proven that high recycling rates are possible with strong policies and efficient systems. To tackle the growing problem of plastic waste, countries need to improve how they manage waste, invest in better recycling methods, and cut down on single-use plastics. This growing divide between production and recycling highlights the need for global cooperation to minimize the harm caused by plastic pollution.

Why is recycling so important ? Recycling is one very good way to reduce the creation of waste, preserve resources, and reduce pollution of the environment. Recycling reduces the amount of rubbish sent to landfills and incinerators, hence reducing pollution and saving precious space. By recycling such materials as paper, aluminum, and plastics, the need to extract new material from the earth can greatly be reduced. Less extraction means less energy used, which can be one of the steps to stop climate change. Plastic waste is also becoming a growing threat for our oceans. Millions of tons of plastic enter the oceans every year, damaging ecosystems and animals. Recycling plastics could also significantly lessen this issue. It reduces the amount of waste and energy used; it uses fewer resources, which helps to keep the environment clean. All these together help to create a healthy planet for future generations. In short, recycling is important because it saves resources **and** energy.

1.2 Precious Plastics

Precious Plastic Overview

Precious Plastic is one of the most innovative answer to the global plastic waste crisis, putting this problem in the hands of the community for recycling. The founder, Dave Hakkens, built this project in 2013 to solve plastic pollution by making open-source designs for small-scale recycling machines.
Machines such as shredders, extruders, and injection molding units make it possible for people and the community to recycle discarded plastic into reusable materials and new products in an accessible and practical manner.

Figure 1.3: Precious plastic logo [5]



Figure 1.4: Example of objects that have been made thanks to the Precious Plastics project [5]

Precious Plastic is all about using plastics in a smart way. Figure 1.4 shows us the variety of objects that can be done thanks to the Precious Plastic projects. We can see boxes, plates, or even 3D filaments which can then be used to print any shape/object needed.
Instead of throwing away waste, people can reuse it. This method helps to reduce the need for new plastic by preventing waste from going to landfills and oceans, which helps with environmental problems. By making recycling simpler and cheaper, it lets people help in the fight against plastic waste. Being open-source, Precious Plastic lets a lot of recyclers worldwide work in a very collaborative manner. The community can take off with machine designs and make them or improve the designs as necessary on the ground in cities or rural areas. This versatility of Precious Plastic has grown into an uprising by small-scale recyclers who each uniquely contribute to one common goal of sustainable plastic management.

In short, Precious Plastic focuses attention on the problem of plastic waste and creates active community involvement in recycling processes.

Distributed and Open Source Design

Precious Plastic is distributed and open-source design and is intended to be as accessible as possible for any person. Three key aspects that make a project highly accessible include :

- Shareable Design
- Available Materials
- Replicable Manufacturing

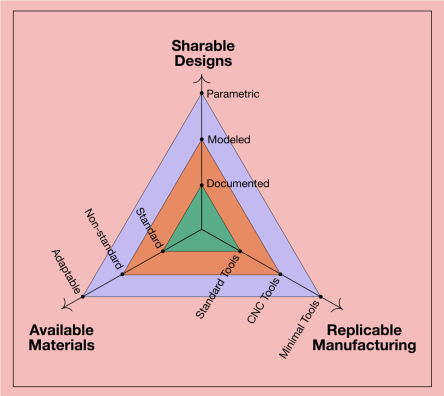


Figure 1.5: Distributed Design Radar [6].

Shareable design encompasses the aspect of giving parametric, modeled, and documented information with which people can derive what they need from it. The use of *available materials* is encouraged by the initiative to make it as accessible as possible, as well as *replicable manufacturing* by means of both standard and CNC tools.
All the way, this open-source aspect creates an enabling atmosphere where members share knowledge, experiences, and resources. On platforms such as the Precious Plastic Bazar, the community can sell and buy parts or finished products made with the machines, hence further supporting a circular economy.

Community Impact

Precious Plastic works because it's driven by the community: people from all over the world have made their shredders, among others, adapting to local needs and resources. Adaptability thus created a very large range of products from recycled plastic: furniture, household items, art, accessories, and many more.
Precious Plastic has become the prime example of a revolutionary shift in facing plastic waste through a technological, collaborative, and open-source platform for the creation of a circular recycling economy. By empowering local initiatives, a practical solution is created to the most daunting environmental challenge of our era.

The Machines

Precious Plastic originally designed four primary machines for facilitating plastic recycling: the Shredder, Extruder, Injection Machine, and Compression Machine. Each has a unique function in transforming the waste into a useful material or product.



Figure 1.6: From left to right : Extruder, Shredder, Injector, Compressor [5]

1. Shredding is usually the first machine when recycling plastic. This is when plastic or part of plastic can be cut or shredded into smaller parts called flakes. This is only with smaller sized flakes that the other machines will be able to work. Shredding is then essential to being able to remodel/reshape the plastic or further processing.

2. We then have the extruder or extrusion machine which melts the flakes and force it to go through a duct/nozzle, creating long shapes likes pipes, beams or even 3D filaments. This process works great for making long or structural parts.

3. The injection molding machine melts plastic flakes and propels them into molds. It would be used in the production of detailed objects, like combs or small buttons, where precision and repeatability are important.

4. The compression molding machine, on the other hand, heats and presses the plastic flakes in order to shape them according to the mold. This machine will be perfect for making larger items, like tiles or plates, and is really good at creating artistic or irregular designs.

These four machines together form a great working system to recycle plastic waste into new products. With the growth of the project, newer "Pro Machines" were built that could process larger volumes and more complicated jobs in recycling, hence allowing users to set up small recycling businesses.

More about the shredder

The Precious Plastic shredder is a strong, useful piece of equipment that is designed to transform the waste plastic into small reusable pieces that could be recycled. The

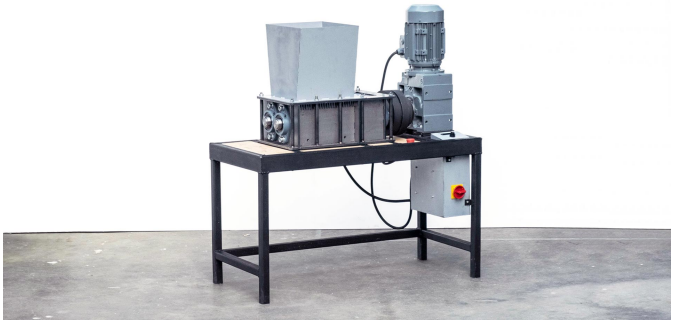


Figure 1.7: Precious plastics shredder [5]

normal components of the machine are a strong steel frame where connected blades are placed onto a hexagonal shaft with motor power between 2.2 kW and 4 kW. It can shred different kinds of plastic, such as HDPE, PP, and PET, into pieces of approximately 5–20 mm in size, depending on the setup of the blades and it can shred approximately 15–20 kg of plastic per hour under good conditions. The shredder is quite big, about 1 meter tall and weighing over 100 kg, so it does require some special space to work. Building the shredder, based on the original Precious Plastic designs, would cost around €1,500–€2,000. This is because it requires strong steel blades, a tough frame, and a good motor[5].

1.3 Fablab manufacturing

FabLabs, short for Fabrication Laboratories, are creative spaces equipped with digital tools and machines that allow individuals to design and prototype virtually anything. Originating from MIT's Center for Bits and Atoms, the FabLab concept has grown into a global network of over 2,000 labs in more than 100 countries. These labs provide access to 3D printers, laser cutters, CNC mills, and other manufacturing tools, enabling users to create prototypes and develop projects with relative ease. For example, the FabLab in Louvain-la-Neuve also called "Makilab", features a variety of machines including 3D printers, laser cutters, vinyl cutters, and CNC mills, all of which are used to prototype and develop solutions for local needs, such as the ongoing work on improving a plastic shredder for recycling initiatives. A key part of the FabLab model is the emphasis on collaboration, open-source design, and knowledge sharing, creating a community where individuals can learn, innovate, and contribute to sustainable development through digital fabrication.



Figure 1.8: Makilab Logo [7]

Chapter 2

State of the art

2.1 Shredding

2.1.1 Shredding in recycling

Shredding is one of the most important steps in plastic recycling and is usually considered an initial breakdown into manageable pieces. This increases the effectiveness of further steps, such as sorting, cleaning, and melting. Shredding materials to a uniform size can provide a better flow in various machines, such as extruders and injection molders. Of the various methods of recycling, such as mechanical and chemical recycling, shredding is one of the easiest and known methods. However, mechanical recycling requires more energy and complicates machinery, especially if the plastics are mixed or contaminated. It remains way more approachable in comparison with other forms of recycling, such as chemical recycling, where the plastics are degraded into their monomers on a molecular level and thereafter into new plastic through re-polymerization. It can recycle a wider range of plastics compared with mechanical recycling, but it also much more complex. On the contrary, shredding is best suitable for clean and single-type plastics and can be easily adapted into local and small-scale recycling initiatives.

2.1.2 Shredding principle

During shredding, plastic material experiences increased stress while it is conveyed in the shredder. If this stress outweighs the yield stress of the plastic, it deforms and starts to bend and twist by changing its shape [8]. If the applied force goes on increasing beyond, it reaches a fracture strength of that material and breaks into small pieces. Yield stress and fracture strength are different for the various types of plastics. For instance, high-density polyethylene has a yield stress of about 26 MPa, whereas polystyrene has a yield stress of about 35-55 MPa [9]. Efficient shredding will, therefore, be dependent on whether the shredder can apply forces which exceed this yield stress for different plastics to break tough materials like polypropylene and polyethylene into manageable

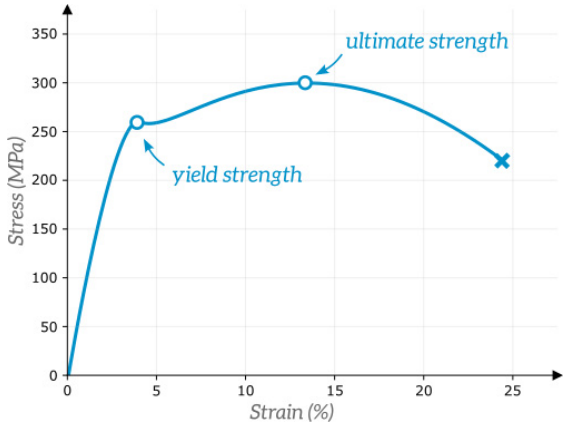


Figure 2.1: Yields stress and fracture strength [10]

sizes. That includes design and sharpness, since sharper edges provide lowered force that will be required to initiate deformation and hence optimize energy utilization in the shredding process. Proper alignment and rotation speed of the blades is also important in maintaining continuous stress on the plastic to result in an efficient breakdown into fragments which can easily be recycled.

2.2 Plastic

2.2.1 Types of plastic



Figure 2.2: 7 different types of plastics [11]

There are seven broad different types of plastics with their individual properties and commonplace products. PET or Polyethylene Terephthalate can be essentially used for clear water bottles and jars because it has all the qualities like transparency, strength,

etc. HDPE stands out for shampoo bottles and grocery bags because it is much stronger in nature. Cleaning product containers and sheeting usually find their material as PVC : very versatile, waterproof quality. LDPE stands for Low-Density Polyethylene, used in bread bags and plastic films because it is very flexible. PP stands for Polypropylene, which can be found in yogurt cups, straws, and hangers since it is strong and resistant to heat. PS stands for Polystyrene, found in take-away packaging, toys, and disposable cutlery because it is lightweight. Other plastics include nylon and baby bottles, which are mixed or less common plastics with a wide range of uses. This categorization facilitates the understanding of recycling possibilities and environmental impact.

2.2.2 Properties of plastic

In plastic recycling, knowledge of the physical properties of different plastics is substantial in improving the shredding process. The inherent property of each plastic determines how it responds to applied mechanical stress. Here are some examples of different material properties and their usages.
For example,**Polyethylene Terephthalate (PET)**, has a density in the range of 1.29 to 1.39 g/cm^3, and a maximum tensile strength σ_{UTS} of 55 to 60 MPa; hence, it is very dense and strong. PET also has a melting point range of 200–260°C, allowing it to be easily recyclable in high-heat processes.
High-Density Polyethylene (HDPE) has a density from 0.952 to 0.965 g/cm^3 and tensile strength from 26 to 31 MPa. This allows HDPE to handle a lot of stress while being more flexible than PET; that is, its strength helps it resist breaking, which is helpful when shredding.
Low-Density Polyethylene (LDPE) is used in many plastic bags and films. It has a density between 0.917 and 0.932 g/cm^3. Its tensile strength ranges from 13.3 to 26.4 megapascals. Because it has lower yield strength, LDPE is more prone to changing shape, which can be tricky when shredding as it stretches rather than breaks when under tension.
Polypropylene (PP), used in many car parts and as packaging material, has a density between 0.897 and 0.906 g/cm^3 and tensile strength in the range of 26 to 50 MPa. It has high strength for its weight, melts between 151–167°C, and is good for recycling.
Polystyrene (PS), used in disposable cutlery and packaging, has a density between 1.04 to 1.05 g/cm^3 and a tensile strength in the range of 35.9 to 51.7 MPa. Its rigidity and brittle nature allow it to break easily under stress; thus, shredding is efficient. Lastly, **Polylactic Acid (PLA)**, a biodegradable plastic, is often used in environmentally friendly products, with a density ranging from 1.00 to 3.41 g/cm^3 and tensile strength between 20 and 30 MPa. PLA has lower thermal resistance, with a melting temperature range of 135–181°C, which makes it better applicable where high heat resistance is not necessary.

Differing densities, strengths, and yield properties of plastics will determine how they will behave in the shredding and recycling process. By knowing these properties, recyclers can adjust shredding conditions so that the material breaks apart well and is prepared

for recycling.
Here is a table that summarizes the different plastic properties.

Material	**Density** [g/cm^3]	σ_{UTS} [MPa]	**Melting temperature** [°C]	**Young modulus** [GPa]
PET	1.29 - 1.39	55 - 60	200 - 260	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	3 - 3.5
PLA	1.00 - 3.41	20 - 30	135 - 181	1.06

Table 2.1: Properties of different materials used in plastic recycling [12]

Differing densities, strengths, and yield properties of plastics will determine how they will behave in the shredding and recycling process. By knowing these properties, recyclers can adjust shredding conditions so that the material breaks apart well and is prepared for recycling.

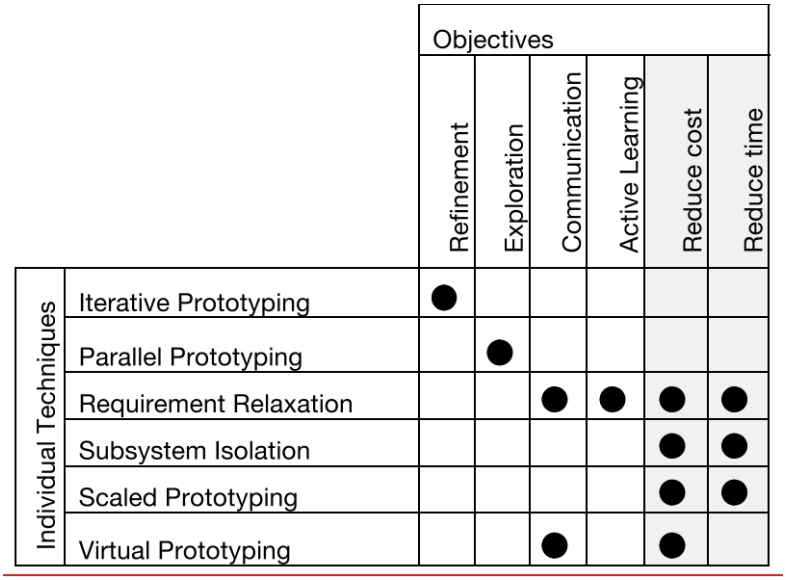
2.3 Prototyping

2.3.1 Prototyping Techniques

Prototyping is a critical step in the product development process, allowing a tangible approximation of the final design. Different methods are employed for prototyping, each having different requirements satisfied according to the project's needs and resource constraints.

Iterative prototyping: A work style that involves repetition of the steps in a design making, testing, and improvement process. Each new prototype is an improvement over the previous one. This allows to test and improve designs in an iterative manner and find and fix problems early in the development process. Other benefits of building the prototype repeatedly include efficiency, finding large design problems early, and saving money by using fast prototyping tools such as CNC machines, laser cutters, or 3D printers. The repeated making of prototypes helps to get the users involved so that they can give early feedback, which can make the final product easier to use.

Scaled Prototyping: Scaled prototyping is a valuable technique in product development that involves creating smaller versions of large or complex systems to test design and functionality. By building a prototype at a reduced scale, engineers can study key aspects like structure, load distribution, and movement without the high costs of a full-size model.
In scaled prototyping, geometric similarity is important, meaning all dimensions are proportionally reduced to keep the original shape. Engineers also consider material properties and load scaling—adjusting forces on the model to mimic the stresses and strains of the real object.



[13]

Figure 2.3: Mapping between techniques and commonly associated objectives

Parallel Prototyping involves developing a number of prototype concepts simultaneously and then comparing each to determine which is best. This approach works effectively when the costs of projects can change and when it's important to explore different ideas. Parallel prototyping encourages new ideas and variety because it creates many together at once, helping teams look at different design options side by side [54].

Subsystem Prototyping Subsystem prototyping allows for working on parts of a complex system separately before putting everything together. This approach is very helpful in large projects, where different parts usually require special testing and improvements. Using this approach, engineers can improve specific functions without affecting the other parts of the design, and hence, problems are easily found and fixed. When each subsystem prototype meets its performance requirements, they are integrated into the main system. This will make the assembly process smoother and reduce the chances of errors in the whole system. Subsystem prototyping also fits well with modular design principles. These principles allow flexible design, easier maintenance, and future upgrades. This way, it makes sure that every component is fine and also that the whole system is efficient. It even helps to reduce time spent on solving problems during the final stages of product development.

What we will use

Subsystem prototyping, is the best approach for developing the shredder because it allows us to address each critical part — such as the hopper, blades, frame, motor, gearbox, and shredder mechanism — individually while continuously refining the design. Subsystem prototyping enables us to isolate and optimize specific components by testing various designs, materials, and configurations for each part. For example, we can start working on the hopper to improve usability and replicability while the motor has to be optimized for its torque and efficiency, and then continue working on the durability of the blades and integrability of the frame : all subsystems at the same time.
With this method, one can improve each subsystem on its own while making sure that they work in smooth integration. This approach allows for easier assembly and continuous improvement of the general design.

2.4 Assessment

To refine this first shredder prototype, a systematic process has to be done on every subsystem through 3 crucial steps, see Figure 2.4.
This assessment will be done on each and every subsystem in Part II of this master thesis, to help us improve each subsystem by choosing a better solution.

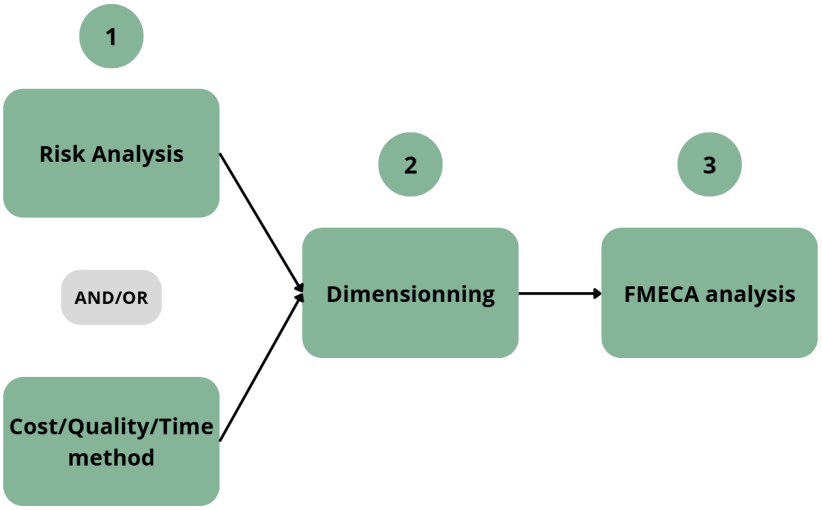


Figure 2.4: Subsystem refinement

1
First, an analysis step evaluates the performance of the subsystem by indicating any eventual weaknesses, which could lead to possible improvement. This analysis is done through the use of two methods: the cost/quality/time and the risk analyses. With a "AND/OR" relation between them so that any evidence showing inefficiency between risk analysis or quality/ cost/time assessment must consider improving the subsystem. If both methods point to problems simultaneously, it enhances the need for immediate amelioration.
On one hand, the risk analysis should pinpoint where potential safety hazards, inefficiencies, or lack of effectiveness may lie regarding key components. Subsystems with large risks or an inability to perform will be given priority for redesign.
On the other hand, the balancing cost, scope, and time method of the triangle will be used in searching out and assessing if a better subsystem exists. It allows us to check if the current subsystem addresses the necessary requirements efficiently or if some adjustment of this will create a better balance within the triangle. For instance, it considers if the cost can be reduced without sacrificing performance, if the time required for making or purchasing can be shortened, or if the range of features can be expanded while keeping costs and time within acceptable limits. This will allow a systematic assessment of the potential alternatives, such as a custom-made solution from a Fablab versus an brand

new subsystem bought online, ensuring that the selected option has the best possible balance for the project.

2

Once a solution is selected, we will move on to dimensioning calculations, where we will determine the specific physical and functional requirements, such as power, strength, weight, and size, to ensure the redesigned subsystem fulfills its role.

3

Following this, we will perform an FMECA (Failure Modes, Effects, and Criticality Analysis) to evaluate long-term reliability, identifying potential failure points and ensuring the subsystem is durable and dependable over time. This process, applied step by step to every single component, will refine each and every one for better performance, safety, and reliability and bring all subsystems into a more efficient shredder design.

2.4.1 Risk analysis

A full risk analysis using a structured risk factor evaluation approach will be done to make certain that the technology of the plastic shredder is usable. The approach will be done as demonstrated in the table 2.5 below, using Kinney's theory [14] and its associated tables. It views the potential risks along three dimensions of concern, namely:
Risk Exposure - how often the facility encounters the risk.
Likelihood - the probability of an adverse event.
Consequence - the impact if the risk materializes.
This matrix allows the calculation of the risk factor, by which each identified risk can be labeled as high, medium, or low to allow for prioritized mitigation strategies.

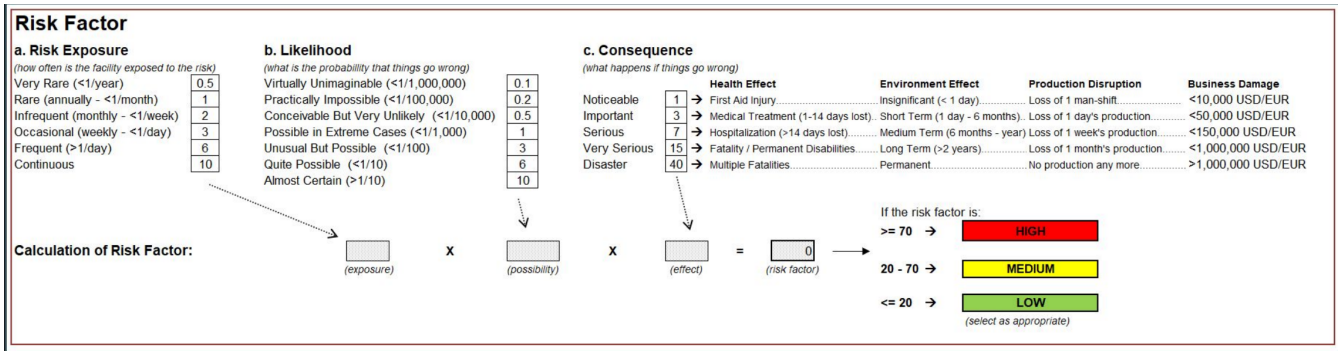


Figure 2.5: Kinney's Risk analysis table [14]

With the values computed for Risk Exposure, Likelihood, and Consequence, we will use the following formula:

$$\textbf{Risk Factor} = \textbf{Exposure} \times \textbf{Likelihood} \times \textbf{Consequence} \tag{2.1}$$

We will then compare the obtained value of Risk Factor to threshold values given in the table:
Low Risk ≤ 20: The risk is acceptable; no urgent action is required.
Medium Risk 20–70: It is a moderate risk and may require corrective/preventive measures in order to reduce the risk.
High Risk ≥ 70**:** It is a critical risk, and immediate action needs to be taken in order to eliminate it or bring it as low as reasonably practical.

The risk analysis will be conducted on several subsystems of the shredder that needs improvement in safety by using the table as follows :

Category	**Score**	**Description**
a. Risk Exposure (Frequency of Exposure)		
Very Rare	0.5	Less than once per year (annually)
Rare	1	Annually but less than once per month
Infrequent	2	Monthly but less than once per week
Occasional	3	Weekly but less than once per day
Frequent	6	More than once per day
Continuous	10	Continuous exposure
b. Likelihood (Probability of Failure)		
Virtually Unimaginable	0.1	Less than 1 in 1,000,000
Practically Impossible	0.2	Less than 1 in 100,000
Conceivable But Very Unlikely	0.5	Less than 1 in 10,000
Possible in Extreme Cases	1	Less than 1 in 1,000
Unusual But Possible	3	Less than 1 in 100
Quite Possible	6	Less than 1 in 10
Almost Certain	10	Greater than 1 in 10
c. Consequence (Impact if Failure Occurs)		
Noticeable	1	First Aid Injury
Important	3	Medical Treatment (1–14 days lost)
Serious	7	Hospitalization (more than 14 days lost)
Very Serious	15	Fatality or Permanent Disability
Disaster	40	Multiple Fatalities

Table 2.2: Risk Factor Categories: Exposure, Likelihood, and Consequence

2.4.2 Triple constraint method

The triple constraint method or triangle method is a method to review the performance of a subsystem, such as a shredder, by looking at three main factors: time, scope, and cost.

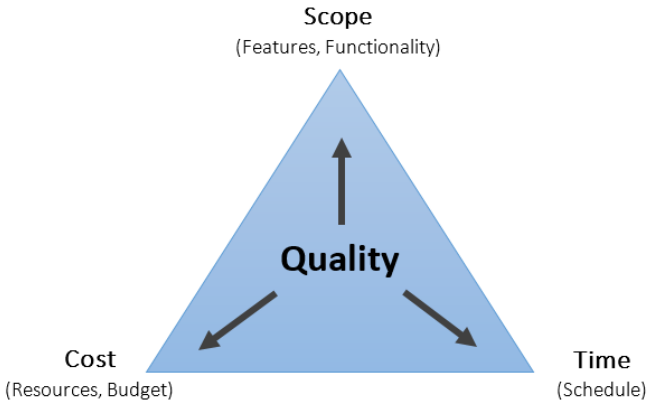


Figure 2.6: Triple constraint triangle [15]

Time obviously tells us about the time needed to acquire a solution, in other terms, in how much time can this solution be available. Whereas the scope is about the extent of the system's functionality, such as the variety of materials it can manage, the volume of plastic to be processed, and generally its capacity to achieve set goals. Cost covers the amount of money it would take to build, run, and maintain the system over time. The triangle method guides decisions in prototyping, during which a product is progressively constructed and improved step by step. At each remake, the designers have to make a decision about how the system can be improved. For example, in a first prototype of a shredder, designers might optimize the scope by using better quality materials , but that would perhaps increase the complexity of the design, possibly raising the cost and lowering the overall time of the solution. The balance between time, scope, and cost is calculated by the designer by means of the triangle so that the final product might be as good as it can be. This helps assure that, in the final analysis, the shredder can be made in a given amount of time with the right capabilities, and at the right cost.

The triangle method can be very useful in our case for example, when we have to decide between making the part in Fablab or actually buying the part on the internet.
Time: Creating the subsystem in Fablab would require some time to design, adjust and finally only create the part with a 3D printer or a CNC for example. Whereas buying the system online would only cost you the time to choose online and wait for it to be delivered.
Scope: The scope of a fablab-built subsystem is defined by the design choices during prototyping, and can be tailored to the needs of the capabilities required for the subsystem, such as material handling or processing speed. A commercially available subsystem will

likely have more features than actually needed, which can make it more complicated and costly than it needs to be.
Cost: The fablab-made subsystem would be cheaper, given the access to tools and materials is available, but in turn, the time used for the development may increase the overall cost. An online-bought subsystem has an already specified price, which can contain additional features not needed, hence adding to the overall cost.

To assess scope, time and cost, it will be quantified with a ladder scale of 1 to 5 on each of the triangle's faces, see Figure 2.7

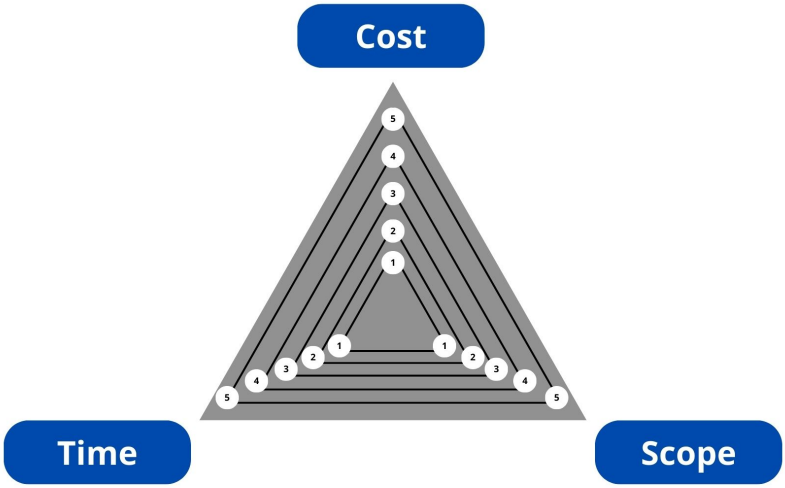


Figure 2.7: Ladder used for the triple constraint method

Each of these aspects is evaluated separately. The range of 1 means poor performance, or the lowest score, and 5 represents excellent performance, or the highest. Table 2.3 will help us to quantitavely choose the score for each face of the triangle.

Score	**Cost (€)**	**Time (Hrs)**	**Scope (Capability)**
1	>300€	>5 hours	Very limited functionality or specific to one use.
2	100–300€	3 hours - 5 hours	Limited functionality, few applications possible.
3	50–100€	1 hour - 3 hours	Moderate functionality, meets most needs.
4	25–50€	10 minutes - 1 hour	Broad functionality, adaptable to multiple uses.
5	<25€	<10 minutes	Highly versatile functionality, easily scalable.

Table 2.3: Scoring Criteria for Cost, Time, and Scope in the triple constraint method

The sum of the three scores is obtained to identify the design total score. If the total score from an improved design is higher, then that means the alternative design is better balanced, functional, and therefore worth fabricating or purchasing. This provides a

structured method of ensuring that design options are comparable. The triangle method balances these factors in order to come up with the best option.

Example

Let's apply the triple constraint theory to the example mentioned before : we will compare a frame ordered online against a frame designed and fabricated in a Fablab. (Data and values are estimations used to illustrate the example only.)

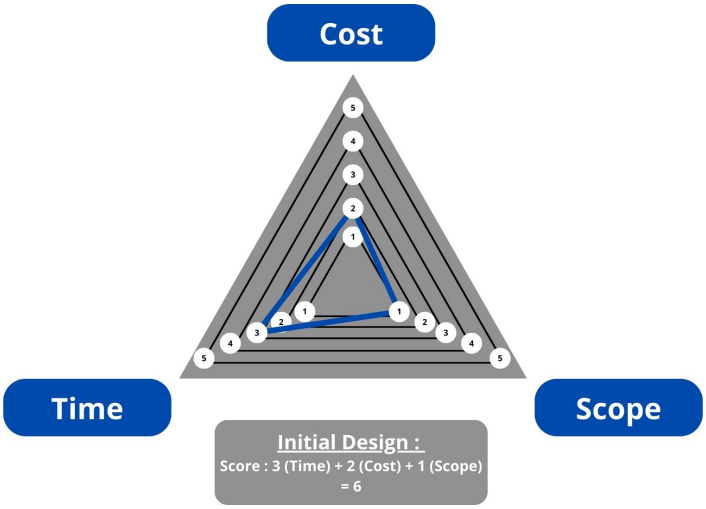


Figure 2.8: Triple constraint method on a frame bought online

For the initial design/solution, the frame was ordered from an online retailer. Let's say it costed 100€, as a result, its cost score was 2 for the combined material and shipping price. Although the integration time was small, it still took about 1 hour to take the good measurements to make sure that it would fit, the score of 3 is moderate. The scope was limited because the construction was to fit the specific dimensions of the frame that had been purchased, so the score here is low at 1, as it has no flexibility for adjustment or modeling in the future.
In contrast, the improved design of a custom-sized frame through a CNC-machined DXF file designed for the project's scope greatly improves scope to 4, as it allows the design to be revised and resized with ease. Cost improves to 4 since only the material needs to be paid for in addition to negligible electricity consumption for machining (around 30€). However, this design process entails more time consumption in designing from scratch and cutting the frame, maybe making a mistake along the process, where in total it took more than 5 hours reducing the time score to 1.
The final result of the comparison, through the triple constraint evaluation method, shows that both designs have some trade-offs. The first design has an overall score of **6** (the Cost has 2, Time is 3, and Scope is 1). It shows that the solution might be very fast and straightforward but not adaptable and with higher costs like shipping and material

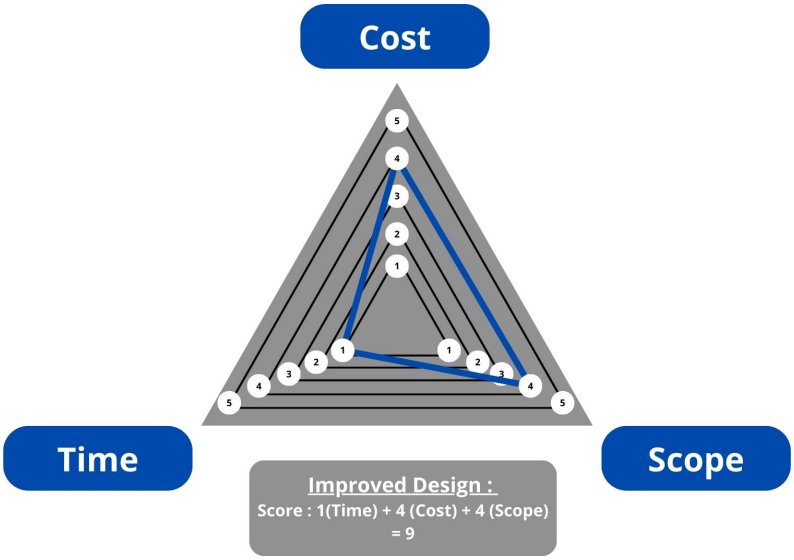


Figure 2.9: Triple constraint method on a Fablab-made frame

costs. On the other hand, the improved design has an overall score of **9** (Cost 4, Time 1, Scope 4) in total scores. Although it takes more development time, it will still be cheaper and also will offer more flexibility for extension.
As shown here, the improved design is to preferred because it provides a better long-run solution, and simply adds value. Although this would involve a little more work at the beginning, it is the best approach when projects attach higher value to adaptability and efficiency. This example shows how structured evaluation can help to quantitatively choose between 2 available solutions.

2.4.3 Dimensioning

Dimensioning refers to the setting up of size, maximum stress, shape, and specification of the parts that constitute a system so as to meet its functional, mechanical, and operational requirements. In a shredder system, for instance, proper sizing would relate to dimensioning elements like the size of the motor, size of the cutting blades, and size of the frame, such that the entire system performs the intended duty, such as capacity in shredding or speed.
This process is very much related to the triangle method: performance, scope, and cost. If time is an important constraint, for example, then dimensioning needs to take into consideration components that are easily available and easy to assemble so that the system can be built or bought in the shortest time. If the main concern is about the cost, dimensioning may involve choosing cheaper materials or simplifying the design in order to cut down on overall costs, even if this slightly affects the performance or scope.
Another important aspect of dimensioning is prototyping: during the early stages, when time is of essence, prototypes are dimensioned by using simpler, off-the-shelf components.

With each iteration that improves the design, a more accurate dimensioning may be used, even with custom-made parts, for better compliance with performance and scope.

2.4.4 FMECA analysis

The FMECA, or Failure Modes, Effects, and Criticality Analysis, is the final step in assessing and performing iterative prototyping on the shredder. It includes the systematic identification of possible failure modes in such key components as the motor, blades, and frame, together with an evaluation of their effects and prioritization with regard to their severity and likelihood. It is a powerful tool to make sure the shredder can run in a reliable way without breakdowns or costly repairs later on using it.
The process of conducting an FMECA on, for example, a shredder, has to be done on every subsystem of the system itself. It should list all subsystems along with the possible ways a failure can occur in them, like overheating in a motor or wearing of a blade. This would then be followed by analyzing how those failures would impact the system, identification of the severity of each failure, coupled with the likelihood of the occurrence. Besides, detectability considers how easily the problem can be spotted in advance of causing major damage. These factors are combined to give the Risk Priority Number, the product of severity, likelihood, and detectability.

$$\textbf{RPN} = \textbf{Severity} \times \textbf{Likelihood} \times \textbf{Detectability} \tag{2.2}$$

This looks similar to the risk analysis explained in section 2.4.1 but this time is about the failure modes of the subsystem, rather than the danger related to it. The higher the RPN, the more critical the failure mode is and thus it deserves higher priority.
Once the RPN is found, strategies are developed to eliminate or reduce these most critical failure modes. FMECA is important in making the solution last longer, improving reliability and durability. Early identification and mitigation of failure risks in the design will make the shredder more capable of performing consistently for a long period of time with reduced maintenance, hence prolonging its lifetime.
Besides, FMECA contributes to sustainability in terms of designing more durable systems, hence reducing the number of repairs and replacements that will lower waste.

The FMECA analysis that will be done on each subsystems will be drafts, based on initial predictions and assumptions about the design. The numbers and conclusions are estimates and should be taken with caution, as they are not final. This analysis serves as a starting point to identify potential risks and prioritize areas for improvement. As the design progresses and more testing is done, the analysis will need to be refined to ensure more accurate and reliable results. However, the FMECA method on the subsystem will provide a great framework to understand the failure modes in the subsystem and shredder in general.

2.5 Technology assessment according to Ashby

2.5.1 Context

Before any new technology is introduced to the real world, it is very important to conduct an overall assessment that critically evaluates risk, efficiency, and sustainability of the technology. As emphasized in Materials and Sustainable Development by Michael F. Ashby [16], technology assessment is critical :

> *"Technological innovation should provide for the needs of the present without compromising the ability of future generations to meet their needs."*

The full assessment would not limit itself to the immediate benefits of the technology but should also consider long-term consequences. For example, a new technology may improve short-term efficiency but cause environmental degradation in the long term if its need for energy or resources are not sustainable. Similarly, beneficial technologies may introduce new risks for users or communities when proper safety is not considered. Such considerations are important, since new technologies may give rise to unwelcome or unexpected side effects, including environmental degradations, resource depletion, and public safety hazards.
Incorporating a framework for technology assessment allows developers and stakeholders to finalize a technology before the latter releases into the market : a process that maximizes their sustainability by minimizing risks. Identifying potential problems early, improvements can be made in order to enhance efficiency and safety, and make sure that the technology is appropriate for long-term environmental and social goals.

Sustainability and Material Selection

Material selection for sustainability is a very important step towards the goal of minimizing environmental problems throughout a product's or technology's life. This will be achieved by choosing materials that optimize energy consumption during production, use, and disposal to meet the requirements of sustainable development. Selection of materials should be done, as explained by Michael F. Ashby in his work Materials and Sustainable Development, with consideration of resource availability, recyclability, toxicity, and energy. A very important concept is considering materials in terms of performance but with respect to future resource availability. Using such tools as material selection charts, see Figure 2.10, the designer and engineer will be able to see the trade-off between material properties and their environmental impacts and make a more sustainable choice.

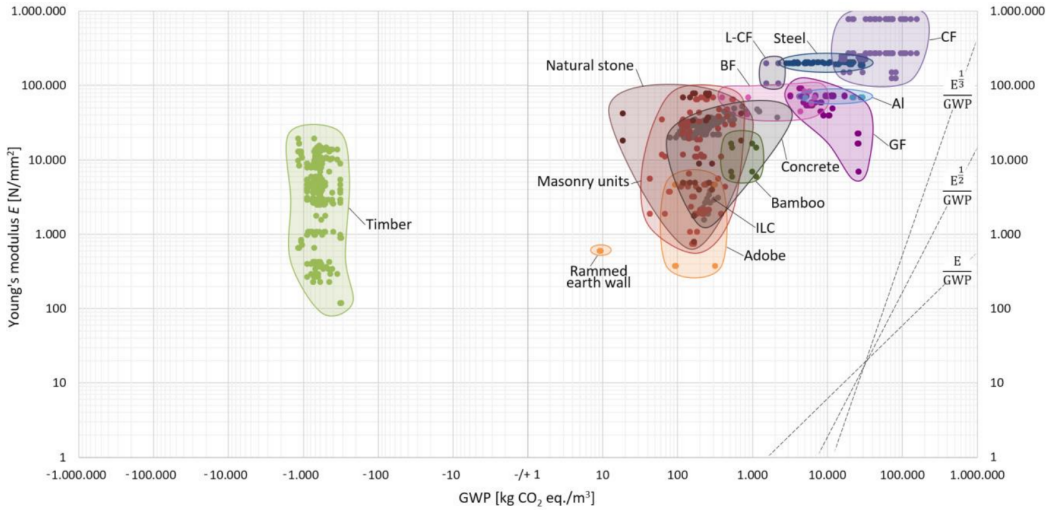


Figure 2.10: Material selection chart showing the trade-off between carbon footprint and stiffness (Young's Modulus)" [17]

Importantly in this approach, non-renewable materials should be substituted, where possible, by renewable or recycled ones to help the development of the circular economy and minimize the use of virgin materials.

Sustainable technologies

They are technologies designed to consider the long-term environment and social effects caused by them, minimize waste, conserve energy, and better manage resources. According to Ashby, for a technology to be counted as sustainable, it needs to contribute positively towards both the conservation of the environment and to human society while being economically viable [18]. Examples include energy technologies such as solar panels and wind turbines, which are progressively reducing dependence on fossil fuels and lowering related greenhouse gas emissions. In many cases, the focus of sustainable technologies is also designing products for durability and recyclability to extend the use phase, and facilitate the end-of-life reuse or recycling. In developing such technologies, however, it is equally important to consider their life cycle, from raw material extraction to disposal, while not creating new problems, whether in resource depletion or possible pollution from production processes. The core principle for sustainable technologies is that they must be able to meet present needs while proving capable of adapting to future environmental and social challenges.

2.5.2 5 steps technology assessment

To assess the sustainability of a technology, Michael Ashby suggests a 5 step method that allows a comprehensive evaluation of the **environmental, social and economic** impacts of this technology. Figure 2.11 below represents this 5 steps structured process for the sustainability assessment of a technology.

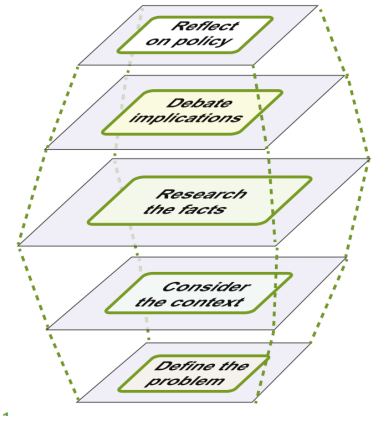


Figure 2.11: "Layering as a way of thinking about complex problems" [16]

It starts with the definition of the problem, by identifying the main objectives that the technology should reach. This step will make certain that the goals are specific, measurable, and in line with the bigger context of sustainable development.

The second level is about setting the context of the technology where the environmental, social, and economic variables will again be important.

The third and most detailed phase, "Research the facts", is focused on collecting objective data about the technology. There are exactly 6 sections that will be of interest, see Figure 2.12.

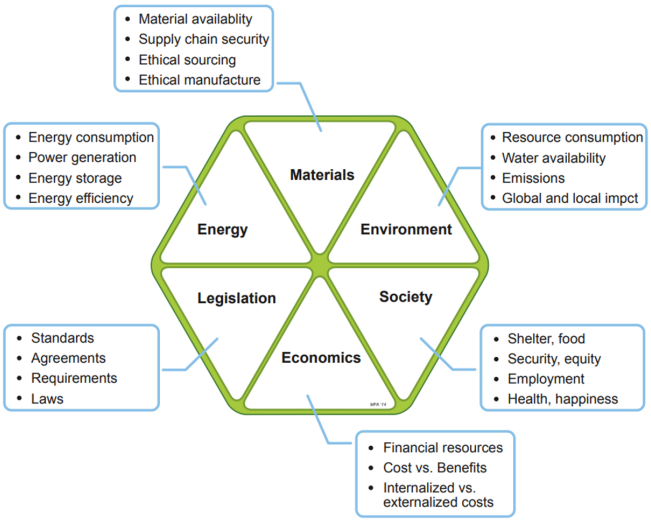


Figure 2.12: Six key dimensions of sustainability — Materials, Energy, Environment, Society, Economics, and Legislation [16]

This covers **material** resources used, their source, and life cycle impact, as well as **energy** production and functionality. It also encompasses **environmental** impact, which includes any emission, waste, and legal compliance issues, besides **social** and **economic** parameters like accessibility, equity, affordability, and long-term sustainability. Last section will be about the **legislation** related to the technology, by searching laws and standards of using a plastic shredder. This evidence-based analysis will be very important in giving full insight into the impact the technology has on the pillars of sustainability.

Fourth phase involves discussing and debating the implications in general after the research work: the synthesis of the information obtained by weighting different possible scenarios of the designed and put-in-action technology..

The last phase of reflection will make us think of how the technology could evolve. It will make us understand how such a system could be improved and what are the alternatives to achieve the same set goals and objectives.

This framework shall be applied to the plastic shredder once all improvements to its subsystems have been effected. This way, we will follow a structured process that not only ensures the shredder meets its technical goals but also is in concert with the principles of sustainability, hence serving as an optimal tool for responsible plastic recycling.
This 5 steps method will be used in Part III of this master thesis, to assess the sustainability of the V2 version of the shredder

Chapter 3

Previous work

3.1 Introduction

As a contribution to the solution of the plastic waste problem in the world, Héloïse Nolf and Marine Poudrel have taken up the challenge to redesign the Precious Plastic shredder within the framework of their thesis project. Precious Plastic was started to give people, groups, and companies the choice to start recycling plastics in an open-source way. However, the Precious Plastic shredder had some key limitations in its design: advanced technical competencies were required, not everybody can be in possession of such specialist machines. In such a context, the production and use of the shredder in resource-constrained settings became difficult to practice. Héloïse and Marine tried to bridge this gap by redesigning the shredder for easier manufacturability in FabLabs while ensuring overall performance would be maintained or improved.
Their output was a working prototype that could be fabricated with more accessible equipment and resources, thereby allowing plastic recycling to be more accessible to a wider audience. This chapter describes the main enhancements they made to the design of the shredder, the materials chosen, and the methods of prototyping used.

3.2 Design Objectives and Constraints

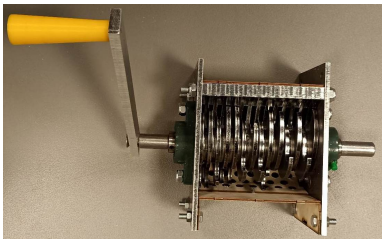
In other words, the primary objective of Héloïse and Marine was to create an improved manufacturability shredder in relation to the FabLab environment. Precisely, their goal was to create a design that can be feasibly manufactured using common tools in any FabLab: CNC machines, 3D printers, or laser cutters. The biggest challenge was simplifying the design without sacrificing the performance of the shredder in processing plastic wastes.
The original Precious Plastic shredder design required a rather advanced manufacturing technique, like laser cutting of steel and complicated assembly procedures, and in this way, made the machinery less accessible for most people. Redesign was meant to break this barrier so that communities all around the world could build and operate the shredder with much fewer resources.

3.3 Material Selection and Sustainability

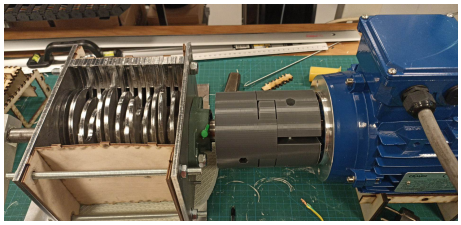
Selection of the alternative material for the blades of the shredder is one of the critical enhancements made by Héloïse and Marine. In the original design, the blades were in steel and thus needed specific know-how in cutting and welding. They investigated the use of polyoxymethylene-a resistant plastic that can be cut by laser cutters commonly available in FabLabs. This greatly reduced the complexity of making the shredder and created access to this technology for non-industrial users.
However, POM had some drawbacks, like poorer wear resistance than steel. To make the blades tougher without complicating the production process, they decided to reinforce the blades with pieces of aluminum. The reason for choosing alternative materials-POM and aluminum-lies in their sustainable focus: these materials are easier to access and take less energy to process when compared to steel.

3.4 Prototyping and Iterative Design

After that, the 2 girls went through an extensive process of prototyping the shredder design, trying it iteratively at each stage and improving on previous designs. This designing and prototyping of the shredder were divided into six different versions, each addressing some specific challenges or issues related to the previous one.



(a) Version 1



(b) Version 2

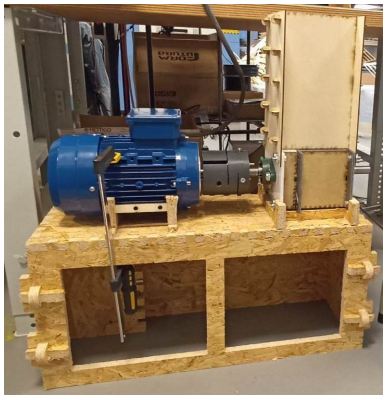
Figure 3.1: Images from their master thesis[19]

Version 1 : Manual Shredding Box - The first prototype was a manual version of the shredding box, which would be helpful for the team to get to know functionality for every part. This version is also used for early shredding tests to understand how to improve, especially in blade design and assembly of the shredding box itself.

Version 2: Electrical Shredding Box - In the second version, the introduction of an electric motor was added instead of a hand crank. This enabled the group to further research shredding capability with different types of plastics and the speed of the motor. A coupling system was, therefore, designed to connect the motor to the shredder, and the lessons learned from this iteration were critical in refining the system for motor-to-blade power transmission.



(a) Version 3

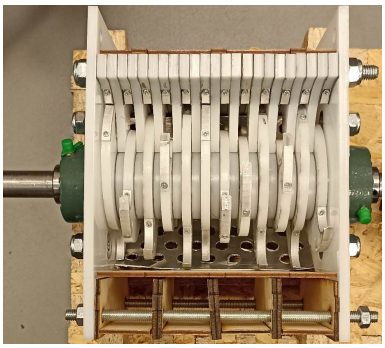


(b) Version 4

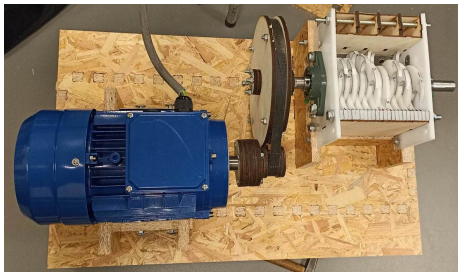
Figure 3.2: Images from their master thesis [19]

Version 3: First POM Elements-First POM Application - In this version, Héloïse and Marine started testing blades of different shapes and materials to find the optimal shape for the shredding of plastic. This iteration also showed that sharper blade tips cannot bear the deformation generated by stress since in the later versions, these were added with aluminum reinforcements.

Version 4 : Complete Shredder with Frame and Hopper - The fourth version included a more complete shredder unit, which contained the frame in order to stabilize the motor and the shredding box. A hopper was also added so the plastic would stay inside the shredder when it was on-the fact that the plastic was inside, not anywhere else, improves safety and efficiency.



(a) Version 5



(b) Version 6

Figure 3.3: Images from their master thesis [19]

Version 5: Full POM Shredding Box - This version had a fully functional shredding box entirely made from POM, with aluminum reinforcements on the blades. In this version,

extensive testing was done by comparing POM and steel blades regarding shredding efficiency, wear resistance, and output quality.

Version 6: Reduction System - The last version used in the adjustment of the motor's speed and torque was the belt-driven reduction system. This system had helped to resolve most of the problems which have to deal with the jumping out of plastic pieces out of the shredding box during operation. Though the system developed some technical problems, it gave them insight into how to improve it.

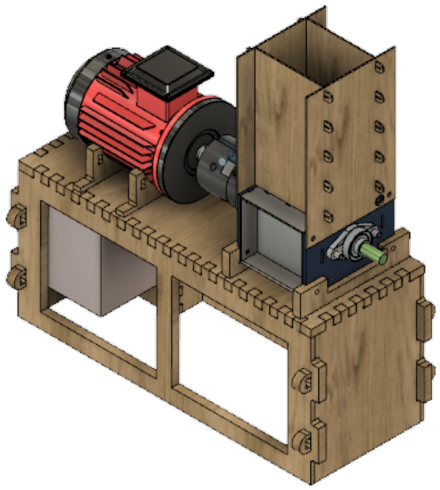


Figure 3.4: Final version of their shredder

The results of testing each prototype iteration led to subsequent design decisions. An iterative approach allows Héloïse and Marine to make continuous improvements to the shredder toward fulfilling its functional and manufacturability design requirements.

Performance and Testing

The final prototype was tested with different types of plastic: HDPE, LDPE, and PLA. Performance of POM blades was measured against the original steel blades in terms of shredding efficiency, wear, and quality of flakes produced. While the POM blades were able to shred plastic into larger flakes than the steel blades, they were fairly successful in volume reduction of plastic waste.
The final tests proved that the new shredder was only slightly less effective than the original Precious Plastic shredder but much easier to fabricate and service. This manufacturability vs. performance trade-off was considered acceptable given the wider accessibility provided by the new design.

Conclusion

Héloïse and Marine's contribution toward the redesign of the Precious Plastic shredders represents a big step in the field of small-scale plastic recycling. They have opened the possibility for more communities to take up plastic recycling by making the design simpler and more accessible. Focused on sustainability, selection of materials, and iterative prototyping, they came out with a machine easier to manufacture and at the same time environmentally responsible.

3.5 Specifications and Performance

The deliverable of the project is a redesigned plastic shredder that can be fabricated in a FabLab. It was based on an original Precious Plastic shredder, which was adapted to increase accessibility. Components like the frame, blades, shredding box, or the coupling system of the shredder were either modified or newly re-designed for fabrication within an environment like that of FabLab. It is made out of OSB with processing through a CNC milling machine. It is dimensioned to provide a solid base that will be able to withstand the forces from shredding. This frame also includes a modular pin assembly system for fast and efficient disassembly, making access for the users to change-out or adjust parts relatively quick and easy.
One of the most profound modifications in the shredder blades are the following:. This shredder uses 14 POM blades with aluminum claws instead of the usual steel blades in the Precious Plastic design. The POM blades have been used here to be durable enough, and to be compatible with laser cutting because of their thickness, producing larger flakes that average between **3 and 5 mm** compared to finer flakes produced by the original steel blades. Each of the blades is machined to an optimal compromise between grabbing and cutting, but testing showed that POM blades with aluminum inserts tended to wear faster than steel when cutting tougher plastics. This did not become a limiting factor in this project, however, since the blade setup proved sufficient for handling common plastics like polypropylene, polyethylene terephthalate, and polylactic acid, which made the shredder effective for small-scale recycling applications.
Regarding the actuation, the motor is a **2.2 kW** motor that was specifically bought for this project and is coupled with the shredding box through a specifically designed coupling system that securely fastens the motor shaft to the blade shaft without requiring extensive machining. The motor should rotate with the help of a drive controller, which can set different output speeds according to the type of plastic. Because the target shredding speed of about **70** revolutions per minute was seldom attained-the motor operates quite well above that for effective shredding-thus, the plastic pieces often jumped around in the shredding box instead of consistently going into the blades. To address this, a metal hopper was added above the shredding box to contain the plastic during use for safety.
In comparing performance, the original Precious Plastic shredder tends to outperform the final prototype-mostly due to the change in material for the blades. The redesigned

shredder had a plastic processing rate of approximately **570 g/h**, which is sufficient for small-scale and community-oriented recycling but falls behind the industrial performance of about **5 kg/h** realized in this work with the use of the original model. Further, flakes produced by the POM blades are larger than that produced by the original blades. This may imply that shredded plastics will still need further processing for a wide variety of recycling purposes. Furthermore, while in original the shredder steel components could remain in service longer because of minor wear, the POM blades showed degradation after prolonged testing and especially when shredding harder plastics.
This project was able to realize great enhancements in manufacturability. It was able to achieve **92.4 %** of components being fabricated in the FabLab-a great improvement from the original Precious Plastic shredder, which only had a manufacturability rate of **0.8%.** The parts produced at the FabLab included the frame, blade spacers, fixed knives, and some coupling system components. Purchased parts included the motor, drive controller, and certain bolts and fasteners.
The project quite succinctly demonstrates that accessible, small-scale machinery for recycling is feasible, in tune with the goals of Precious Plastic to enable local recycling initiatives across the world. Further work may be done by trying different materials or blade geometries that can enhance durability and performance without compromising manufacturability with FabLab.

3.6 Summary for the V1 version of the shredder

Summary of Shredder Results

The final prototype increased efficiency, cost, and functionality: 119 parts comprise the machine, of which 92.4% are made using a FabLab equipped with laser cutters, CNC machines, and 3D printers. The laser cutter was optimized on various materials, such as 6 mm POM (10 mm/s, 70% power, 2 passes) and 6 mm Plexiglas (10 mm/s, 60% power, 1 pass). The total manufacturing cost was estimated at €870 for the whole machine, including locally sourced and externally sourced parts.
Plastic shredded has an average flow rate of 570 g/h and a maximum of 1120 g/h for a 9 Hz shaft frequency. Including the lower frequencies and other materials, it varied in general from 256 g/h to 495 g/h. Great, but just proof that future designs will be needed for durability, safety, and scalability.

Parameter	**Value**
Total Number of Parts	119
% Manufactured in FabLabs	92.4%
Production Cost	€870
Plastic Processed (Maximum Flow Rate)	1120 g/h
Plastic Processed (Average)	570 g/h

Table 3.1: Key Values for the V1 Shredder Prototype

3.7 Proposed enhancements

While functional and accessible for FabLab manufacturing, the redesigned plastic shredder has a number of areas that would need further refinement for better performance in safety and durability. Improvements proposed here will focus on optimization of machine design to handle plastic shredding demands, operational safety, and prolonging machine life, especially in community recycling projects. The paper outlines various improvements that can be made to the design of the plastic shredder:

- **Increased Safety Features**: Inclusion of a full-height hopper covering all exposed parts, incorporating an emergency stop, and sensor-activated safety features to prevent accidental access and enable shutdown in case of malfunctions.
- **Automated Reverse**: Incorporating an automated reverse mechanism to automatically clear blockages, thereby enhancing both safety and usability.
- **Parametric Customization**: Designing the shredder to accommodate different types of plastic by making adjustments in torque, blade configurations, and motor specifications, ensuring that target materials can be shredded optimally.
- **Torque-Boosting Reduction System**: Application of a suitable reduction system to boost torque at lower speeds, particularly for tougher plastics requiring higher shredding force.
- **Reinforcement of the Coupling System**: Strengthening the 3D-printed coupling parts by using more durable materials to prevent failure at high speeds.
- **Simplification of Shaft Design**: Modifying the shaft to a standard round shape to facilitate manufacturing in FabLabs without compromising shredder performance.
- **Blades and Fixed Knives Stabilization**: Increasing stability by using adhesives on bolts or adjusting bolt placement to prevent loosening due to operational vibrations.
- **Heat Loss Reduction**: Reducing heat generation in the motor and other parts to increase energy efficiency and extend the machine's operational life.

Part II

Subsystem Optimization on V1

Subsystem Optimization

Improvement of the V1 version of the plastic shredder will be realized through a prototyping approach where the shredder is decomposed into key subsystems. We are therefore able to focus on one piece at a time, such as the blades, frame, and coupling system, in refining and testing before putting them into the integration of the overall design. As stated in section 2.4, this method will be conducted in 3 steps on all subsystems: the risk analysis and the triangle method, the dimensioning and the FMECA. This systematic approach ensures efficiency in the improvement process, offering the right solution while thinking about the long term.

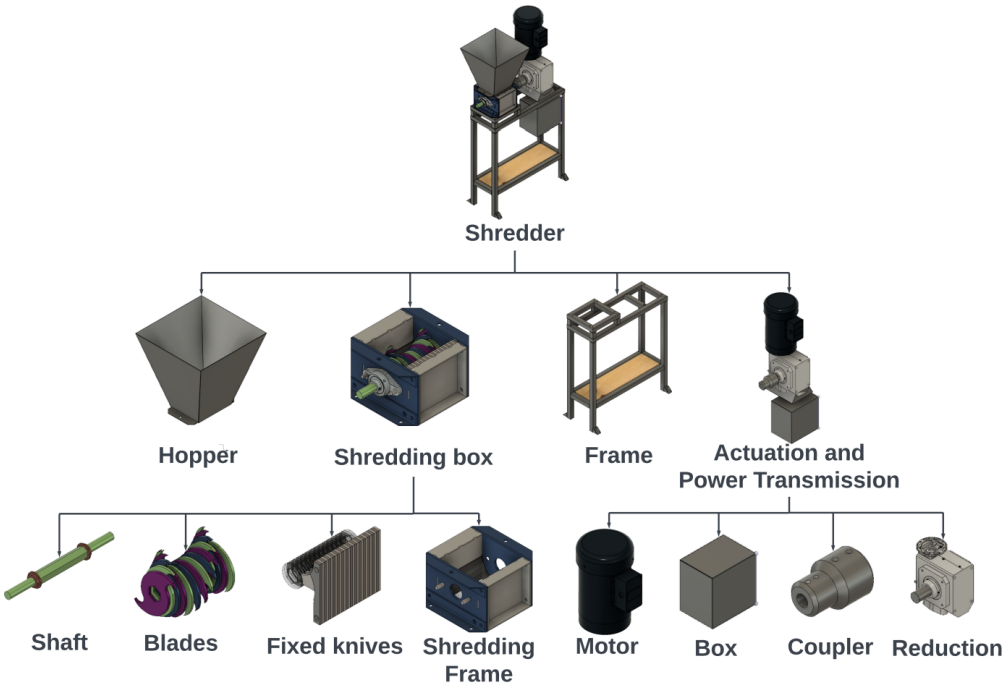


Figure 3.5: Shredder overview, divison into parts and sub-parts.

Chapter 4

Blades

In the first version of the shredder's blades, they were manufactured with POM and at the tip, they had aluminum reinforcements to make them more resistant, see Figure 4.1b. These blades, during their operation of basic shredding, showed considerable limitations after some time. The main problems were rapid wear, loss of sharpness, and deformation under prolonged use, especially with harder plastics.

4.1 Risk analysis

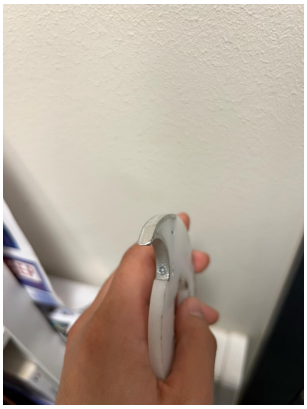
Generally speaking, blades will always be considered as a danger to the user of a shredder. However, this is not the blades that are dangerous for this version but the access to the blades. The risk analysis will be then conducted by the hopper and we will focus on optimizing the blades through the triple constraint method here.

4.2 Triple constraint method

The shredder's original design used POM blades with reinforced aluminum ends, combining affordability and durability. After a while, though, major disadvantages of this design showed up.
The blades were easy to fabricate in a FabLab and worked acceptably for a short time, but the material properties of POM were insufficient to bear the long loads caused by shredding plastic. Particularly, the POM blades would wear out after extended use even with the aluminum reinforcement on the ends. The wearing out not only reduced the efficiency of the blade in cutting but also increased maintenance hence reducing the overall reliability of the system.



(a) Blades from the final V1 version



(b) Default on the metal end

Figure 4.1: POM Version of the blades

With respect to the triple constraint method, the cost of the POM blades is low since POM is a generally inexpensive material to work with, and reinforcement did not add much expense to the overall part cost (25-50€). For cost, a rating of **4 out of 5** will be accounted for the blades. Scope was, however, severely limited for this design. Scoring for scope will be **2 out of 5** because the POM blades are not able to shred harder plastics consistently or with extended use. For the time constraint, as it only consisted of a simple first manufacturing process, with some possible adjustments and/or replacements, their score over time is **3 out of 5**, as we will count around 1 and 3 hours. The overall rating, hence, for POM blades is **9 out of 15**, see Figure 4.2.

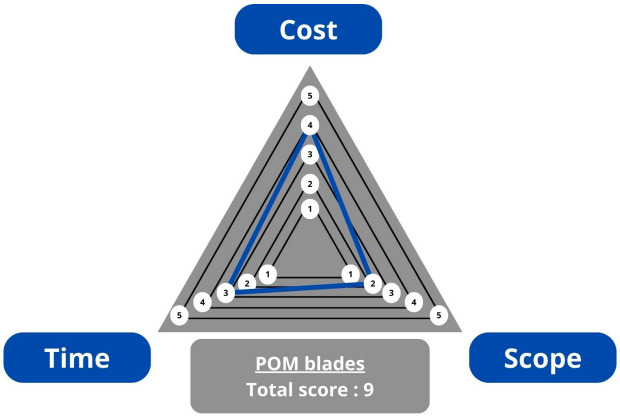


Figure 4.2: Triple constraint method on the POM blades

Keeping this in mind, a follow-up decision was taken to test the first run blades from Precious Plastics as a potential replacement for the current blade stock. First run blades have received great feedback throughout the Precious Plastics community for their ease and enduring nature. Being specifically designed for shredding plastics, they solve many

problems related to the POM blades.



Figure 4.3: Precious Plastics blades

For cost, the Precious Plastics blades are a bit more expensive due to their material and the shipping costs involved, but their durability reduces the need for replacements to a minimum, hence a score of **3 out of 5** ($\sim$ 100€). For scope, these blades do very well. They can shred a wide variety of plastics and are designed for extended use, earning them a score of **5 out of 5**. In terms of time, the blades are pre-manufactured and tested but let's take the shipment and integration time on the shredder into account. This nets a time score of **3 out of 5** ($\sim$ 2 hours). The total score for the Precious Plastics blades is **11 out of 15**, see Figure 4.4.

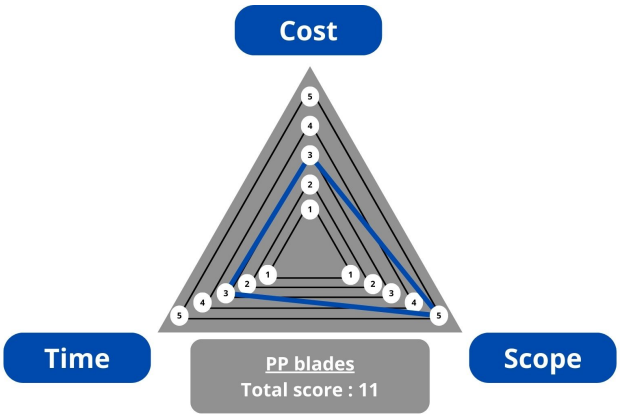


Figure 4.4: Triple constraint method on the original Precious Plastic blades

In comparing the two designs, Precious Plastics blades are on top with 11/15 against POM-metal blades, which had only 9/15, especially in scope and long-term reliability. Even with reinforced aluminum ends, the POM blades were not strong enough to be

effective; this increased maintenance needs and reduced their scope of application.

4.3 Dimensioning

The Precious Plastics purchased come in fixed sizes, which will ease the selection of the blade but requires further adjustments in other components of the shredder. Particularly, the entry shaft and shredder box must be dimensioned by the exact dimensions of the blades, meaning the shaft should be compatible with the mounting system of the blade and the shredding box must provide enough space and alignment for shredding. As for the blades, they are made from EN8 steel, which is hard and wear-resistant, and so it is for effective cutting. The shredder consists of 21 rotating blades of 5 mm in a 3-shear configuration to optimize plastic shredding [20]. Each blade is 6 mm wide, adding to the cutting precision and capacity.

4.4 FMECA

Failure Mode	**Severity (S)**	**Likelihood (L)**	**Detectability (D)**	**RPN (S × L × D)**
Blade Wear	6	4	5	120
Improper Mounting	7	4	6	168
Corrosion	5	6	6	180

Table 4.1: FMECA for Shredder Blades

This table gives the first estimation of the FMECA for the blades. Values for severity, likelihood, and detectability are predictions and should be considered with much caution, since they are based on the current design. These are not the final results but rather the first try to understand which potential risks will have more impact. Further testing or real-world data will have to be considered to refine these numbers and make this analysis more accurate.
Even as a rough estimate, the table shows some very important failure modes: blade wear which is still possible even after installing some steel blades, while corrosion and improper mounting point to the need for better environmental protection and assembly precision. This analysis provides a useful basis to improve the subsystem in possible futures iterations.

4.5 Final decision

Given the better score that the bought Precious Plastics got in comparison with the Fablab ones made, this subsystem will be improved by integrating these blades. This decision will ensure an improved overall cost, time and scope as section 4.2 showed us.

Chapter 5

Hopper and detection button

The first version of the hopper was designed as a very simple yet important part in the shredder for both the safety and usability of it. Its major function was to guide plastic waste to the blades while forbidding users from accidentally reaching inside and touching the cutting mechanism. The hopper was developed as a vertical structure of wood 3 mm thick, pinned together, and bolted to the shredding box. It had been designed to be sufficiently high to prevent hands from reaching the blades. This also overcame the problem of plastic jumping out of the shredder when operating at high speeds and improved efficiency and safety. Although functional, the initial design was identified as improvable in terms of safety.

5.1 Risk Analysis

The current hopper design poses severe problems in safety and usability. First, the open structure allows the possibility of a user accidentally reaching into the blades and is highly susceptible to getting hurt. Second, operating the shredder requires users to lean over the hopper, aligning their eyes with the axis of the cutting blades, see Figure 5.1. Such a layout reduces operational safety and makes the shredding process less effective while being non-ergonomic.



Figure 5.1: Top view of the hopper

The following table evaluates the risk associated with the potential user contact with the shredder blades:

Risk Factor	Value	Explanation
Exposure	10	Continuous exposure during shredder operation.
Likelihood	3	Unusual but possible if hands approach blades.
Consequence	7	Hospitalization

Table 5.1: Risk Analysis for Blade Contact Hazard

Risk Factor Calculation:

$$\textbf{Risk Factor = Exposure x Likelihood x Consequence = 210} \tag{5.1}$$

The risk factor for user contact with the shredder blades is calculated at **210**, in the range of High Risk. This is an extremely critical safety issue that needs **immediate corrective action**. The high exposure value indicates a continuous risk owing to the exposed blades during operation, and the high consequence score illustrates the intensity of the injury, including permanent disability or fatality. It is, therefore, important to ensure that users are not injured with safety features such as guards, interlocking devices, or automatic cut-offs so that the design will meet set safety standards in the industry. Limiting the occurrence of accidents will, therefore, be a priority to bring about an overall improvement in the safety profile of the shredder.

5.2 Triple constraint method

Proposed solution :

To improve upon the original hopper design, a new version will be introduced using Plexiglass as the primary material.

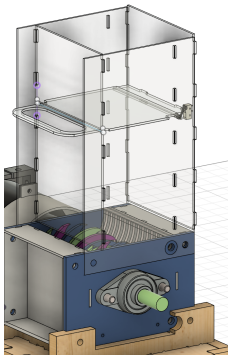
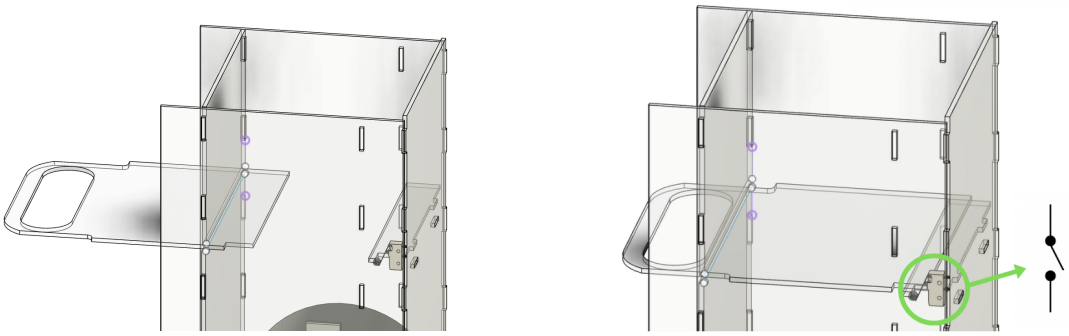


Figure 5.2: Improved Plexiglass version of the hopper

It provides better visibility without necessarily aligning your eyes with the blades for observing the shredding process, hence minimizing the hazards involved. The material provides a better aesthetic appeal and improves the interaction of the user. The new

hopper design will be a clip-on which will reduce the number of screws and bolts it requires for assembly and integration onto the shredder.
Safety and usability are two major features of the hopper. First, it will feature a handle that doubles into a removable "door" through which plastic is put into it. Once plastic is added into it, the handle replaces into its position within the hopper. The hopper also integrates an end-of-travel switch indicating whether the hopper is closed or not. The safety mechanism involves disabling the operation of the shredder in case the hopper is not properly closed so that one would avoid the risk of accidental contact with the blades.



(a) Handle being removed from the hopper

(b) Handle pushes on end-of-travel switch

Figure 5.3: Handle position and scenarios

Section 10 will provide further details on the wiring and scenarios related to the emergency stop button and the end-of-travel switch. Such design has been developed not only to raise the level of safety and functionality but also to bring an improved user experience.

Calculation of cost, time and scope

Using the triple constraint method, the two versions of the hopper were evaluated based on cost, time, and scope. The time for both versions is almost alike because the manufacturing and assembling processes require almost the same effort. Therefore, it scores 3 for both hoppers (∼1 hour). Cost-wise, the new Plexiglass hopper is slightly more expensive (see costs in Table C) because of the higher material cost and additional components like the handle and end-of-travel switch; it scores 4 (∼25€) compared to the greater affordability (score of 5) of the original hopper (∼15€). The scope of the new hopper is significantly improved, however. It's transparent, therefore it allows better visibility for safety and monitoring; the added handle and switch provide better safety and functionality, hence it's adaptable and scalable for many use cases. That gives the new hopper a 4 for scope, while the original had a 2, given its limited functionality.

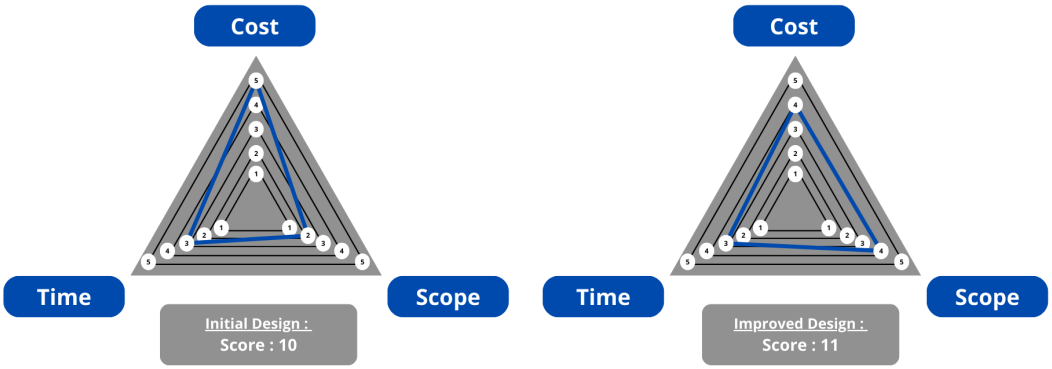


Figure 5.4: Triple constraint method for the hopper

Summing up, the new design obtains a higher total score, and since it is only marginally more expensive, it appears to be more versatile and safer.

5.3 Dimensioning

For the hopper, we selected dimensions that securely integrate with the shredder while offering enough volume to handle plastic efficiently. The height and width of the hopper were calculated to block access to the blades for safety. We used Plexiglass due to its durability and transparency, allowing the user to view the process. The mechanism which allows clipping on and the handle were dimensioned to make the assembly easy and fit with the end-of-travel switch.
The end-of-travel switch was dimensioned so it would fit neatly in the hopper design to reliably detect when the hopper is closed. Since its compact size and rather precise placement ensure that this would not get in the way of the usability, together, the hopper and switch were dimensioned for an easy integration with the shredder system.
Plexiglass used for the hopper will be cut thanks to the laser cutting machine through 3mm sheets. All plans and dimensions can be found in appendix G.

5.4 FMECA

The FMECA for the hopper points to several key possible failure modes, their impacts, and design improvements that need attention. The highest RPN is 252 for a possible malfunction of the end-of-travel switch, which is critical for ensuring operational safety and preventing access to the blades when the hopper is open. The other high-risk failure

Failure Mode	Severity (S)	Likelihood (L)	Detectability (D)	RPN (S × L × D)
Plexiglass Cracking	7	5	6	210
Clip Misalignment	6	4	7	168
Handle Misalignment	5	6	5	150
Switch Malfunction	9	4	7	252

Table 5.2: FMECA for the Hopper

mode is Plexiglass cracking, with an RPN of 210, which might affect the structural integrity and safety of the hopper. Other failure modes, such as clip misalignment (RPN: 168) and handle failure (RPN: 150), are less critical but still require attention to maintain functionality and usability.
Once again, it is important to note that the data and results are estimations. They only give an idea of the potential risks and areas of improvement. The shredder will need more testing and validation to refine these values.

5.5 Final decision

Since the improved design of the hopper enhances its scope but more importantly its safety, we will make it the preferred choice for the V2 version of the shredder. Being in Plexiglass improves visibility, the handle and end-of-travel-switch improve both safety and convenience and the clipable design simplifies the assembly in general, making the improved design a more reliable solution than the initial one.
The end-of-travel switch shown in Figure 5.5 is a normally closed switch. However, for the system to work as explained, a normally open switch would be required. Since only a normally closed switch was available for free at the Makilab, it was used in this setup. If replaced with a normally open switch, the wiring would remain exactly the same.



Figure 5.5: Actual photo of the final version of the hopper

Chapter 6

Reducer

The first prototype used a motor with a power of 2.2kW. However, it was found that the shredder did not have enough torque to properly crush plastics (especially hard or thick types) without a reducer. Indeed, the plain motor couldn't provide the needed forces to the shaft for an efficient shredding process.
We then thought of adding a reducer to the motor, which would turn the motor's speed into more force : the shredder should then work for a wider range of plastics and improve its overall performance.

6.1 Risk Analysis

Since no reducer was present in the first V1 of the shredder, we will only assess its added value via the triple constraint method.

6.2 Triple constraint method

Using the triple constraint method, the set of a motor only versus that with a reducer are evaluated based on cost, time, and scope. Time-wise, there is no difference between them, since the integration time of the reducer does not add much to the time of the whole assembly. Hence, both score 3. Cost: with the only motor, the set scores 5 since nothing more is needed, while with the reducer, it scores 2 due to the addition of the worm gear Transtecno CM063 90B14 reducer at a cost of €222.30 [21]. However, the scope makes a radical improvement with the reducer. While the motor-only system struggled to get a 1, as it has a hard time reaching sufficient torque to shred harder plastics effectively, the addition of the reducer increases torque output, allowing for a wider array of materials to be tackled; this deserves a 5.

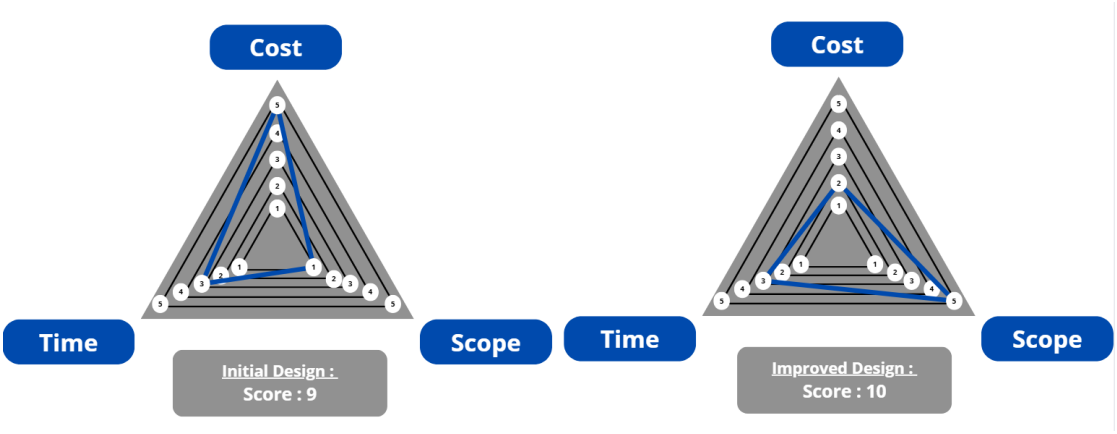


Figure 6.1: Triple constraint method for V1 (without reducer) against V2 (with reducer)

In summary, the improved design (with the reducer) gets a score of 10 whereas the initial design with the motor only gets a lower score of 9. This illustrates the fact that adding the reducer contributes to the overall shredder's value.

Why a worm gear reducer

The triple constraint method confirms that the worm gear reducer was the best for our use and application. Other types of reducer like a planetary, helical, spur, or bevel gear were possible alternatives. By employing the triple constraint method for selecting a reducer, the worm gear has turned out to be the optimum. Worm gears are small in size and give high torques, which is indeed what the design of this shredder needs, given its compact configuration.

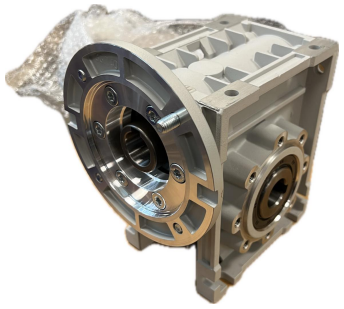


Figure 6.2: Worm gear Transtecno CM063 90B14 reducer

Besides, worm gears are quite affordable and simple to implement, thus fitting very well within the cost of the project and the manufacturing concept of the FabLab. Price constraint really drove the choice here since other kinds of reducers were about 2/3 times more expensive. One could argue that a worm gear is not suitable for our application since its irreversibility does not give us the possibility to make the blades rotating by

hand, if a piece of plastic was stuck for example. However, the risk analysis made on Table 5.1 showed us that we should avoid this scenario.

6.3 Dimensioning

The relation between power, torque and rotational speed gives us :

$$P = \omega \times \text{Torque}$$

For a given motor power (P), decreasing ω via a reducer increases the torque. For shredding hard plastics, this increase in torque is essential. To address this issue, a Transtecno CM63 worm gear reducer was integrated into the design. This worm gear reducer has a reduction ratio of 15:1 [21], which significantly amplifies the torque output. The shredder's motor has a power of 2.2 kW and an input speed of **3000 RPM**, the output speed (ω_{out}) can be calculated using the reduction factor:

$$\omega_{\text{out}} = \frac{\omega_{\text{in}}}{\text{Reduction Factor}} = \frac{3000}{15} = 200\,\text{RPM}.$$

To convert this to radians per second (rad/s):

$$\omega_{\text{out}} = 200 \times \frac{2\pi}{60} \approx 20.94\,\text{rad/s}.$$

The torque at the output shaft is then calculated using the expression:

$$\text{Torque} = \frac{P}{\omega_{\text{out}}} = \frac{2200}{20.94} \approx 105\,\text{Nm}.$$

The integration of the Transtecno CM63 reducer [21]increased the torque to a suitable level for shredding, enhancing the machine's efficiency and durability.

6.4 FMECA

Failure Mode	**Severity (S)**	**Likelihood (L)**	**Detectability (D)**	**RPN (S × L × D)**
Gear Wear	8	3	5	120
Lubrication Failure	7	4	4	112
Overheating	5	2	4	40

Table 6.1: FMECA for the Transtecno CM063 Reducer

The Transtecno CM063 reducer should be reliable since supplied by a well-known mechanical parts supplier [21]. On the other hand, everything related to mechanics may easily carry potential risks of gear wear, lubrication failure. Such failure modes could be unexpected manufacturing defects, improper installation, or extended use beyond recommended conditions. Although the reduction of those risks by a specialized supplier is real when quality parts are available, it's still prudent to be circumspect with the

probability of failures when designing systems and accounting for long-term functionality and system reliability.

6.5 Final decision

The worm gear increases the value of the shredder greatly, as the scope is increased to shred materials that it could not before with much more torque and safety. The modification satisfies the goals of the project in functionality and reliability, thus it will be implemented in the updated design in order to ensure better performance and adaptability.



Figure 6.3: V2 version with its reducer

Chapter 7

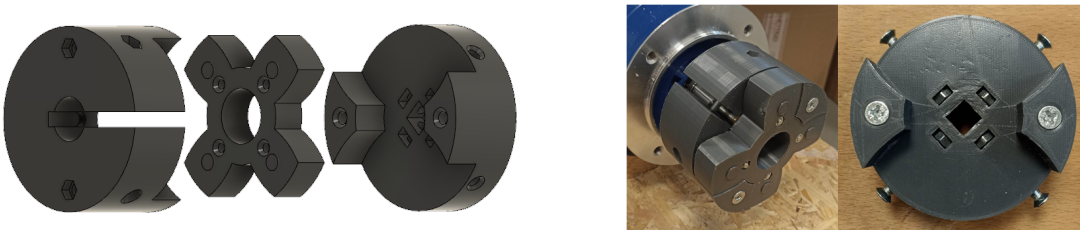
Output shaft

The motor's exit diameter matched the reducer's entry diameter, ensuring compatibility at the motor flange. However, the reducer's exit diameter was different from the motor's, leading to a mismatch with the existing coupling system. To resolve this, we designed a new shaft that adapts to the reducer's exit diameter while being compatible with the coupling system and the blades' shaft.
Since the reducer will be integrated into the V2 shredder, **the new shaft is a necessary addition, and no further risk analysis or triple constraint evaluation** is required for this component.



Figure 7.1: Connecting shaft between the reducer and the coupling system

We included key slots and keys in the new shaft design to make sure we have a good power transmission. These features were dimensioned to match the available geometry of both the coupling and the reducer. This enabled us to have a proper torque transfer between all elements.
As a reminder, the coupling system was designed to connect the motor shaft to the shredding shaft. It was a 3D-printed coupling, reinforced with screws, with a pin on the motor side and a square-shaped tip on the shredder side for secure attachment. Full coupling assembly can be found in appendix F.



(a) CAD file

(b) 3D printed version

Figure 7.2: Coupling system

7.1 Dimensioning

Since the inclusion of the reducer increased torque through the shaft by orders of magnitude, it remains to be seen whether the current 3D-printed PLA shaft could support such loading conditions. Subsystem-level prototyping enables concentration on the shaft in isolation, determining the mechanical performance of the shaft before freezing its geometry and material. Calculation of shear stress and its comparison with PLA material properties at 30% infill will lead to the conclusion as to whether the design of the shaft is good enough or further refinement is needed to come up with a reliable and safe system.

Given Information

- **Torque (T):** 105 Nm
- **Shaft Diameter (d):** 22 mm = 0.022 m
- **Material:** PLA (printed with 30% infill, horizontal direction, 0.6 being an estimate between the material ultimate strength and ultimate shear strength)
  - Ultimate Tensile Strength (σ_u): 60 MPa (for 100% infill)
  - Shear Strength (τ_u): $0.6 \times \sigma_u = 36$ MPa
  - Effective Shear Strength ($\tau_{\text{effective}}$): $0.3 \times \tau_u = 10.8$ MPa (scaled for 30% infill)

Calculation

Step 1: Polar Moment of Inertia (J)

The polar moment of inertia for a solid circular shaft is given by:

$$J = \frac{\pi d^3}{16}$$

Substituting $d = 0.022$ m:

$$J = \frac{\pi (0.022)^3}{16} \approx 5.54 \times 10^{-8}\,\text{m}^3$$

Step 2: Shear Stress (τ)

The shear stress in the shaft due to the applied torque is calculated as:

$$\tau = \frac{T}{J}$$

Substituting $T = 105\,\text{Nm}$ and $J = 5.54 \times 10^{-8}\,\text{m}^3$:

$$\tau = \frac{225}{5.54 \times 10^{-8}} \approx 4.06\,\text{MPa}$$

Step 3: Compare Shear Stress to Material Strength

The effective shear strength of PLA with 30% infill is $\tau_{\text{effective}} = 10.8\,\text{MPa}$. Since $\tau = 4.06\,\text{MPa}$ is less than $\tau_{\text{effective}}$, the shaft can theoretically withstand the applied torque with a margin of safety.

Conclusion

The calculated shear stress on the PLA shaft (4.06 MPa) is within the effective shear strength of PLA printed at 30% infill (10.8 MPa). This indicates that the current shaft design is sufficient to handle the torque from the reducer under static conditions.

7.2 FMECA

Failure Mode	**Severity (S)**	**Likelihood (L)**	**Detectability (D)**	**RPN (S × L × D)**
Shaft Wear	7	5	4	140
Key Slot Deformation	8	4	5	160
Coupling Misalignment	6	3	6	108
Fatigue Failure	9	3	4	108

Table 7.1: FMECA for the New Shaft

From the FMECA for the new shaft, some potential risks have been identified for long-term operation. The most critical failure mode is the deformation of the key slot, with an RPN of 160, because high torque load will undermine the efficiency of the shaft in power transmission. Other critical risks include wear of the shaft (RPN: 140) and misalignment with the coupling (RPN: 108), which could reduce operational efficiency and stability. Fatigue failure can be a problem, too: dynamic loads may degrade the material, so RPN turns to be 108. Those assessments are initial and not critical. In summary, due to the relatively low durability of PLA, tendency to wear and fatigue processes at dynamic loads, long-time reliability could be achieved with stronger materials like metal for example or could be improved by redesigning its structure.

Chapter 8

Frame and motor integration

In the V1 design, the 2.2 kW motor was fixed rigidly to the frame. While this provided stability, it brought a number of limitations. A rigidly fixed motor cannot accommodate minor misalignments between the motor shaft and either the coupling or reducer. As such, these components are subjected to increased mechanical stress. This fixed design also made the whole power transmission system more subject to any sort of vibration, which could travel easily along the frame, causing instability that could damage or interfere with other components.



(a) V1 version - horizontally placed motor

(b) V2 version - vertically placed motor

Figure 8.1: Motor placement

The V2 design will have a floating motor, while the reducer will be fixed to the frame. A floating setup does provide several advantages. In particular, a floating motor is more capable of adjustments for slight misalignments, decreasing mechanical stress in the coupling and other parts, which would avoid wear. It will provide better damping of vibrations, thus minimizing the effect on the shredder frame for smoother operation. The change not only adds to the durability but also to the efficiency in power transmission, hence superior to the rigidly fixed motor in the V1 design.

By adding a reducer and making the motor floating instead of fixed, we need a complete new design of the frame for both dimensions and fixations. The frame should be adjusted to fix the reducer instead of the motor, accounting for the change of size and weight of the combined motor-reducer system. The frame will actually be smaller than the V1 version, as the motor will be placed vertically instead of horizontally. This vertical placement is more suitable for our kind of configuration, where it will reduce the forces acting on the components, by better aligning the gravity forces, which will improve stability and stress. Once again, since **we need the new frame for the V2 version of the shredder, we can see it as a necessary addition, and no risk analysis or triple constraint is required for this component again.**

8.1 Dimensioning

The frame for the V2 shredder was designed to be smaller than its V1 version, which allowed for a more compact and efficient structure. It was still cut from 18mm OSB to keep ease of manufacturing. In addition, the frame provided dedicated places with specially designed features for the emergency stop buttons. All designs and plans can be found in appendix G
The reducer (6.2 kg) and motor (15 kg), together weighing 21.2 kg, place a significant load on the 18 mm OSB plank used for the frame. To ensure the plank can handle this weight without excessive deflection, we will check whether the possible deflection is acceptable.

Deflection of the Top Frame

The deflection of the top frame plank is calculated by summing both the weigth of the motor (15 kg) and the reducer (6.2 kg), placed at approximately one-sixth (9.5cm to be exact) of the length of a 55 cm OSB plank with a thickness of 18 mm. The deflection is computed using the beam deflection formula for a point load at a specific position along the beam.

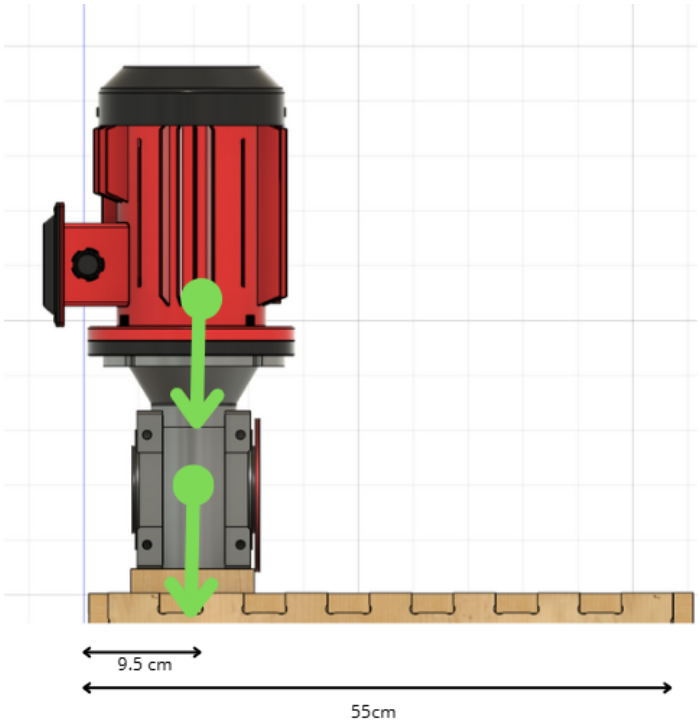


Figure 8.2: Possible deflection from the combined load

Given Data

- Length of the plank (L): 55 cm = 0.55 m
- Depth of the plank (d): 18 mm = 0.018 m
- Elastic modulus of OSB (E): $3000\,\text{MPa} = 3 \times 10^9\,\text{Pa}$
- Weight of the motor (W_{motor}): $15\,\text{kg} \times 9.81\,\text{m/s}^2 = 147.15\,\text{N}$
- Weight of the reducer (W_{reducer}): $6.2\,\text{kg} \times 9.81\,\text{m/s}^2 = 60.82\,\text{N}$
- Total weight (P): $147.15 + 60.82 = 207.97\,\text{N}$
- Position of the load (x): $\frac{1}{6} \times L = \frac{1}{6} \times 0.55 = 0.0917\,\text{m}$
- Moment of inertia (I) for a rectangular cross-section: $I = \frac{d^3 \times b}{12} = \frac{(0.018)^3 \times 0.55}{12} = 2.673 \times 10^{-7}\,\text{m}^4$

Deflection Formula

The deflection of a beam under a point load at a specific position is given by:

$$\delta = \frac{P \cdot x \cdot (L^2 - x^2)}{6 \cdot E \cdot I \cdot L}$$

where:

- P: Total load (N)
- x: Position of the load (m)
- L: Length of the beam (m)
- E: Elastic modulus of the material (Pa)
- I: Moment of inertia of the beam cross-section (m^4)

Calculation

Substituting the values:

$$\delta = \frac{207.97 \cdot 0.0917 \cdot (0.55^2 - 0.0917^2)}{6 \cdot 3 \times 10^9 \cdot 2.673 \times 10^{-7} \cdot 0.55}$$

$$\delta = 2.118 \times 10^{-3}\,\text{m} = 2.12\,\text{mm}$$

Conclusion

The deflection of the OSB plank under the combined load of the motor and the reducer, only about:

$$\boxed{2.12\,\text{mm}}$$

Thanks to the good placement of the load, close to the edge, this deflection is negligible and will not pose problems for further use of the shredder.

8.2 FMECA

Failure Mode	**Severity (S)**	**Likelihood (L)**	**Detectability (D)**	**RPN (S × L × D)**
Frame Instability Under Load	8	4	5	160
Deflection at the Top Part	3	8	4	96

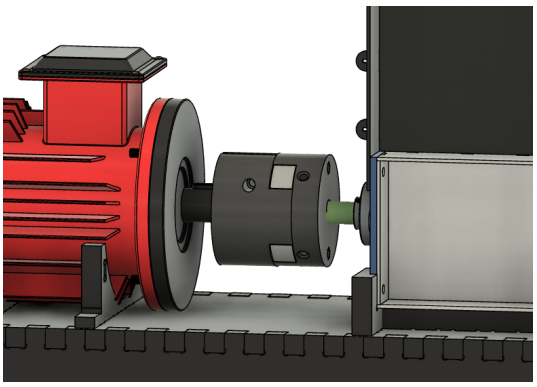
Table 8.1: FMECA for the New Frame Design

The FMECA of the new frame identifies key risks related to frame instability at load conditions (RPN: 160) and top part deflection (RPN: 96). While this deflection is minor (2mm) the higher RPN due to frame instability underlines the importance of proper structural support for the motor and reducer.
Once again, these values are estimations and should be taken with caution.

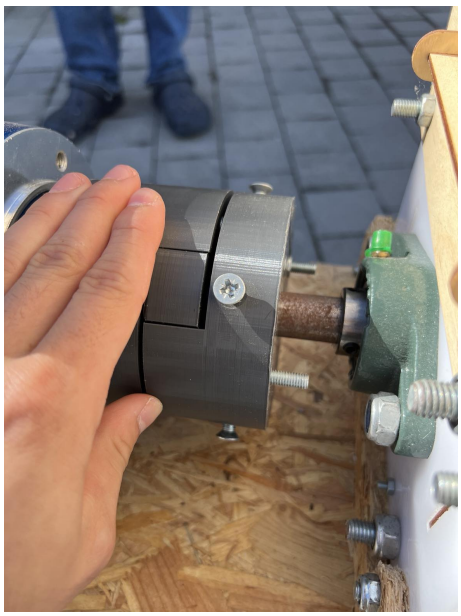
Chapter 9

Rotating parts

With its first prototype, the shredder had one issue where screws that held the components together would come loose after some time due to excessive vibrations during its use. Also, the screws were a little too long, so they stuck out of the machine, forming a safety hazard. This is a high-risk design flaw, as it would be easy for people with long hair to get their hair caught in the exposed screw while the machine is on, leading to serious injury. This is a very important problem regarding the shredder's safety.



(a) 3D view of the coupling sytem



(b) Screws sticking out of the rotating part

Figure 9.1

9.1 Risk Analysis

The following table evaluates the risk associated with the rotating and loosening screws in the shredder design:

Risk Factor	Value	Explanation
Exposure	6	Frequent, as screws are always present during operation.
Likelihood	3	Possible if hair or clothing gets close.
Consequence	15	Severe injuries, including scalp damage.

Table 9.1: Risk Analysis for Protruding and Loose Screws

Risk Factor Calculation:

$$\text{Risk Factor} = 6 \times 5 \times 7 = 210$$

Thus, the risk factor for the visible and loose screws is found to be **210**, hence falling into the High Risk category. This can be regarded as a critical hazard, in whose regard **immediate attention is required**. The high frequency of exposure to this hazard and the possibility of serious consequences from the types of injuries involving hair or clothing being pulled in call for redesigning this feature of the shredder.

9.2 Triple constraint method

Proposed solution

In the V2 version, a cover will be added to the rotating parts, attached to both the reducer and the shredding box. The goal of the cover is to protect from dangerous contact with rotating components, preventing accidents resulting from contact with protruding screws or moving parts. This will also serve to help protect the connection between the reducer and the shredding box shaft, thus enabling smooth operation in safety. This simple solution makes the shredder so much safer to use.

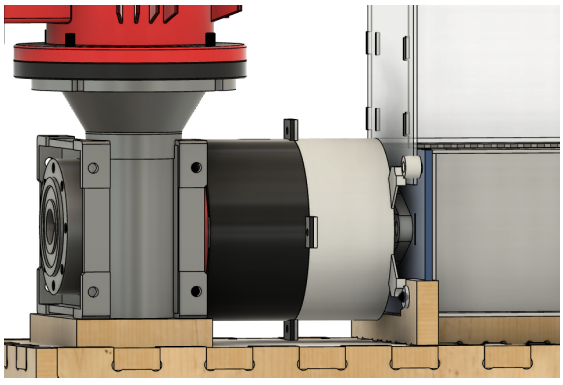


Figure 9.2: PLA 3D printed cover for the rotating parts

Triple Constraint Evaluation for the Protective Cover

Using the triple constraint method, the protective cover can be evaluated as follows:

Cost: The cover will be 3D-printed in PLA, which is rather inexpensive, though it does incur some material and printing costs. Compared to the initial design without a cover (cost = 5), the cost score decreases slightly to 4.

Time: It takes some time to design and 3D-print the cover, but the process is not very long. Compared to the original design, which required no additional effort (time = 5), the time score decreases to 4 due to the added steps of design and printing.

Scope: The cover greatly enhances the safety of the shredder by preventing accidents with exposed rotating parts. It increases the functionality and usability of the shredder, especially in public or shared spaces. The score for scope increases from 2 in the initial design to 5 with the new cover.

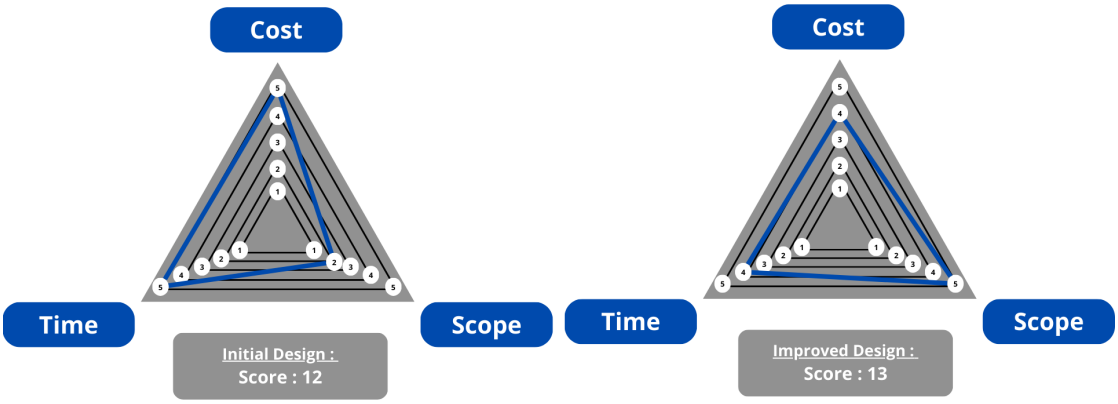


Figure 9.3: Triple constraint method for the PLA cover

Overall Scores:

- **Initial Design:** Cost (5) + Time (5) + Scope (2) = **12**
- **Better Design with Cover:** Cost (4) + Time (4) + Scope (5) = **13**

This evaluation demonstrates that while the protective cover slightly increases cost and time, it significantly improves scope, making it a valuable addition to the V2 shredder design.

9.3 Dimensioning

The 3D PLA printed cover was designed only for safety rather than structural performance. We have then no need to calculate stress or load situations. We chose this cover to have a depth of 3.5 mm, being enough for its purpose of simply covering the shafts and coupling system. All designs and plans can be found in appendix G

9.4 FMECA

Failure Mode	**Severity (S)**	**Likelihood (L)**	**Detectability (D)**	**RPN (S × L × D)**
Cover Cracking	6	4	5	120
Detachment During Operation	8	3	4	96

Table 9.2: FMECA Analysis for the Protective Cover

The FMECA analysis for the protective cover highlights key risks, with interference with moving parts (RPN: 126) and cover cracking (RPN: 120) as the most critical.

9.5 Final decision

Since the improved design of the cover for the rotating parts improved both safety and scope, it will be the preferred choice for the V2 version of the shredder.

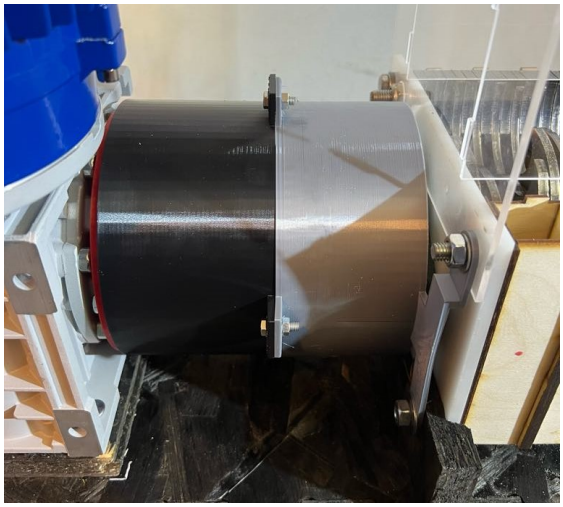


Figure 9.4: Cover on the rotating parts of V2

Chapter 10

Emergency button and switches

The first shredder design did not incorporate an emergency stop button : a feature very crucial in such a machine. Shredders are characterized by having fast-moving parts that are usually very dangerous to deal with in use, in the instance of an accident or malfunction or even catching in the machine. Without an emergency button, it is less safe to operate the shredder since there is no way to quickly stop the shredder in case of an accident. Adding an emergency stop button will be necessary to make the shredder safer, allowing for quick shutdown of the shredder in emergencies, hence reducing the chance of injury.

10.1 Risk Analysis

This risk analysis is performed on the V1 version of the shredder, having no emergency button whatsoever. The risk analysis in the absence of an emergency stop button is a

Risk Factor	**Value**	**Explanation**
Exposure	8	Frequent, as the shredder is used regularly, and emergencies can arise at any time during operation.
Likelihood	3	Possible, as an accident or malfunction requiring immediate shutdown could occur.
Consequence	7	Hospitalization

Table 10.1: Risk Analysis for the Absence of an Emergency Stop Button

serious safety hazard. The exposure score is high, at 8, since frequent use of the shredder presents a realistic possibility of emergencies happening. The likelihood of an incident is moderate, with a score of 3, but the consequences are grave, scoring 7, since possible injuries may occur without the quick way of stopping the machine. Total score is $168 > 70$, which is a critical risk and immediate action needs to be taken.

10.2 Triple constraint method

Proposed solution

In the V2 version, an emergency stop button will be added to the shredder to enhance safety. This button provides a quick and easy way to shut down the machine in case of emergencies and preventing accident. The emergency button has to be central to be reachable by anyone using the shredder.

Triple constraint method for the emergency button

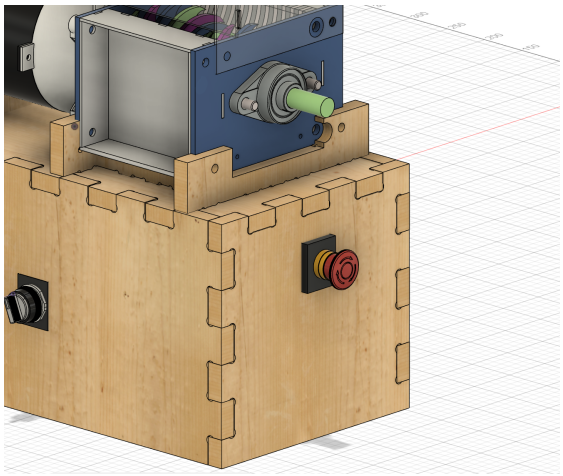


Figure 10.1: Emergency stop button integrated into the shredder

Triple Constraint Evaluation for the Emergency Button

Using the triple constraint method, the emergency stop button can be evaluated as follows:

Cost: The emergency button is once again a relatively inexpensive component but incurs some additional material and installation costs. Compared to the initial design without a button (cost = 5), the cost score decreases to 4.

Time: Installing the emergency button requires a bit of time for mounting and wiring, but this process is not really time consuming. Compared to the original design, which required no additional effort (time = 5), the time score decreases to 4.

Scope: The emergency button significantly improves the shredder's safety and functionality, especially in emergency situations. This addition makes the shredder more suitable for public or shared use. The scope score increases from 2 in the initial design to 5 with the emergency button.

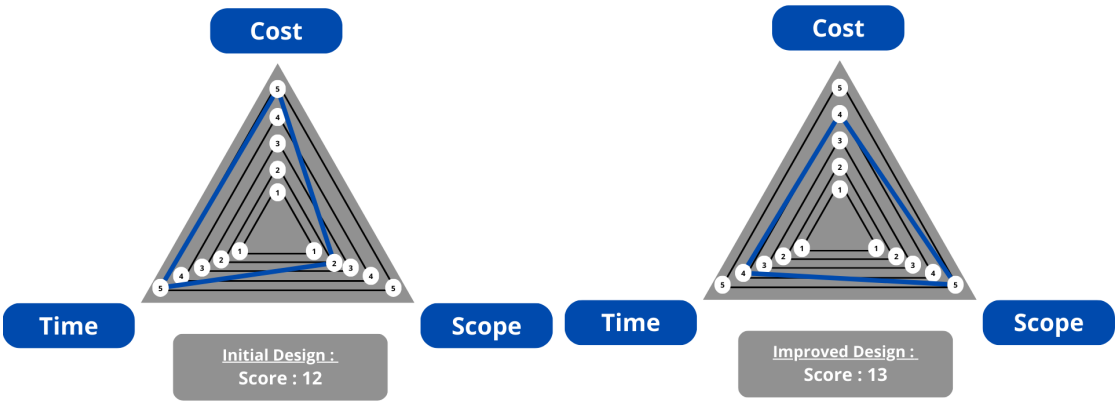


Figure 10.2: Triple constraint method for the emergency button

Overall Scores:

- **Initial Design:** Cost (5) + Time (5) + Scope (2) = **12**
- **Better Design with Emergency Button:** Cost (4) + Time (4) + Scope (5) = **13**

10.3 Dimensioning

In this section we will detail the different wiring and connections of the emergency button (2 on Figure 10.3) but also how it is linked to the end-of-travel switch (3 on Figure 10.3), located in the hopper to sense whether it is closed and that nothing can reach the blades except the plastic and the basic switch (1 on Figure 10.3) of the motor (turning the motor ON or OFF).

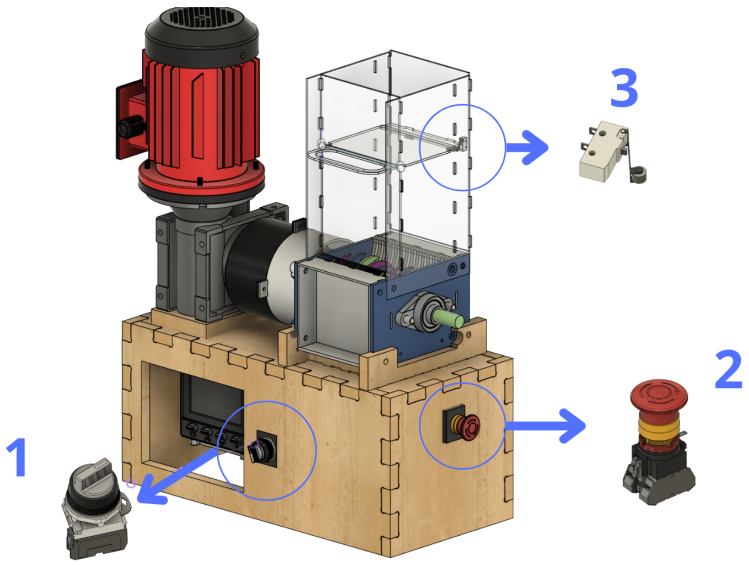


Figure 10.3: Visual of the shredder and its switches

The Siemens SINAMICS V20 driver[22] can be configured in a special way called the CN003, see Figure 10.4 : there is a simple connection between DI1 and 24V, where the motor operation is controlled by the state of the circuit. A closed circuit allowed the motor to run, while an open circuit stopped the motor.

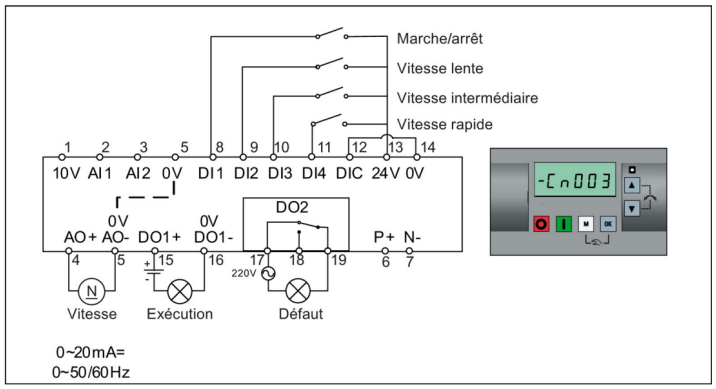


Figure 10.4: Initial configuration of the Siemens SINAMICS V20 motor driver with a basic open/closed circuit control for motor operation [22]

But we can configure it in such a way that the 3 buttons can control the motor. More specifically, DI1 is connected to 24V via a series connection through the basic switch, the emergency stop button, and the end-of-travel switch. The series connection means all of the switches are in a single continuous path; for this circuit to be complete, all the

switches must be closed, or connected. In such a case when the circuit is complete or closed, the driver sees that as a "go" and the motor starts. On the other hand, if any one of the switches is opened, an open circuit results, flow of current is interrupted, and the motor driver takes it as a "stop" signal, immediately stopping the motor. This setup provides a robust way to control the motor while ensuring safety and reliability. The motor driver is designed to interpret the open or closed state of the circuit as standard "go" or "stop" commands, making this configuration compatible with its built-in logic. Several scenarios can occur with this setup, each impacting the circuit differently:

Rest Operation

When the switch is not activated, the system remains in a resting or idle state, with an open circuit between the switch and the emergency button.

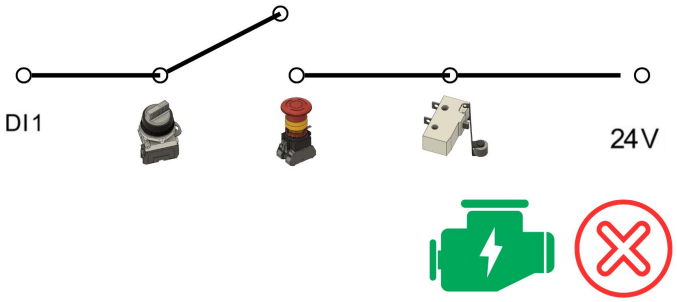


Figure 10.5: Rest operation - switch off

Normal Operation

All switches in the series are closed, creating a continuous circuit between DI1 and 24V. The driver receives the "go" signal, and the motor runs as intended.

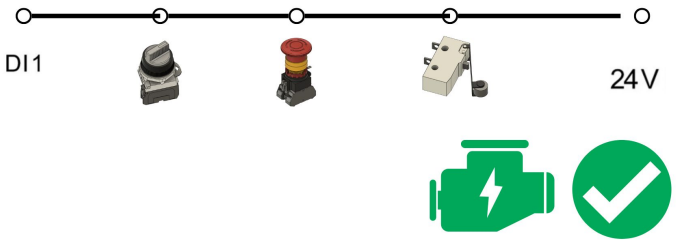


Figure 10.6: Normal operation -switch on

Basic Switch Open

When the basic switch is opened by the operator, the circuit is interrupted, and the driver receives a "stop" signal. This is the standard method for stopping the motor during normal use. This is the same scheme as Figure 10.5.

Emergency Stop Button Pressed

If the emergency stop button is pressed, it immediately opens the circuit, cutting power to DI1. The motor stops instantly, providing a critical safety feature to prevent accidents or damage in case of an emergency.

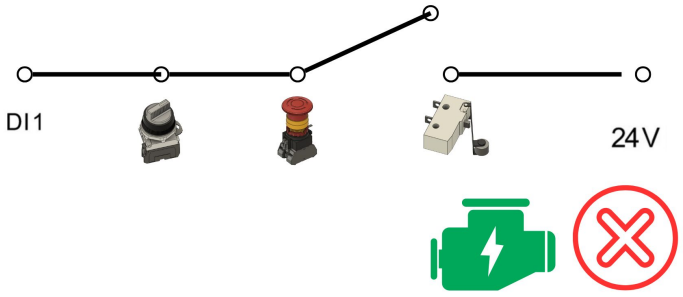


Figure 10.7: Emergency button activated

End-of-Travel Switch activated

If the end-of-travel switch is activated (e.g., when the mechanism reaches a physical limit), it opens the circuit. This prevents the motor from running further, protecting the system from overtravel or mechanical damage.

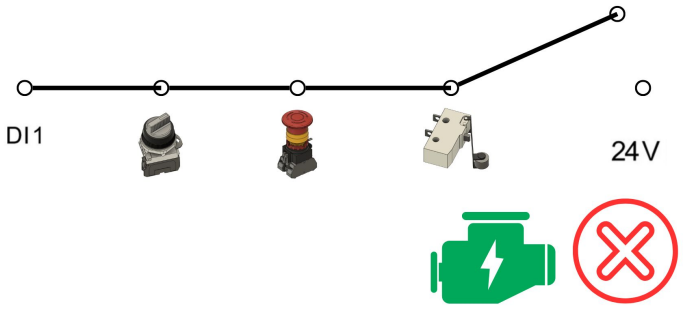


Figure 10.8: End-of-Travel switch activated

Multiple Switches Open

If more than one switch in the series are open simultaneously (e.g., the emergency button is pressed and the end-of-travel switch is triggered), the circuit remains open, and the motor stays off. The system is designed to stop the motor as soon as any single switch breaks the circuit, ensuring maximum safety.

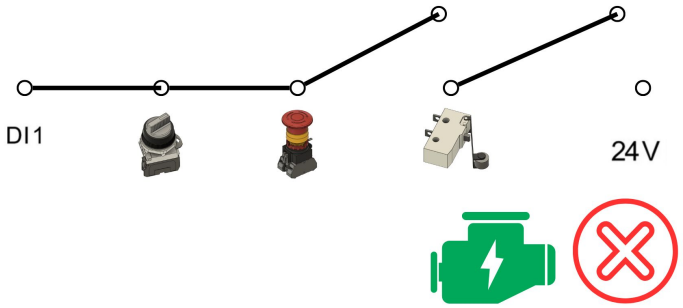


Figure 10.9: Multiple switches activated

Arrangement in series is quite efficient because it ensures that the motor will only operate when all the safety and operational conditions are satisfied.

10.4 FMECA

Failure Mode	Severity (S)	Likelihood (L)	Detectability (D)	RPN (S × L × D)
Emergency stop button fails to open the circuit when pressed	10	3	3	90
Emergency stop button is obstructed	9	3	3	81
Basic switch fails to close the circuit when switched	5	3	4	60
End-of-travel switch fails to be activated	6	3	3	54
End-of-travel switch is triggered by mistake	6	5	4	120

Table 10.2: FMECA Analysis for the Motor Control Buttons

From this table, working on the end-of-travel switch being triggered by mistake seems the priority regarding the score it gets (120) due to its high likelihood. However, the high severity that gets the emergency stop button needs attention. A button of high

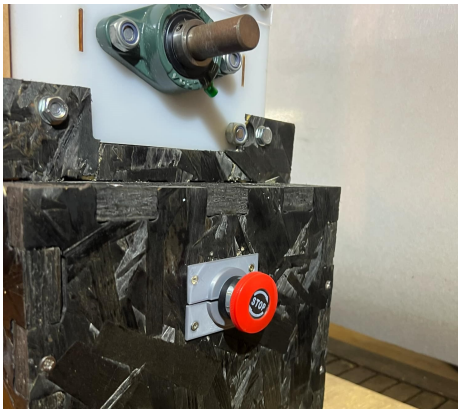
reliability should be chosen for this application since its failure mode could lead to severe consequences if the emergency stop cannot be activated.

10.5 Final decision

Because the series connection of the switch, the emergency button, and the end-of-travel switch minimizes risks and increases operational scope, it will be the chosen solution for the V2 version of the shredder. This setup will guarantee that the machine will operate in an environment that is safe and without accidents.



(a) Switch button



(b) Emergency button

Figure 10.10: Added buttons on the V2 version

Part III

Results and assessment of V2

Chapter 11

Results and comparison

This section will the cover the features and results of the final version of the V2 shredder, see Figure 11.1 and will also be used to compare this improved version to the first version made during the 2022-2023 school year.

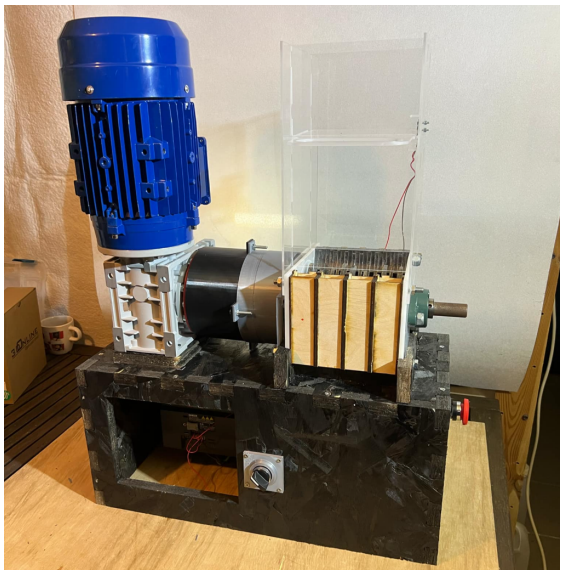


Figure 11.1: Final version of V2

The aim for the V2 was to come up with a better shredder that still be mostly fabricated in a FabLab. The challenge was to find the trade off between a shredder that can be made almost entirely in FablaB and a shredder that meets safety standards and works well for practical use. This section will examine those important features, showing the progress made and pointing out areas that need further improvement.
We will start by making a summary of the improved features and subsystems of the V2 version and how it has changed from the first version.
We will then compare the bills of materials (BOM) and manufacturability of both shredders by focusing on the number of parts and percentages that were produced in a

Fablab for each design.
We will then look at the shredding results and user experience from both versions.
Lastly, we will think about the possible improvements that the improved version of the shredder could have.

11.1 Summary of the improved subsystems

Both V1 and V2 final version can be seen in Figure 11.2 and 11.3 respectfully. These visuals give a clear idea of how the system used to be/work and how it changed and improved (colors are only indicative, where in reality the V1 is beige and the V2 is black). Figure 11.4 below the 2 visuals summarizes in a tabular form the key subsystems that were improved or added to the design.

Explanation of the Table

The table is organized into five columns:

- **Subsystem**: The component or area of the system that is being addressed.
- **Identification on Figure 11.2**: Indicates where the subsystem is labeled on the original design.
- **Problem**: Describes the problem or limitation identified in the subsystem of the initial design.
- **Solution**: Details the corrective actions taken to address the identified problem and the improvements made.
- **Identification on Figure 11.3**: Specifies where in the new design the feature has been improved or added.

In this way, the table provides an intuitive understanding of how issues were resolved, visually linking the original design to the enhanced version through Figures 11.2 and 11.3.

Example from the Table

Subsystem: Motor

- **Identification on Figure 11.1**: The motor is labeled as **1**.
- **Problem**: The motor was directly attached to the frame, making it inflexible and prone to alignment issues.
- **Solution**: The motor was changed to a floating motor, allowing for easier alignment and reducing wear on the system coupling.
- **Identification on Figure 11.2**: The floating motor is labeled as **A**.

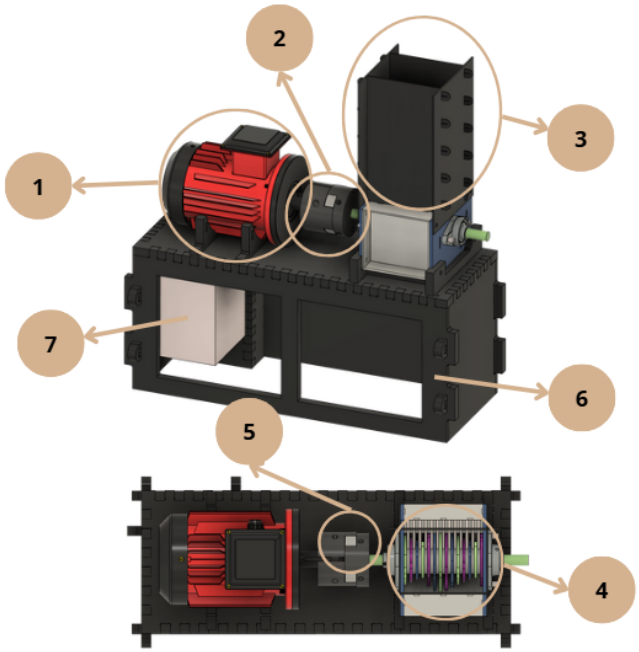


Figure 11.2: Final V1 version (2022-2023)

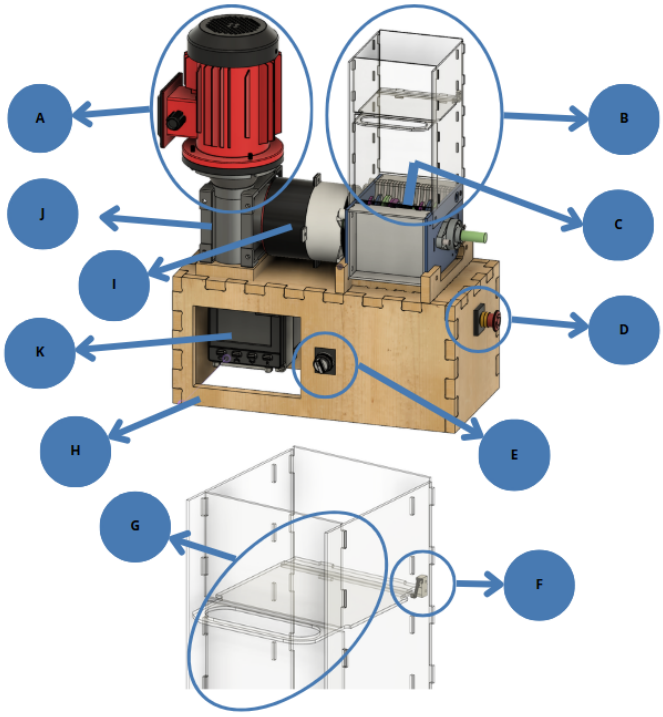


Figure 11.3: Final V2 version (2024-2025)

SUMMARY

Modifications and added features

Subsytem		Problem	Solution		Thesis Section
Motor	1	Fixed Motor	Floating Motor	A	8
Coupling System	2	Reducer added coupling problems	Addition of a shaft between the coupler and reducer	I	7
Hopper	3	Hopper was not convenient	Redesign of the hopper and its integration	B	5
Blades	4	Non-durable POM blades	Replacement with Precious Plastic blades	C	4
Coupling System	5	Rotating parts uncovered	Addition of a cover between reducer and shredder	I	9
Frame	6	Disposition of elements changed	Improved frame design	H	8
Emergency Button	/	No emergency button	Addition of an emergency button	D	10
Switch	/	No switch	Addition of a switch	E	10
Reducer	/	No reducer	Addition of a reducer	D	6
Hopper	3	Access to the blades was permanent	Integration of end-of-travel switch and handle for safety	G,F	5
Frame	6	Non efficient and voluminous design	Resizing of the frame and enhancing of the design	H	8
Driver	7	Driver was not programmed	Addition of programms	K	10

1 Identification on V1

A Identification on V2

Figure 11.4: Summary features

11.2 Fablab manufacturability comparison

As a reminder, the very first shredder was based on an early Precious Plastics design and had poor manufacturability in a FabLab setting, with only **0.8%** [19] of its components that could be made using the tools available. Then came along the V1 prototype, reaching the high score of **92.4%** (see Table 11.1) that could be made in a FabLab. From this, the V2 version was developed with a slightly lower manufacturability rate of **86.9%**, see Table 11.2. This reduction was primarily caused by adding the reducer, switches and blades (14 of them), which needed to be acquired externally. It still represents a very respectable accessibility level for FabLab production, however.
The next step is to find out if this trade off remains beneficial by evaluating the V2 version in terms of its efficiency and safety improvements.

	Hopper	Frame	Power	Box	**Total**
Total parts	5	14	5	95	119
FabLab Parts	5	14	3	88	110
FabLab percentage	100%	100%	60%	92.6%	**92.4%**
Machines	Laser cutter	CNC	3D-printer	Laser and water jet cutters, 3D printer, driller, CNC	

Table 11.1: Results final V1 prototype, Table from previous Master thesis [19]

	Hopper	Frame	Power	Box	**Total**
Total parts	9	11	6	111	130
FabLab Parts	9	11	3	90	110
FabLab percentage	100.0%	100.0%	50.0%	81.1%	86.9%
Machines	Laser cutter	CNC	3D-printer	Laser and water jet cutters, 3D printer, driller, CNC	

Table 11.2: Results final V2 prototype (Updated version).

11.3 Cost comparison

The BOM of the first shredder sums up to 870€, where the second BOM (that represents the updated design) is 416€; see Appendix C making a running total of 1 286€ for the updated version. It is, however, worth pointing out that this total does in fact reflect the 'bottom up' cost generated by improving the machine subsystem by subsystem. This likely created several inefficiencies and wastes of money. If someone were to rebuild this machine from scratch with the improved design, the overall cost would be less than the combined total of these two BOMs, since redundant modifications and incremental upgrades could be avoided.

11.4 Shredding comparison

The results of shredding revealed that the new shredder V2 outperformed its predecessor, V1. Whereas the V1 shredder could only manage an average mass flow rate of 570 g/h, the V2 shredder achieved an average of **1822 g/h (see Appendix E)**, a factor of over three times. Among the key differences between the two designs comes the mechanism of shredding. The V1 shredder primarily shredded plastic through impacts, which was less efficient and often inconsistent. The V2 shredder will be using shear deformation to break down the material, which is better method to achieve consistent flake sizes.
Additionally, it clearly shows the improved mechanical power within the two designs: the V1 only had a torque of 7 Nm, which is was small to shred bigger or stronger materials. This compares to the V2 with an higher torque of **105 Nm**; thus, larger and more difficult inputs can be managed. It is also worth noting that during our tests, the V2 shredder was not pushed to its maximum capacity. The steps were done almost in crescendo, gradually building in size and size of input, so that through the process it could be clear that the engine was able to sustain the increasing workload continuously without any problems. This in return avoided the risk of an overload/failure.

11.5 Risk comparison

Table 11.3 highlights the key differences in safety features between the V1 and V2 shredder designs.

Risk/Feature	V1 Shredder	V2 Shredder
Rotating Parts	Exposed, creating a high risk of contact.	Fully covered to eliminate the risk of accidental contact.
Blade Accessibility	Blades were easily accessible, increasing the likelihood of injury.	Blades made inaccessible by adding a handle with an end-of-travel switch. The shredder operates only if the handle can cover the shredding box.
Bolts	Bolts were starting to unscrew during operation, potentially causing structural instability and danger.	Improved design to prevent bolts from loosening during operation.
Emergency Button	No emergency stop button, making it hard to stop the machine in case of danger.	Emergency stop button added, allowing immediate shutdown in emergencies.
Overall Safety	High risk due to poor/no safety features.	Improved safety with protective measures.

Table 11.3: Difference in safety features between V1 and V2 Shredder Versions

11.6 Comparison summary

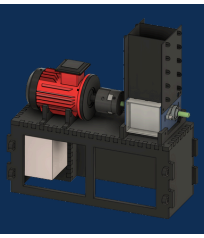
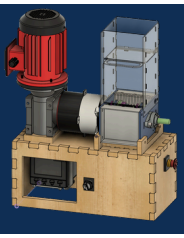
Aspect	V1 	V2 
Cost	Total cost: **870€**. Higher due to inefficiencies and limited optimization in design.	Total cost: **416€**. Lower due to refined design and reduced material usage.
Manufacturability	FabLab manufacturability : **92.4%** of components made in a FabLab.	FabLab manufacturability: **86.9%** decrease due to external parts like blades and reducer.
Shredding	Average mass flow rate: **570 g/h.** Shredding through impact. Torque: 7 Nm.	Average mass flow rate: **1822 g/h**. Shredding : shear deformation Torque: 105 Nm.
Improved Subsystems	Limited safety features, weak motor coupling, and inefficient blade design.	Added safety systems (emergency button, blade cover, end-of-travel switch), improved motor coupling, and blade material.
Risk	High risk: exposed rotating parts, accessible blades, no emergency stop, bolts unscrewing.	Improved safety: rotating parts covered, blades inaccessible, emergency stop added, and bolts secured.

Figure 11.5: V1 and V2 final comparison

11.7 Possible improvements

This section explores how, in the future, the shredder could be improved in order to enhance performance, usability, impact or safety for potential users.

Increasing efficiency and durability even more

The whole development process was to be done using the maximum of FabLab resources in order to keep the cost as low as possible and, therefore, accessible. For this reason, parts like shafts and keys were made by 3D printing with PLA filament. This gave us the ability to prototype rapidly and change our design as many times as needed but reached its limits pretty fast due to the mechanical limitations of PLA, which is not strong enough and resistant to support such high torque and stress.
Improvement could be achieved in collaboration with the CREDEM facility at Louvain-la-Neuve, where some parts like shafts and key could be machined from steel or any other stronger material. Besides, having the opportunity to collaborate with CREDEM, the machining of components would be highly precise with better tolerances.

Automation and programs

Equipping the shredder with smart features could also bring a lot of improvement in functionality to the machine. This can be done by introducing an automatic reverse mode to the motor operation in case of overload or when the shredder chokes. Such reverse operation would facilitate clearing the shredding box without human interference and allow smoother, a "non stop" operation. Furthermore, with the SINAMICS V20 motor driver, torque and frequency settings could be switched automatically, depending on the kind of plastic the system is working with. Depend on the kind of plastic and its mechanical properties, the driver could have different torque and frequency mode to be able to shred the material in the most efficient way possible in terms of shredding and energy use.

Closing the recyling loop

Other Precious Plastic machines, such as an extruder, could be built inside the FabLab in order to completely close the recycling loop. Reusing shredded PLA waste from 3D printing for new filament would cut down on waste and participate to a circular economy. This will enable recycling a material otherwise thrown away while providing a sustainable solution to the large amount of PLA used in FabLab projects. By integrating this process, the FabLab could efficiently recycle its own 3D printing waste while promoting environmentally friendly practices for Fablab users.

Lower the RPN scores

Reliability and safety for the shredder can be improved systematically by addressing the issues highlighted in the FMECA. The main goal should be to reduce the RPN (product

of severity, likelihood, and detectability) for each subsystem in order to enhance overall machine performance. Some of this work has already been initiated since the estimation of RPN for all subsystems has been done in this paper. Hence, based on these estimations, it is now easier to prioritize improvements. For example, an issue like the failure of the emergency button would be more detectable through the addition of visual or audible fault indicators and thus its RPN would significantly be reduced. Again, better design for components such as the end-of-travel switches and motor coupling would reduce both the likelihood and the severity of the failures. By iterating on the subsystems with the highest RPN values and addressing the most critical points first, the shredder's safety, reliability, and efficiency can be once again improved.

User guides and tutorials

A major improvement that could be the creation of a comprehensive user guide or an instructional videos that would clearly walk users through every step in the operation, maintenance, and troubleshooting of the machine. Tutorials and videos could show, for instance, how best practices are done, like safe operation, cleaning between different types of plastics, or changing blades, to make users understand the functionality of the machine. Furthermore, such resources might become useful means of education in the form of workshops or community training, where the participants play an active part of plastic recycling. This would make the shredder more accessible to the anyone that wants to shred or recycle plastic.

Chapter 12

Technology assessment according to Ashby on V2

A structured technology assessment, using the five-step framework that we presented in section 2.5 and inspired by Ashby's principles of sustainability, will be applied on the shredder to assess its environmental, social and economic impact. As a reminder the five steps methods needs to : define the problem, place it in context, do detailed fact-based research, debate implications, and reflect on the policy.

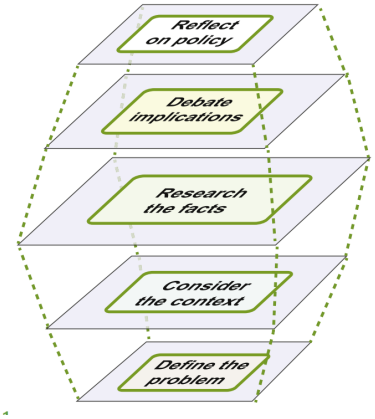


Figure 12.1: Ashby's 5 steps method to assess sustainability [16]

This assessment can be seen as an added value for the shredder, not only for its sustainability but also for accessibility and safety, contributing as valuably as possible to both local and global recycling. This framework will be applied in each step of the subsequent sections to evaluate the shredder design with the intent of improving it.

12.1 Define the problem

Plastic waste has turned into one of the most high-priority environmental challenges of our time, which is further illustrated by the exponential increase in production to **over 390 million tons annually** [23]. Plastics are highly used due to their versatility, durability, and low cost. These characteristics are the very same characteristics that make them abundant and highly persistent in the environment. Plastic does not biodegrade, whereas it breaks down into pieces called microplastics that go ahead and pollute the ocean, rivers, and soil, which causes danger to ecosystems and human health. Besides, the use of single-way plastic has increased lately during the COVID-19 pandemic: disposable personal protective equipment, take-away food containers, and e-commerce packaging are on the rise. This has resulted in the concerning buildup of plastic in landfills, waterways, and natural environment, with estimated values as high as over 11 million tonnes entering the ocean every year. Besides, **less than 10% of all plastic ever produced has been recycled** [1], while most are either incinerated or discarded into the environment, adding to ecological deterioration.
Moreover, plastic production has proved to be one of the biggest causes of climate change. The virgin plastic production in 2019 alone contributed as high as **2.24 billion metric tons of CO2-equivalent, approximately 5.3% of the global greenhouse gas emission share** [24]. This graph illustrates the alarming rise in both production-related emissions of resins and fibers and the incineration of plastics, reaching almost 3 billion metric tons per year by 2050. That is a result of energy-intensive processes using fossil fuels, which contribute to the greenhouse effect and accelerate global warming.

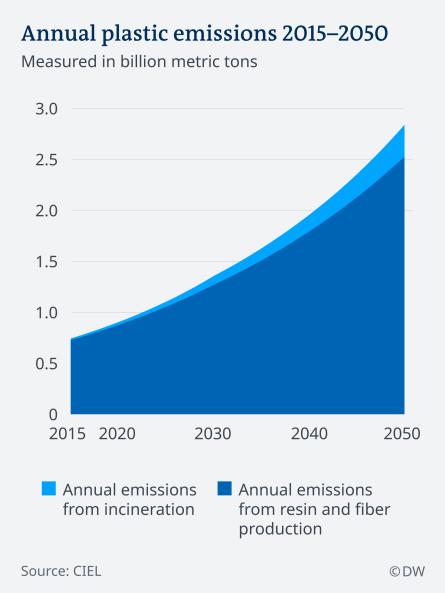


Figure 12.2: Projected annual greenhouse gas emissions from plastic production and incineration (2015–2050). [25]

Recycling provides an important route for reducing such emissions and trying to solve the problem of plastic waste. Recycles will reduce the need for plastic production, which will reduce energy use by as much as 80% in some cases, significantly decreasing emissions at every stage in the plastic life cycle. Also, it stops plastic waste from going to landfills and incinerators, in which it would emit extra CO_2 and methane among other greenhouse gases. As this chart shows, moving into a circular economy that covers the entire life cycle of plastic by way of recycling could give very realistic solutions to mitigate environmental and climatic impacts caused by plastics.

12.2 Consider the context



Figure 12.3: Front page of the 26th of December's belgian newspaper [26]

Figure 12.3 shows the front page of the "L'avenir" newspaper on December 26th 2024. One can see the title " 2024, l'année de l'indifférence climatique" which can be translated in english to :

"2024, the year of climate indifference."

This sounds alarming... And it is.
We are at a very crucial moment in the fight against climate change and plastic pollution. In an article published in 2021 [27], NASA claimed that if by miracle, we ceased all greenhouse gas emissions today, the global temperatures would stabilize within a few years but would still remain elevated for centuries. This underscores the emergency of the situation and the immediate actions that have to be taken.
Graph 12.4 shows the simplified emission pathways necessary to reach critical climate targets, portraying the urgency of action required today on a global scale. Historical emissions, in black, illustrate the unstoppable increase of CO_2 emissions , which must drastically go down to keep within the remaining carbon budgets. The different pathways correspond to various probabilities of staying within a limit of 1.5°C or 2°C of global

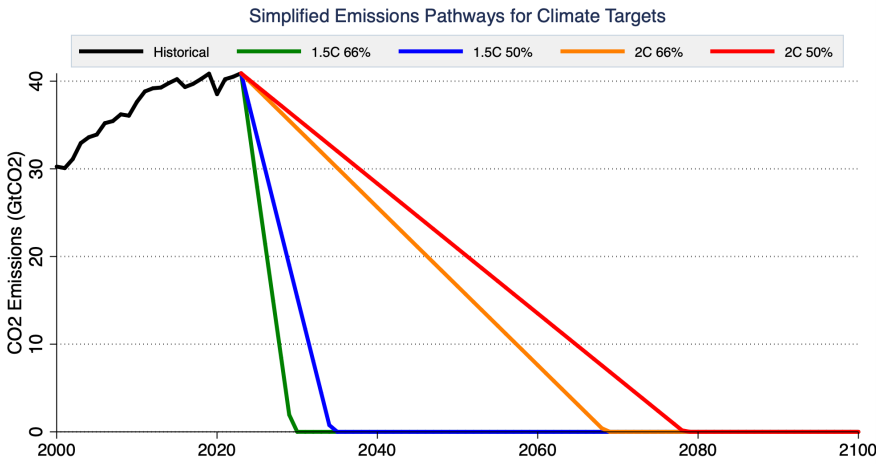


Figure 12.4: Translating the carbon budget into emissions scenarios [28]

warming: respectively in green and blue and orange and red. The steeper the decline, the higher the likelihood of achieving the target. But the steeper the decline, the harder it would be to achieve these goals since the time window is smaller [28]..
The window is fast closing, and the solutions needed against climate change have to be scalable and immediate. Decentralized recycling methods are one of the multiple solutions for tomorrow. They enable the community to process its plastic waste right at the source and thus avoid many inefficiencies of the centralized model. Decentralized methods reduce transportation needs, adapt to the local waste streams, and make the transformation of plastic waste into valuable materials by individuals and small groups possible. It simplifies recycling, making it accessible to all, thus allowing innovation in the fight against plastic pollution. Decentralized approaches, as the world starts shifting toward sustainability, are an appropriate and practical way to deal with the plastic crisis.

12.3 Research the facts

The third step in the sustainability assessment framework is about the collection of factual data for assessing the feasibility and impacts of the proposed technology. The third stage is important for supporting decisions by evidence rather than assumptions that the design would meet its objectives while embracing the principles of sustainability. The research is segmented into six important sections, see Figure 12.5. Each section has to do with one aspect of the shredder namely :

12.3.1 Material

A Life Cycle Assessment, or LCA, helps in the study of the environmental impact associated with a product throughout its life cycle, from material extraction and production to

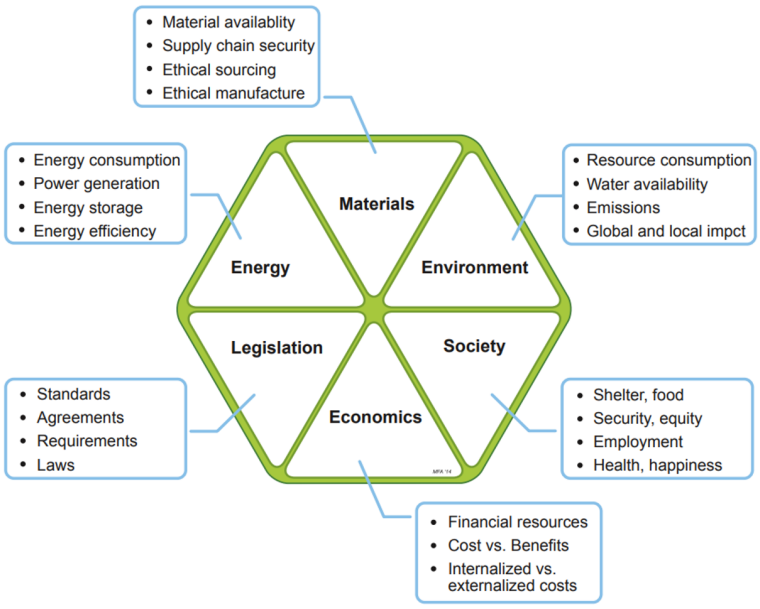


Figure 12.5: Six key dimensions of sustainability — Materials, Energy, Environment, Society, Economics, and Legislation [16]

usage and disposal. For the Shredder Project, we will use the Circular Statistics website that gives standardized data regarding energy use and emissions of greenhouse gases in many materials. This platform allows us to input material quantities (steel, POM, wood, and aluminum in our case)to quickly get estimates for both embedded energy and emissions.

Material	Density (kg/m3)	Data quality (low-very high)	Energy use MJ per kg material (using virgin materials)				Greenhouse gas emissions kg CO_{2eq} per kg material (using virgin materials)				Water use (liter/kg)	Production world (mln ton/yr)	Reserves (mln ton)
			state-of-the-art	typical	old tech	100% recycled	state-of-the-art	typical	old tech	100% recycled	typical		
Iron	7 100	high	19.3	29.7	50	8.5	0.874	1.3	2.4	0.9	45	2 900	81 000
Steel	7 850	high	20.9	27	52.3	8.1	1.64	2.3	3.38	0.68	49	3 900	81 000
Aluminium	2 700	high	73.7	120	174	26	5.16	7.83	17.48	2.6	1 000	47	28 000
Titanium	4 600	medium	361	620	745	81	20.6	36	42.5	6.4	290	0.2	15 000
Magnesium	1 800	high	230	280	320	49		33		2.9	980	1	30 000
Copper and Brass	8 940	high	48.9	57	113.7	25	3.5	3.81	5.05	1.75	310	19	690
Bronze	7700 - 8700	low		69				4					

Figure 12.6: Material properties and environmental impacts of various metals - Circular statistics website [29]

Using the tool, we can make an assessment of the environmental footprint of the shredder and find opportunities to minimize its impact, therefore ensuring a more sustainable design.

The shredder is made from different materials, an estimation would be: around 10 kg of steel, 2 kg of POM, 5 kg of wood, and 1 kg of aluminum. All these materials have different environmental impacts.
All this material has to be manufactured, and that requires a lot of energy—about 560 megajoules (MJ) in total. Of this, steel takes up 200 MJ, POM takes 160 MJ, wood requires 50 MJ, and aluminum takes up 150 MJ. These kinds of numbers put into perspective the energy needs of the production process.
For greenhouse gas emissions, the total impact amounts to approximately 36 kg of CO_2 -equivalent. Steel contributes 18 kg, POM adds 7 kg, wood has a minimal impact of 2.5 kg, and aluminum contributes 8.5 kg. That is to say, these emissions represent the environmental footprint associated with producing the materials for the shredder.

Material	**Quantity (kg)**	**Embedded Energy (MJ)**	**GHG Emissions (kg CO_2-eq)**
Steel	10	200	18
POM	2	160	7
Wood	5	50	2.5
Aluminum	1	150	8.5
Total	**18**	**560**	**36**

Table 12.1: Energy use and Greenhouse Gas (GHG) emissions of shredder materials.

This simple analysis brings out the necessity of charging the environmental prices of materials, especially metals and plastics, but also brings into consideration the lesser impact of natural materials like wood.

12.3.2 Economics :

Operational cost estimation
Basically, the operating cost of a shredder is determined by power consumption and will vary with its power rating and capacity. We can assume so far that the V2 version of the shredder will process around 2kg/hour of plastic, making them ideal for small-scale efforts. Small shredders with 1–2 kW power consumption at a capacity of 2 kg/hour cost approximately **€0.05–€0.10** per kilogram of plastic processed, at an average electricity price of €0.20/kWh [30], calculated with equation 12.1.

$$\text{Cost per kg} = \frac{\text{Consumption (kW)} \times \text{Electricity Price (€ per kWh)} \times \text{Use Time (hours)}}{\text{Processing Capacity (kg per hour)}} \quad (12.1)$$

In contrast, large shredders, consuming 15–30 kW with a capacity of 500 kg/hour, are more efficient, costing only **€0.008–€0.012** per kilogram. Maintenance costs are minimal for small shredders but higher for large, automated ones. Labor costs also differ, with small shredders requiring more manual effort, making them better suited for localized recycling despite higher per-kilogram costs.

Small shredders like the one used for this project are more accessible, affordable, and suitable for local recycling, costing around 800-2000€, with operational costs of €0.05/kg. Conversely, industrial shredders cost €50,000–€100,000, with operational costs of let's say €0.01/kg, but their high capacity (500–1,000 kg/hour) makes them more efficient for large-scale operations. While small shredders empower communities and support decentralized recycling, large shredders achieve economies of scale but are impractical for smaller use.

Aspect	**Small Shredder**	**Large Shredder**
Initial Cost	€800–€2,000	€50,000–€100,000
Operational Cost	€0.05/kg	€0.01/kg
Processing Capacity	2 kg/hour	500–1,000 kg/hour
Best Use Case	Localized recycling	Industrial-scale recycling
Key Advantage	Affordable, accessible	Economies of scale

Table 12.2: Comparison of Small and Large Shredders in Terms of Economic Efficiency.

12.3.3 Environmental :

Section 12.3.1 showed and calculated the environmental footprint of the manufacturing of a small scale shredder. In this section, we will find out how this shredder could contribute towards a positive carbon footprint.
For this analysis, we will assume a small-scale plastic shredder working 5 hours a day and also using 1–2 kW of power and shredding at a rate of 2 kg/hour, just like in section 12.3.2.
Operationally, they would consume 5–10 kWh/day for 5 hours of operation, which is very small compared to the industrial shredders in centralized facilities that may easily use upwards of 50–100 kWh for the same amount of time. Additionally, decentralized shredders save the transportation emissions that could be an extra 0.5-1 kg of CO_2 per km of waste transported to a centralized facility [31]. Operating on a local level, one shredder alone can process up to 3.65 tonnes of plastic yearly, which would keep the material out of landfills and incinerators, therefore saving up to 1.7 tonnes of CO_2 -equivalent annually per tonne of HDPE [32]. Deployed at scale in many communities, these will have a significant effect on the linked greenhouse gas emissions, hence are very much relevant to climate change.

12.3.4 Legislation :

An important part of technology assessment on the final shredder will be the legislation that affects plastics, plastic recycling, and the use of shredders.
Growing efforts by both the EU and national authorities show an urgent need to control plastic waste and make sure that most activities have sustainable effects. The Directive on Packaging and Packaging Waste has set ambitious goals to make all packaging materials reusable or recyclable in economically viable ways by 2030 [33]. Moreover, the Single-Use

Plastics EU Directive banned a list of single-use plastic products, at the same time promoting the development of sustainable alternatives that contribute to reducing plastic waste [34]. These were complemented by EU Regulation controlling recycled plastic materials intended for food contact in compliance with safety standards [35] The Federal Public Service for Health, Food Chain Safety, and Environment is responsible for such regulation enforcement in Belgium, particularly with regard to food-contact materials and recycled plastics.

In regard to shredders specifically, there is no direct EU legislation; their design and use have to be in conformance with broader EU environmental and safety standards.
The Machinery Directive 2006/42/EC [36] requires strong housing and safety guards against access to moving parts. Feeding slots are designed in such a way that hands cannot accidentally touch the blades.
According to EN ISO 13850:2015 [37], every emergency stop system shall be clearly visible and easily accessible without time delay.
Based on the use of Directive 2000/14/EC [38], maximum noise should be < 80 dB for small shredders.
EN ISO 12100:2010 [39] states that a risk assessment has to be made to identify and minimize all hazards such as jams or overheating.
These standards make shredders safe, reliable, and suitable for use in decentralized recycling.

12.3.5 Energy :

The total energy for manufacturing and operating a small-scale shredder for its lifetime offers a meaningful look at the environmental impact that such a device creates. Manufacturing requires about 560 MJ (12.3.1) of embedded energy, where steel makes up the largest portion, 200 MJ, then POM at 160 MJ and aluminum at 150 MJ. Over an average lifetime of 10 years, assuming 5 hours of daily operation, the shredder would consume approximately 18,250 kWh of electricity, equivalent to about **65,700 MJ**. Adding the embedded energy, the total lifetime energy consumption amounts to approximately 66,260 MJ. This would correspond, to put it into perspective, to the energy consumption of an average European household over 3 years, considering that an average household consumes about 20,000 MJ/year of energy. [40] Although the bulk of the energy used is for day-to-day operation, the low power consumption-in the range of 1 to 2 kW-makes this a highly efficient decentralized solution compared to traditional centralized systems, considering avoided transportation and infrastructure emissions. This makes the shredder efficient enough and quite practical for community-level recycling efforts, weighing the environmental costs against the great benefits.

12.3.6 Society :

The project of the shredder aligns with the objectives of the Precious Plastic community, which has contributed a great deal to social development through small-scale recycling

initiatives. Up to the year 2023, Precious Plastic has mobilized activities with **17,951** local recyclers and built **1,881 machines** [5], thus gradually building community involvement in environmental sustainability.
These have created **6,441** jobs all over the world, providing livelihoods and increasing economic stability in many regions. Since 2016, they also started exhibitions and workshops, making it accessible to the general public, even kids, like in China and Thailand, see Figure 12.7. This is a great way to help the next generation take part in solving environmental issues. Precious Plastics wants to make recycling an evidence to kid so they can grow up with values and means for a more sustainable future.



Figure 12.7: Precious plastics workshops for kids - China (left), Thailand (right) [41]

Besides, the community has generated over **$36 million** in revenue, indicating substantial economic benefits.
This project enables the community to be in control of plastic waste through local recycling, hence promoting a clean environment and good public health. It is an opportunity for education in the area of plastic pollution and development of skills related to sustainable practice. This approach supports not only the environmental needs but also the social and economic community development.

Synthesis

This section has fully analyzed the pros and cons of the shredder, such as impacts on human and social capital, natural capital, and manufactured capital. For a comprehensive overview of those points, including all the advantages and challenges identified, please refer to the appendix A, in which the complete synthesis is presented in a tabular form.

12.4 Debate implications

The small-scale plastic shredder implementation in a university-linked FabLab, like the "Makilab in" Louvain-la-Neuve, has impacts on its users at many levels. For students and researchers, the shredder is an excellent educational tool for learning practical machinery operation, recycling processes, and sustainable design. Students of engineering, design, and environmental sciences can use it for prototyping and experimental studies, thus promoting innovation and sustainability awareness.
Other professional users, for example, participants from CREDEM or Openhub, may also consider other applications such as the manufacturing of high-value recycled plastic feedstock suitable for injection molding or 3-D printing.
The general public could also use the shredder for their personal use or to start and be part of the Precious Plastics project. However, safe use and maintenance come about through the robust design for safety, clear instructions and guidance, and support from the staff.
This design can be updated in the future for other applications or projects. Thanks to its Open-Source and distributed design, one could redesign this shredder but for different uses. Thus, modular adaptability will guarantee that it will last and remain relevant during ever-changing needs on the path of society and recycling technologies. The Shredder is a multitool teaching, engaging, and empowering users while being a possible solution for scalable and adaptive solutions toward future recycling challenges.

From a more global point of view, we could talk about the implications of the Precious Plastics project in general. Precious Plastic managed to bring people from around the world to make a contribution towards plastic recycling, indifferent of age, finance, education, or background. Precious Plastic stimulates people, from children in Thailand participating in hands-on workshops, as seen in section 12.3.6 or professionals and community leaders working full-time in countries like Uganda or India, see Figure 12.8

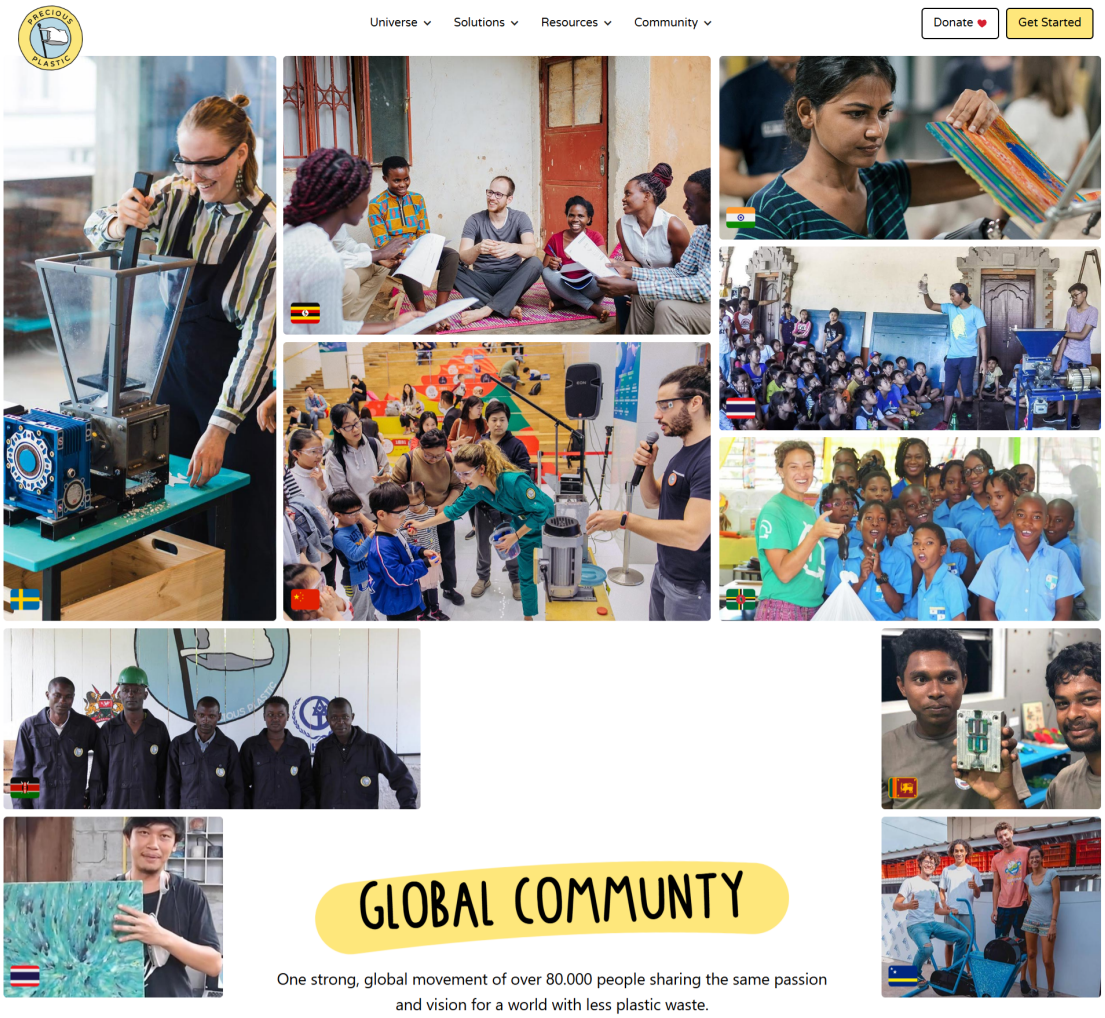


Figure 12.8: Precious Plastics community around the world [41]

Whether it is learning how to operate machines, teaching others about recycling, or finding new uses for materials being recycled, everyone can contribute. The participation, ranging from purely educational activities to long-term involvement, underlines the way the Precious Plastics project can reunite people. What gives the project its strength is its ability to adapt to the local context in which it allows people from all around the world to contribute to plastic recycling. All put together, these contribute toward the bigger vision of a global, decentralized recycling movement and stand as proof that together, small actions can make a difference.

12.5 Reflection

As stated in section 2.4,

> *The last phase of reflection will make us think of how the technology could evolve. It will make us understand how such a system could be improved and what are the alternatives to achieve the same set goals and objectives.*

Let's reflect on the global Precious Plastics project and the shredder.
As a whole, Precious Plastic is an great project that brings great contribution to society : a worldwide network of more than 80,000 people joined together in one mission : fight plastic pollution with the recycling tools open sourced. But if it is to scale up, then it needs to overcome resource limitations in under-resourced areas, extend machine access, and improve educational content. While these challenges may slow progress, the project's adaptability and motivation show great promises for the future. It is here that Precious Plastic could collaborate with governments or industries in scaling up while supporting the infrastructures. These kind of partnerships could empower them to have greater infrastructure, or help them to reach under-resourced area. This could also be the beginning of the integration of educational recycling content into schools, which could raise awareness among the youngest, and amplifying the project's impact.
An other way to see the plastic recycling problem would be to change people mindset about plastic. Instead of thinking of a way to reuse and recycle existing plastic, we could find a way to make communities and people simply reduce their plastic use and need. A change in consumer behavior to lower plastic waste would then decrease the need for recycling; however, the shredder and project would still be needed to handle already existing waste to provide the circular economies.
While challenges might arise with the Precious Plastics project in the short term, its long-term benefits far outweigh the difficulties and ensure that these tools continue to be leading solutions to the global plastic crisis.

On the other hand a reflection on the utility of the shredder can be made and it is about knowing if the benefits of creating and using the machine outweigh the potential negatives, see appendix A.
The summary made in appendix A as well as the climate and plastic recycling crisis mentioned in section 12.2 confirms the idea that such a plastic shredder is and will always be a contribution to the society for environmental, economical and social reasons.
However, considering the role of the shredder, its impact goes far beyond just plastic recycling and opens up broader societal benefits. Here are some ways the system could be improved.
First, the shredder we could consider the end-of-life planning and the machine and plan how the machine and all parts can be recycled or otherwise reused when the it is no longer in operational use. This aligns with circular economy thinking and ensures the shredder will not contribute to waste. The shredder could also be used to make a cultural and educational impact, serving as a tool to raise awareness about plastic waste and

recycling and engaging the communities. Lastly, affordability and access will be always be very critical to its adoption in poorer regions. Subsidizing the cost, or using alternative methods of manufacture could make the shredder even more accessible and further enable more communities to take part in plastic recycling.
With these reflections, the possibility of future enhancements should be considered that could increase the utility and impact of the shredder.
As for the V2 version specifically, its design is effective at the moment, but could, once again be improved to maximize its impact. It has brought great enhancements in usability and efficiency, but there is always room for further development. Such improvements can be found in section 11.7.

Chapter 13

Conclusion

This thesis has detailed the design development of the V2 shredder, an improvement over its V1 predecessor, by addressing critical limitations to do with efficiency, safety, manufacturability, and sustainability. Building from the original design of the V1 shredder, this project upgraded key subsystems, lowered operational risks, improved shredding effectiveness, and completed a sustainability analysis based on the framework developed by Michael F. Ashby.
The V2 shredder incorporated several significant upgrades to both its form and function. The manufacturability percentage dropped slightly to 86.9% due to the incorporation of externally sourced parts, most notably the reducer and steel blades, but still ensures that the majority of parts are producible with local FabLab tools. While this was a trade-off, these extra components considerably improved the operational capabilities of the machine, including a mass flow rate nearly three times that of the V1 shredder, thereby making a considerable improvement in shredding efficiency. The extra costs (416€) of such improvements are acceptable in consideration of the benefits obtained in safety, durability, and performance.

Each subsystem from the V1 was redesigned with a clear and structured methodology, using a combination of risk analysis and the triple constraint method (evaluating cost, time, and scope) to guide decision-making:

Blades: The POM blades from V1, while locally manufacturable, were starting to wear leading to inefficiency. Based on risk analysis and triple constraint evaluation, these have been replaced with durable steel blades from the Precious Plastic design in order to ensure higher shredding efficiency and longer service life.

Hopper: The first version of the hopper did not have any safety features at all. The risk analysis highlighted the danger of permanent access to the blades. The redesign introduced a new hopper with an end-of-travel switch, preventing shredding when the hopper is open. It also added a more convenient and aesthetic Plexiglass version for a better user experience.

Motor and Reducer: Due to torque limitations, the V1 shredder could not shred tougher plastics. To handle this, a reducer was added, which increased the output torque, leading to a more consistent shredding process. The triple constraint method confirmed that this addition would be a high-impact, cost-effective solution despite the need of an external component.

Rotating Components: The V1 design had exposed rotating elements that could also be considered as safety threats. To lower these risks, protective coverings were added to secure these components, and reducing any possible hazards.

Emergency Stop Mechanism: The lack of an emergency stop feature in the V1 shredder represented a significant safety issue. In contrast, the V2 model incorporated an emergency stop button, thereby adding an instant shutdown alternative during emergencies.

Each of these decisions is a trade-off between functionality, safety, cost, and manufacturability to ensure that the V2 shredder is not only more effective but also accessible for fabrication and operation in Fablab environnments.

The evaluation of the technology using Ashby's theory showed that the V2 shredder is in line with the principles of sustainability. The fact research done on legislation, energy, material, society, environnment and economis highlighted the importants informations related to a shredder and its use. The reflection done also showed that improvements was still possible in both the shredder design and the precious plastics project as a whole. However, it was concluded that such technology was sustainable : tt supports a circular economy and reduces the environmental impact of plastic waste because by allowing local communities to recycle their own plastic waste. Socially, it empowers people and encourages cooperation; economically, it is a cheap and scalable solution for recyling. The whole process highlighted the relevance of both the shredder and the precious plastics project.

In other words, the V2 shredder represents a serious step in the development of small-scale, open-source recycling technologies. With optimized functionality, improved safety features, increased shredding capacity, and strong sustainability foundations, it provides communities with a powerful tool for tackling plastic waste. This project contributes to the Precious Plastic initiative and lays the foundation for further development of decentralized recycling technologies, promoting continued development towards a more sustainable and responsible future.

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Part IV

Appendix

Appendix A

Summary table - Facts analysis

This table summarizes the pros and cons of the shredder project, classified under its respective impacts on human and social capital, natural capital, and manufactured capital. This agrees with the sustainability assessment framework of Ashby, since it bases its analysis on the three capitals that any given technology may have wide implications for. The following table systematically examines the contribution of and challenges from the shredder to further determine whether benefits of the project outweigh its cons, while aligning the principles of the project's design and implementation according to those of sustainability.

Category	Key Points
Materials	+ Reduces demand for virgin plastics by enabling local recycling. + Uses durable materials like steel and aluminum, extending machine lifespan. – Manufacturing requires materials like steel, aluminum, and POM, which have a significant environmental footprint. – End-of-life disposal of the shredder could contribute to waste if not managed properly.
Energy	+ Low operational energy consumption (1–2 kW), making it efficient for community use. + Avoids transportation energy by supporting localized recycling. – Embedded energy of 560 MJ for manufacturing adds to its initial environmental impact.
Environment	+ Prevents plastic waste from entering landfills or oceans. + Reduces carbon emissions by saving approximately 1.7 tonnes of CO_2-equivalent per tonne of HDPE recycled locally. + Supports a circular economy by promoting local reuse of plastic. – Small-scale recycling may struggle with highly mixed or contaminated plastics, limiting its environmental efficiency.
Legislation	+ Aligns with EU directives, including the Directive on Packaging and Packaging Waste and the Single-Use Plastics Directive. + Designed to meet EU safety standards, such as Machinery Directive 2006/42/EC and EN ISO 13850:2015 (emergency stop systems).
Economics	+ Affordable (€800–€2,000) for small communities, FabLabs, and businesses. + Low operational costs (€0.05–€0.10 per kg of plastic processed). + Creates economic opportunities by generating income through the production of recycled products. – Higher per-kilogram costs compared to industrial shredders (€0.0125 for industrial alternatives). – Maintenance may be challenging in resource-limited areas.
Society	+ Empowers individuals and communities to take control of their plastic waste. + Provides educational opportunities in schools, universities, and FabLabs, fostering awareness and sustainability skills. + Promotes community-driven recycling efforts and engagement with sustainability goals. – Requires training and support for non-specialist users. – Limited scalability in areas without adequate infrastructure or community support.

Table A.1: Pros and Cons of the Shredder for the Six Key Sections of the Assessment Framework

Appendix B

Reducer Data Sheet

DESCRIPTION

INFO +

Description

Réducteur Transtecno CM63 90B14 roue et vis

Réducteur Transtecno CM63 pour moteur normalisé type 90B14. En le combinant avec un moteur électrique, il permet de réaliser un motoréducteur monophasé ou triphasé. Etanche, il est lubrifié à vie par une huile synthétique longue durée. Il peut se monter dans toutes les positions aussi bien verticales que horizontales. De plus, vous pouvez vous procurez en option sur notre site une bride d'entrée normalisée 90B5 pour modifier le réducteur afin qu'il accepte un moteur type 90B5. Enfin, vous trouverez aussi des kits de sortie: bride, arbre plein simple et double et bras de réaction.

Données techniques

Marque: Transtecno

Taille réducteur: CM063

Matière: aluminium

Diamètre de sortie arbre creux: 25mm

Bride d'entrée: B14 (IEC)

Diamètre extérieur : 140mm
Diamètre entre trous: 115mm
Diamètre de centrage: 95mm
Diamètre arbre d'entrée: 24mm

Lubrification à vie: huile synthétique

Positions de montage: toutes

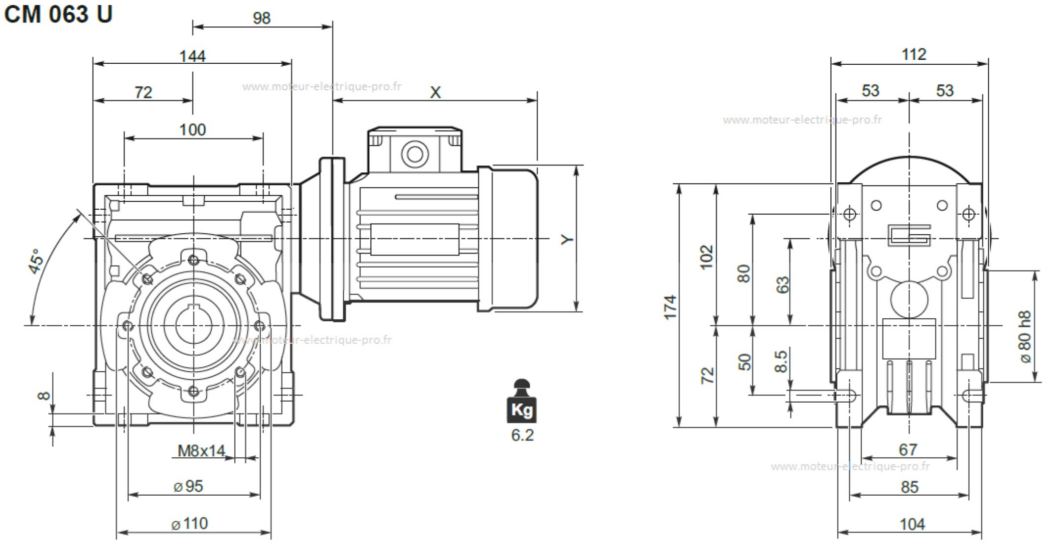
Si vos conditions d'utilisation sont favorables (charge uniforme), utilisation journalière de 4h et moins de 4 démarrages par heure nous indiquons pour un moteur normalisé 1400 tr/min la puissance maximum en kW applicable pour les réducteurs CM dans le tableau ci-dessous:

si vitesse d'entrée = 1400 tr/min (moteur 4 pole)		
Indice	Vitesse de sortie tr/min	Puissance max kW
5	280	1,1
7.5	187	1,1
10	140	1,1
15	93	1,1
20	70	1,1
25	56	1,1
30	47	1,1

Indice	Rs (%)	Rd (%) n1=900	Rd (%) n1=1400	Rd (%) n1=3000
5	73	89	90	91
7.5	71	86	88	90
10	67	84	86	88
15	60	81	84	86
20	55	78	81	84
25	51	75	78	53
30	45	70	75	79

Masse: 6.2 kg

Les dimensions du réducteur CM063U c'est à dire sans accessoire sont données ci-dessous:



Appendix C

Bill of material

This document contains two separate Bills of Materials :

1. **First BOM**: A summary of the BOF of the V1 version (2022-2023).
2. **Second BOM**: The BOM for the V2 version (2024-2025) including newly added components and modifications.

V1 BOM Summary

The first BOM includes components from the original design. Below is a summary of the components with their associated costs and the total value of the BOM:

Component Group	**Cost [€]**
Shredding Box	450
Hopper	25
Frame	100
Electronics	520
Coupling	35
Safety	40
Laser Cutter	20
TOTAL	**870**

Table C.1: First BOM Summary

The total value of the first BOM is **870 €**.

—

V2 BOM

The second BOM reflects the updated design with the additional components.

Machine part	Description	Material	Details	Sizes (Length)	Quantity	Price [€]
Coupling	Reducer	-	15:1 ratio	-	1x	222
Safety	Filament	PLA	Used for 3D printing	-	500g	50
	End-of-travel switch	Plastic/Metal	Safety switch with lever	-	1x	25
	Emergency button	Plastic/Metal	Push button	-	1x	15
Laser cutter	Machine use	-	5€ / 30 min	-	1 x 30 min	5
Frame	OSB wood sheet	Wood	18 mm thickness, cutted	-	1 (600x2400 mm^2)	16
Bolts and nuts	M8 bolts	Steel	Hex head	20 mm, 40 mm	8x	8
	M6 bolts	Steel	Hex head	25 mm, 35 mm	8x	6
	M2.5 bolts	Steel	Countersunk head	10 mm, 15 mm	8x	4
Switch button	Basic switch button	Plastic	Basic switch	-	1x	10
Hopper	Plexiglass sheet	Plexiglass	3mm thickness sheet	400x600mm	1x	20
TOTAL						**416**

Table C.2: Second BOM (Updated Design)

Appendix D

Fabrication and Assembly Plan

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

Appendix E

Shredding results



(a) Initial plastic size (b) Initial plastic weight (c) Plastic flakes

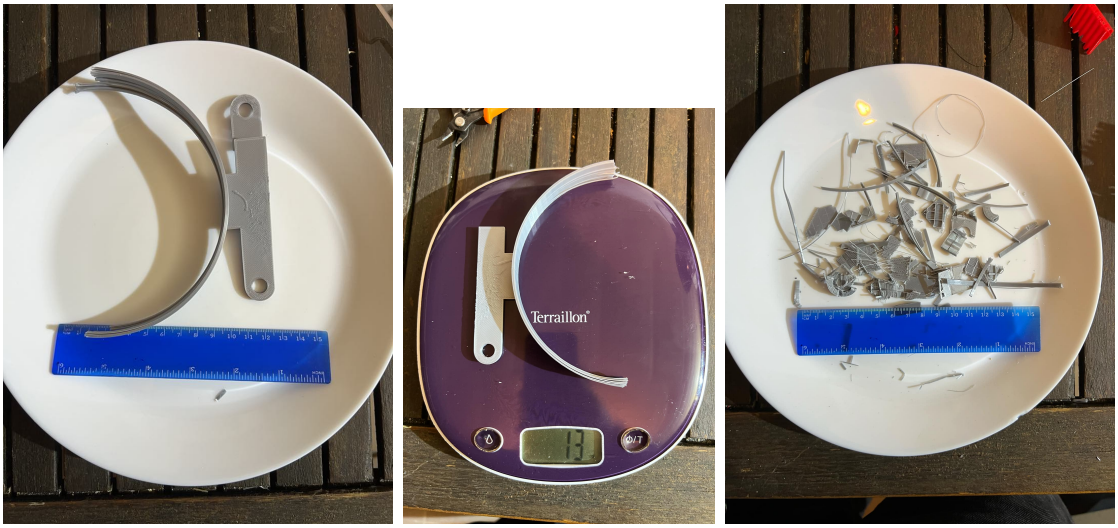
Figure E.1: First test

We tested shredding on a 5 g PLA waste sample from 3D printing. The machine was stopped once the flakes reached an approximate size of 1 cm^2. The process required reintroducing the flakes into the shredding box twice, and the total shredding time was 22 seconds. The resulting mass flow rate of the shredded plastic is calculated as:

$$\dot{m} = \frac{5\,\mathrm{g}}{22\,\mathrm{s}} \approx 0.227\,\mathrm{g/s},$$

equivalent to approximately:

$$\dot{m} = 0.227\,\mathrm{g/s} \times 3600\,\mathrm{s/h} \approx 819\,\mathrm{g/h}.$$



(a) Initial plastic size (b) Initial plastic weight (c) Plastic flakes

Figure E.2: Second test

We tested shredding a grey 3D-printed piece that was originally destined for waste due to incorrect dimensions. The piece weighed about 13 g, and the shredding process took 34 seconds. The resulting mass flow rate of the shredded material is calculated as:

$$\dot{m} = \frac{13\,\mathrm{g}}{34\,\mathrm{s}} \approx 0.382\,\mathrm{g/s},$$

equivalent to:

$$\dot{m} = 0.382\,\mathrm{g/s} \times 3600\,\mathrm{s/h} \approx 1375\,\mathrm{g/h}.$$

It is worth noting that some long PLA filaments were still visible after shredding, indicating that the process was not 100% effective in the way it couldn't turn any piece of the intial piece of plastic into flakes.
The first two tests involved shredding small 3D-printed PLA waste pieces, and the results were recorded in terms of mass flow rate. We then continued the process with larger pieces or multiple pieces at the same time. For each test, we tracked the input weight and the time it took to shred the material into flakes of approximately 1 cm^2. Over the course of 6 additional tests, we calculated a mean mass flow rate of approximately **1822 g/h** for all 8 tests. Below is the summary of the weights and times recorded for these tests.

Test	**Input Weight (g)**	**Time (s)**	**Mass Flow Rate (g/h)**
1	5	22	819
2	13	34	1375
3	16	30	1920
4	22	45	1760
5	19	39	1754
6	25	48	1875
7	24	47	1838
8	18	36	1800
Mean	–	–	**1822**

Table E.1: Shredding Tests Summary

Appendix F

Coupling system assembly

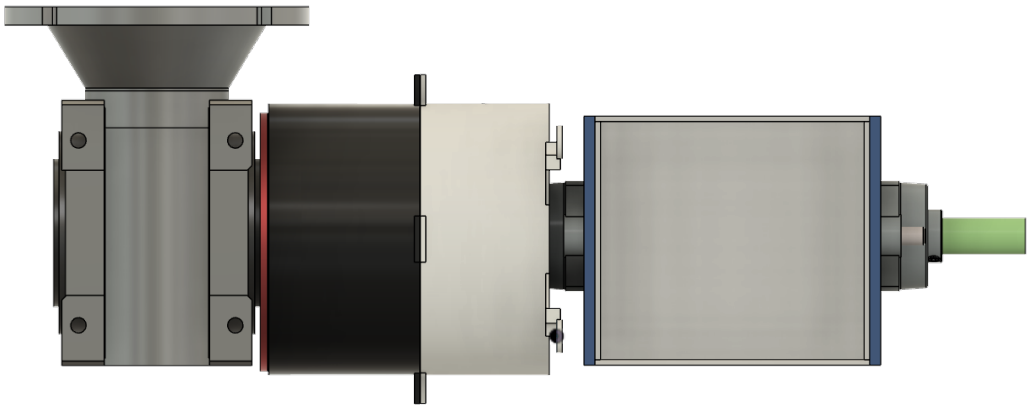


Figure F.1

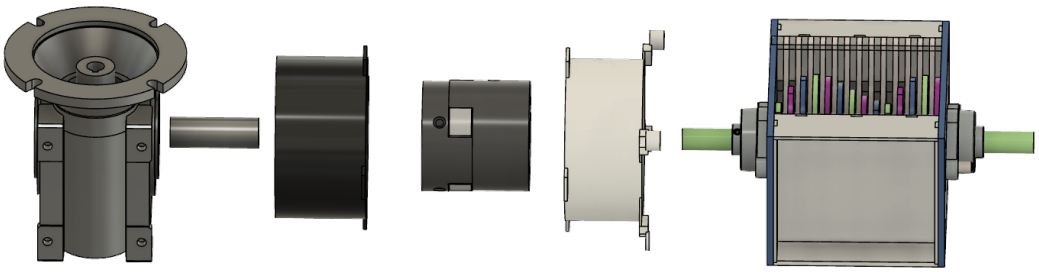
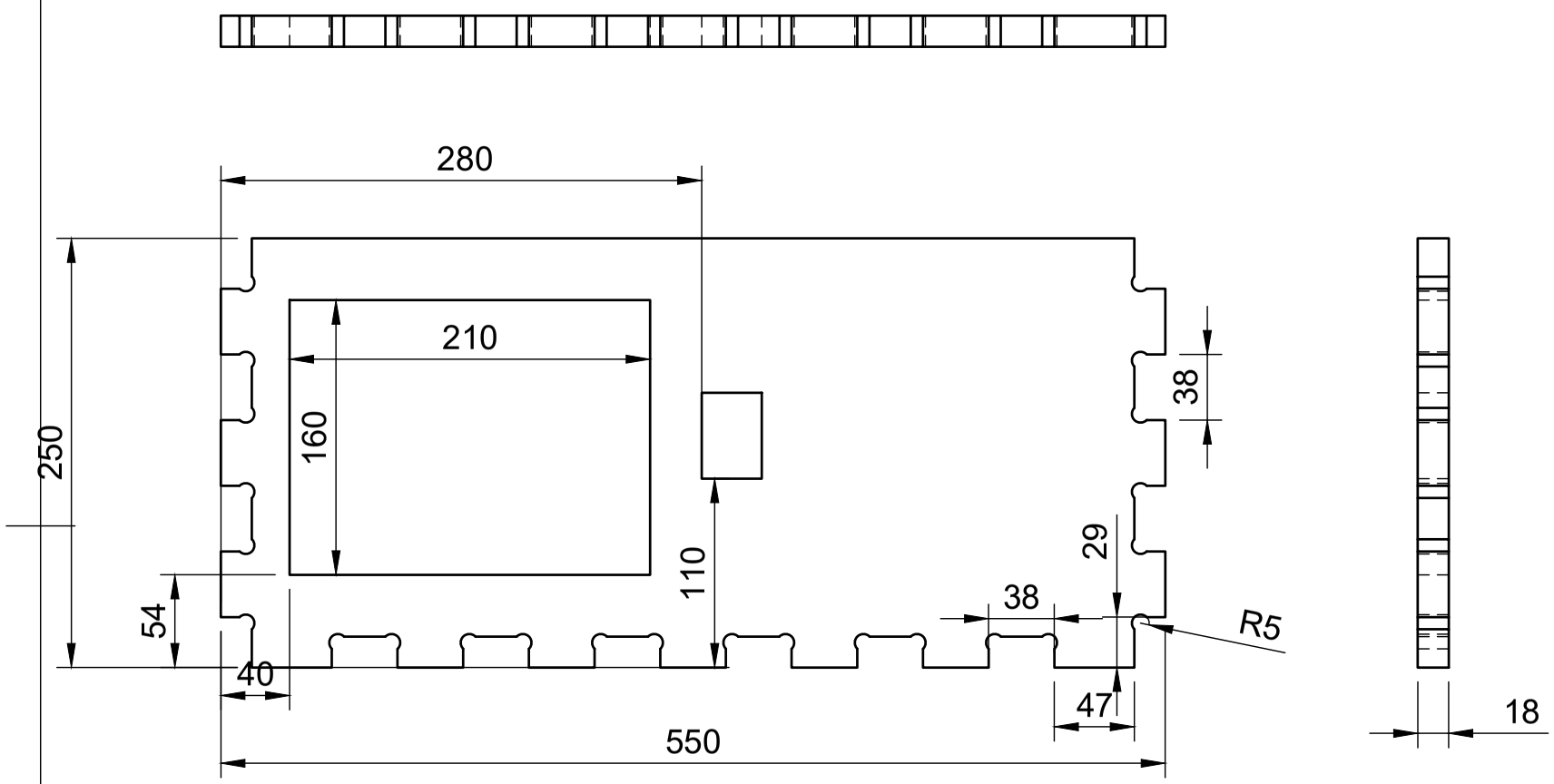
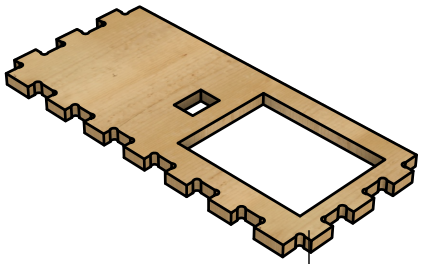


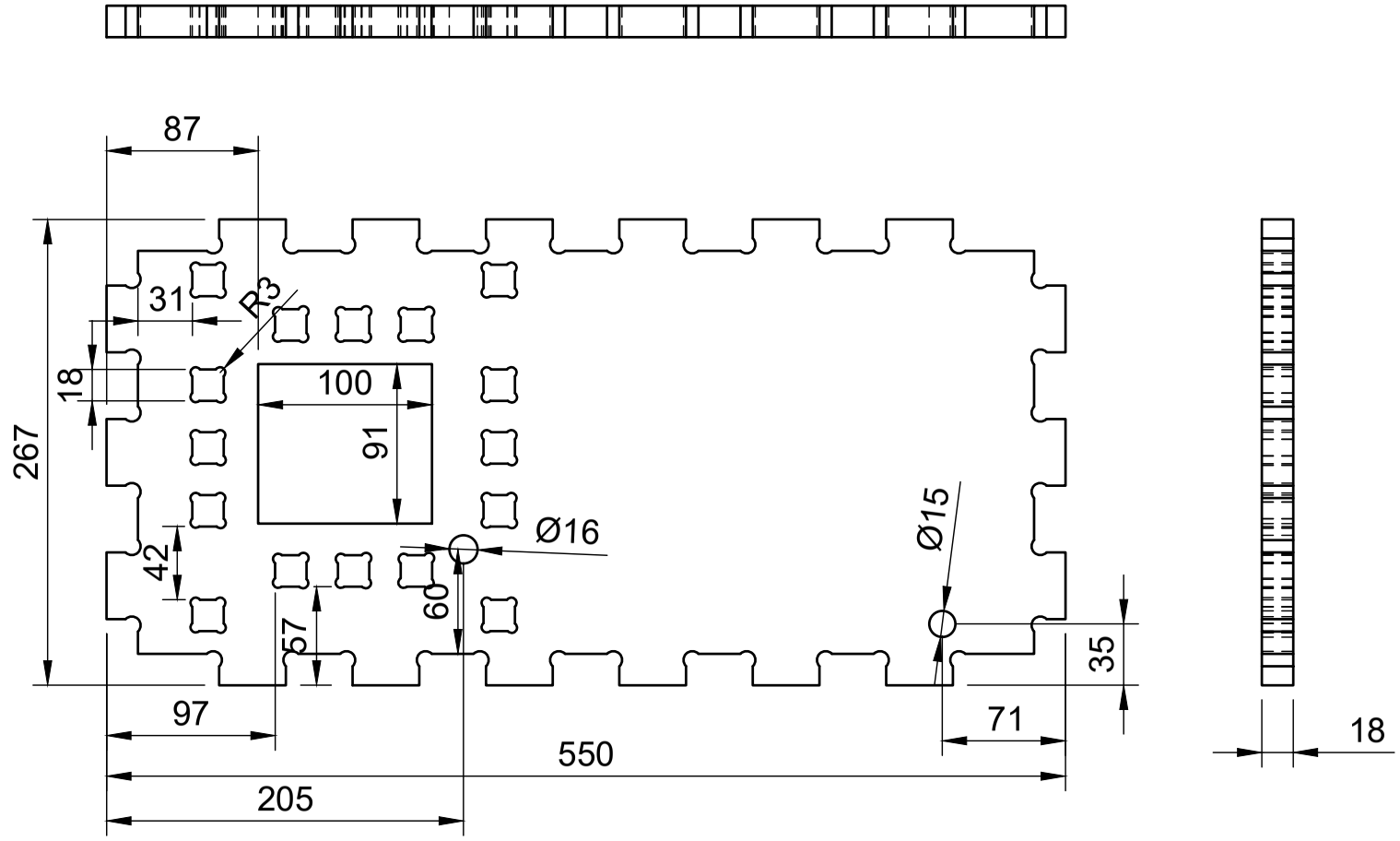
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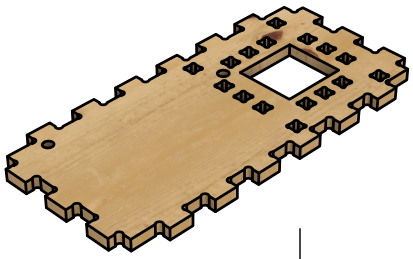
Appendix G

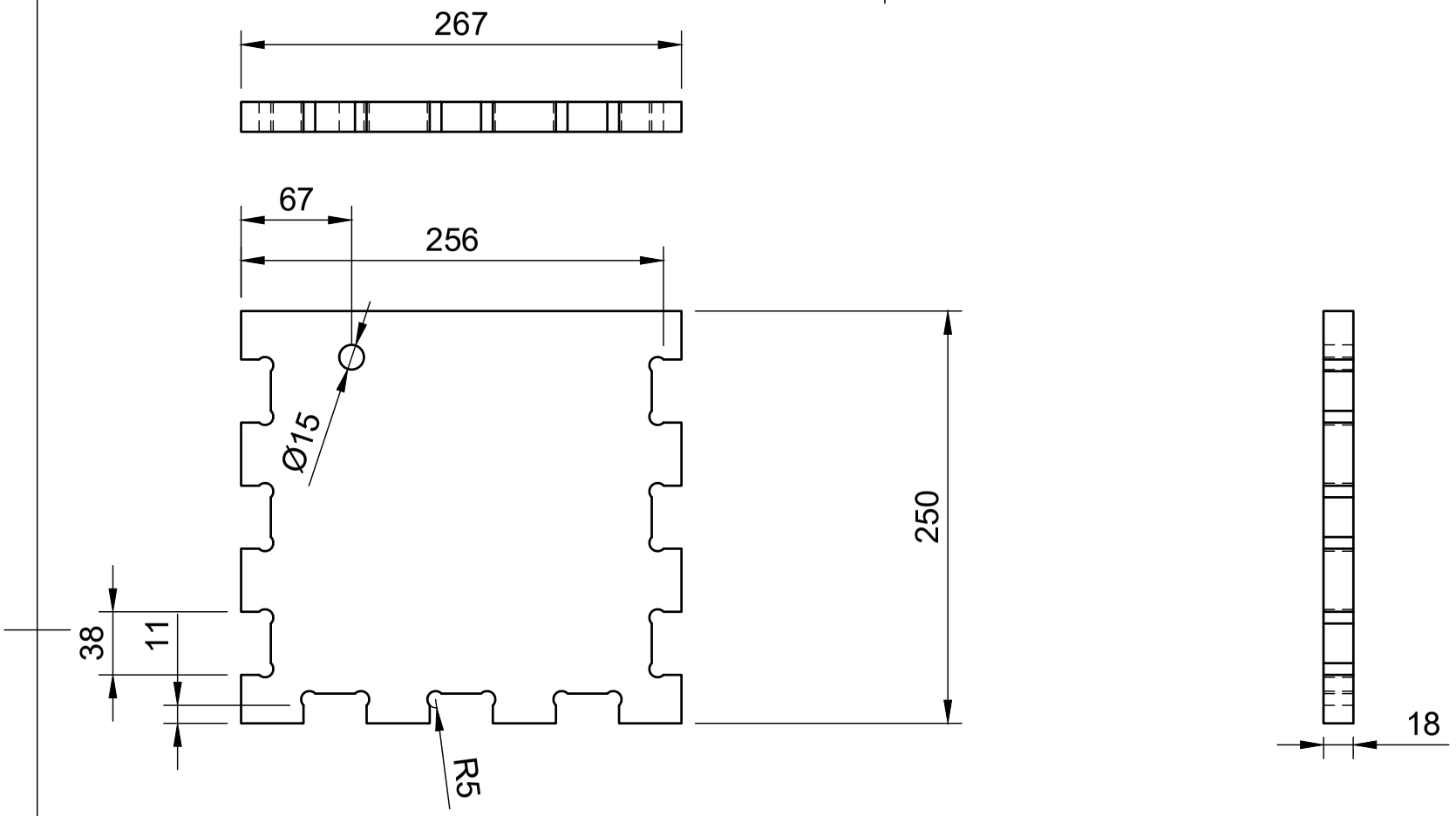
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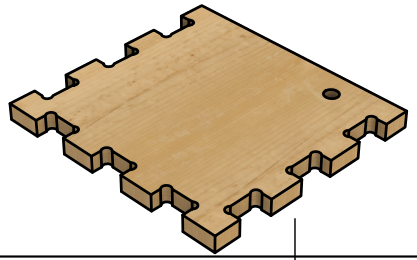


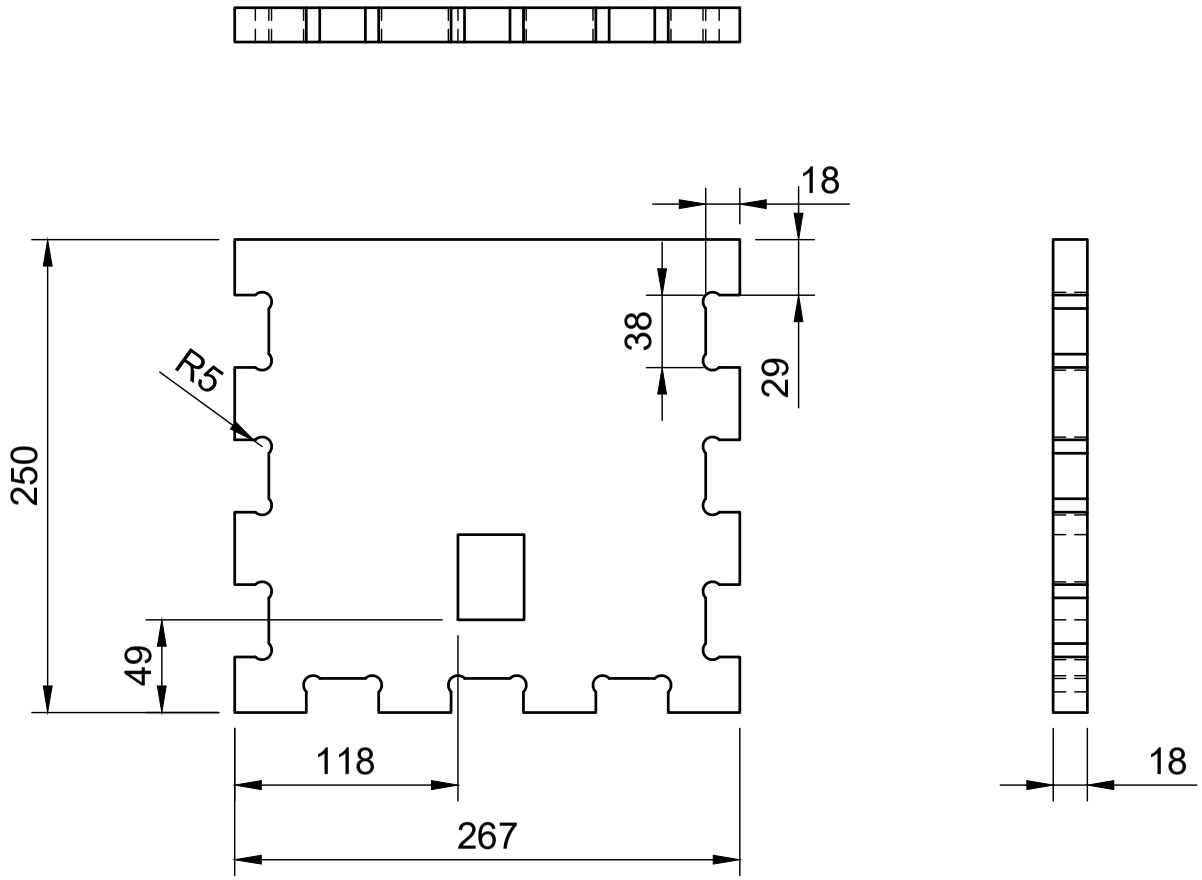
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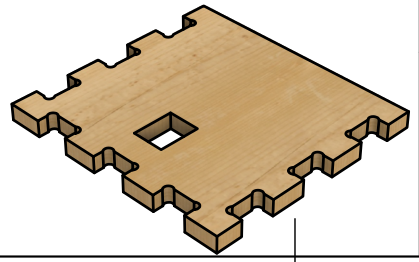


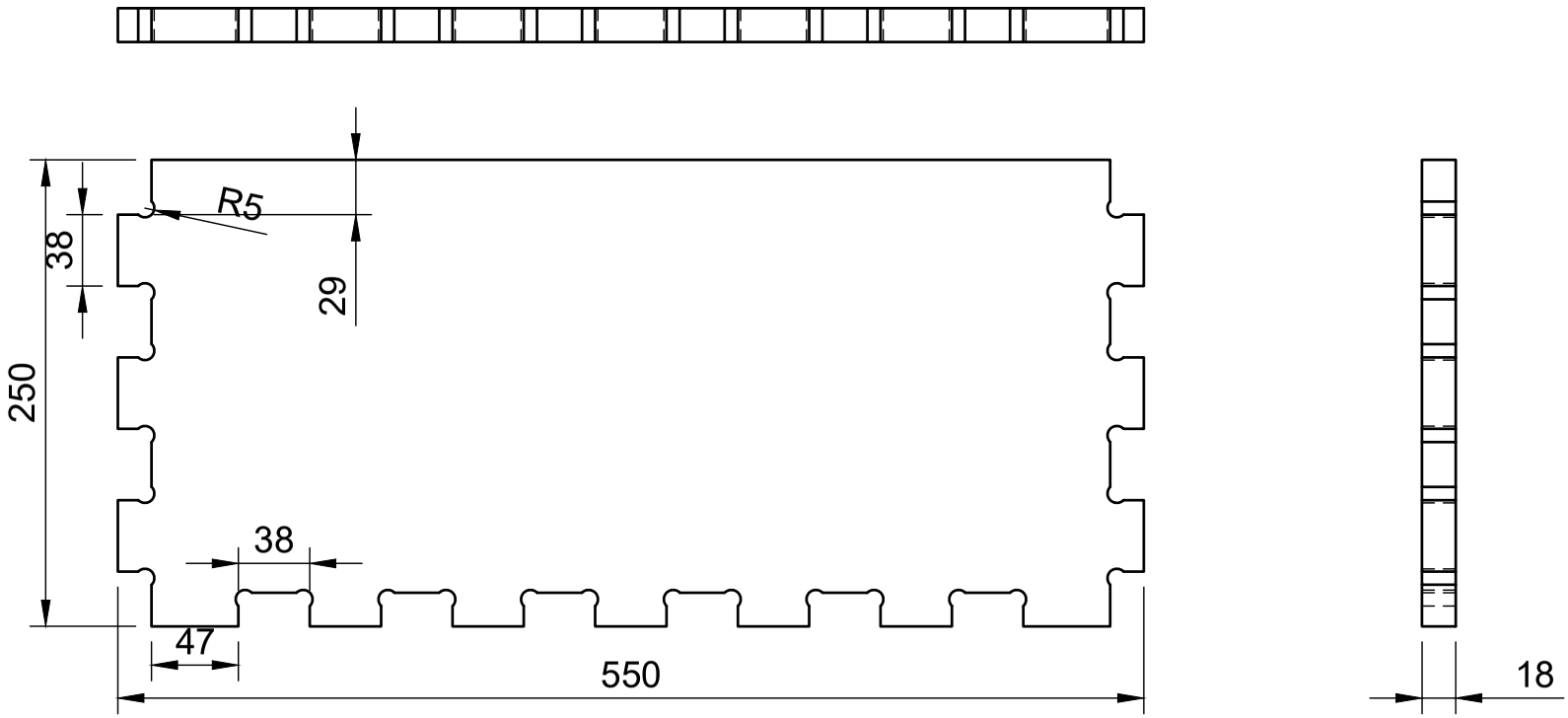
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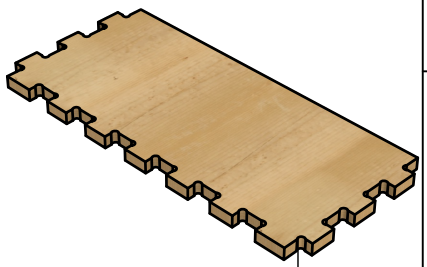


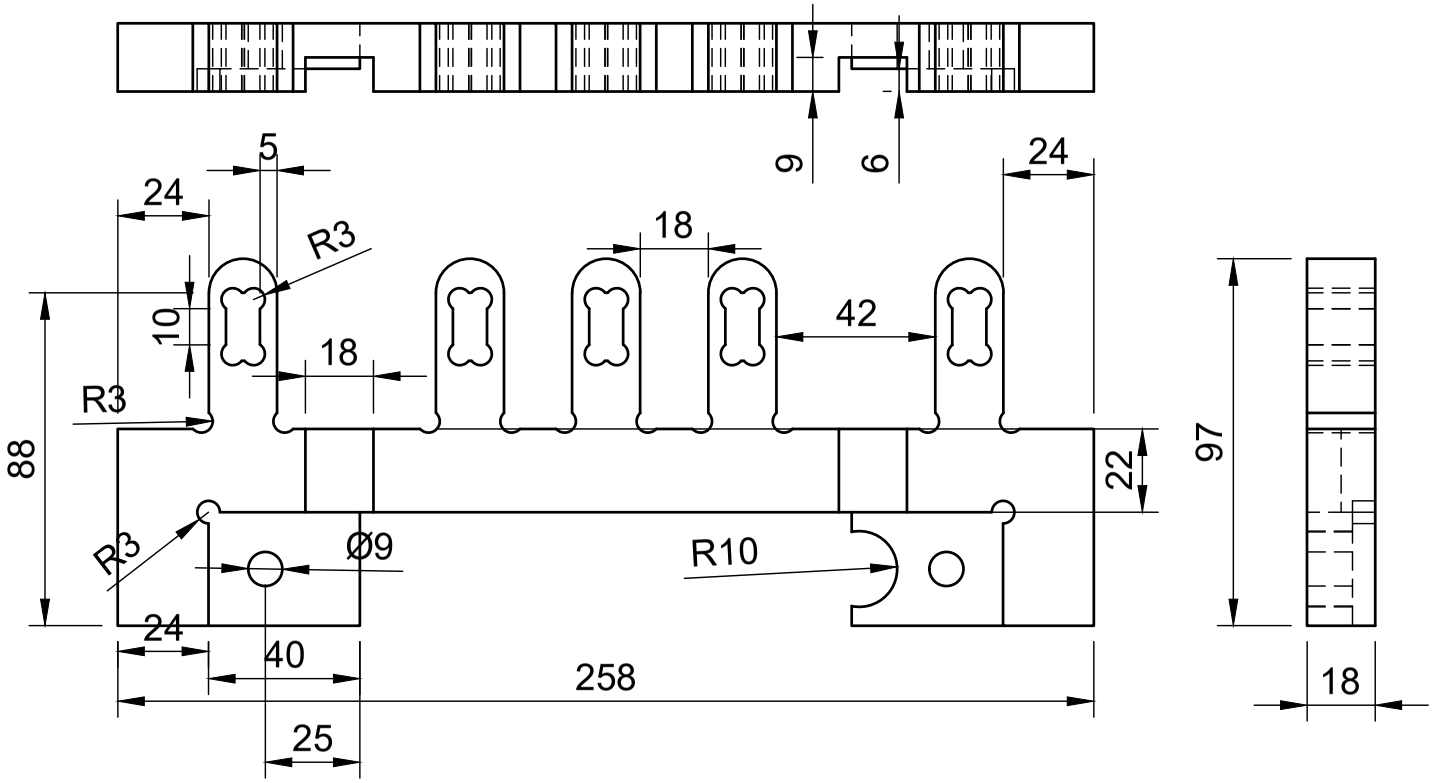
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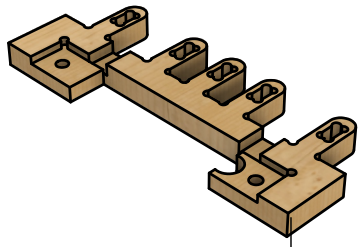


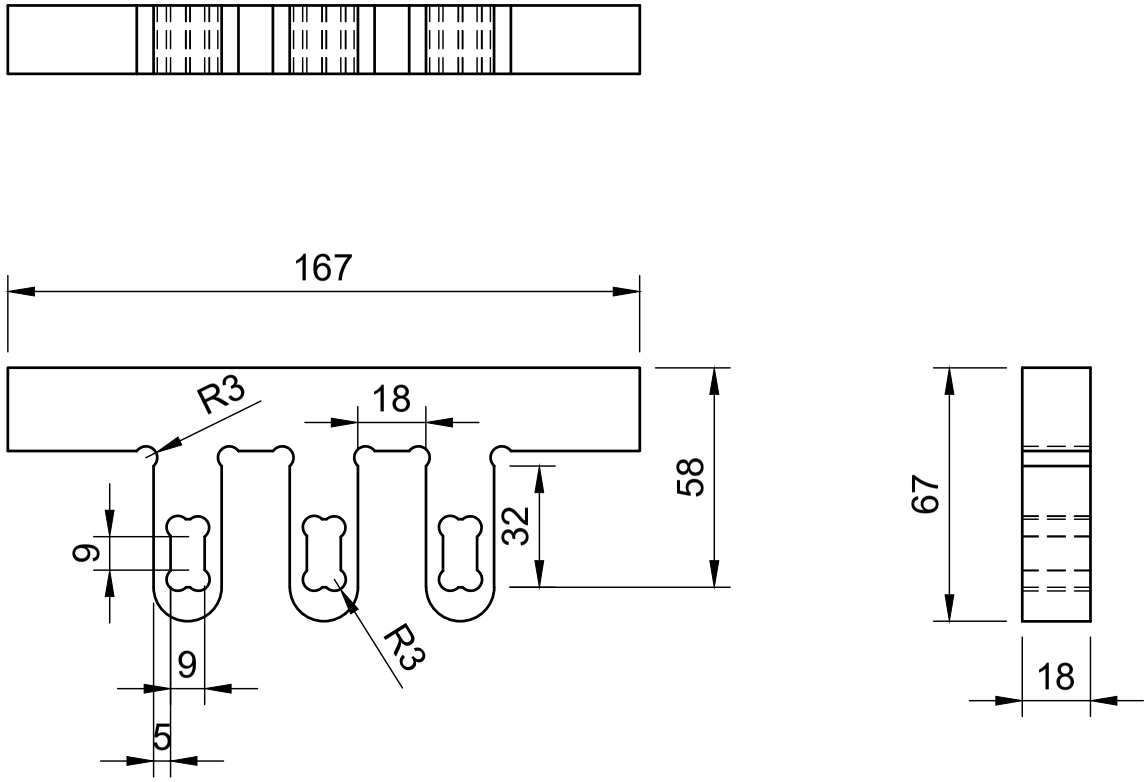
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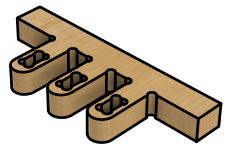


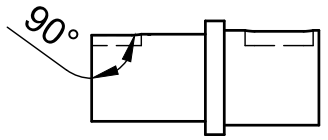
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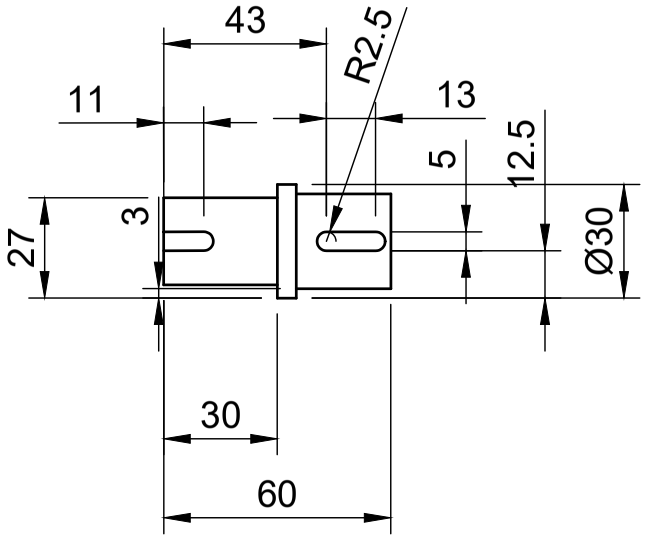


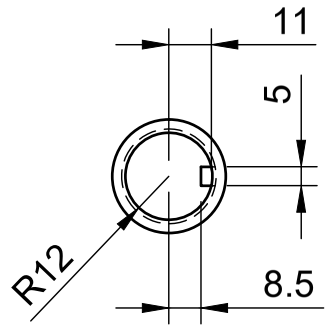
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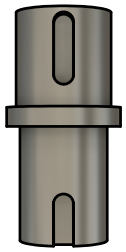


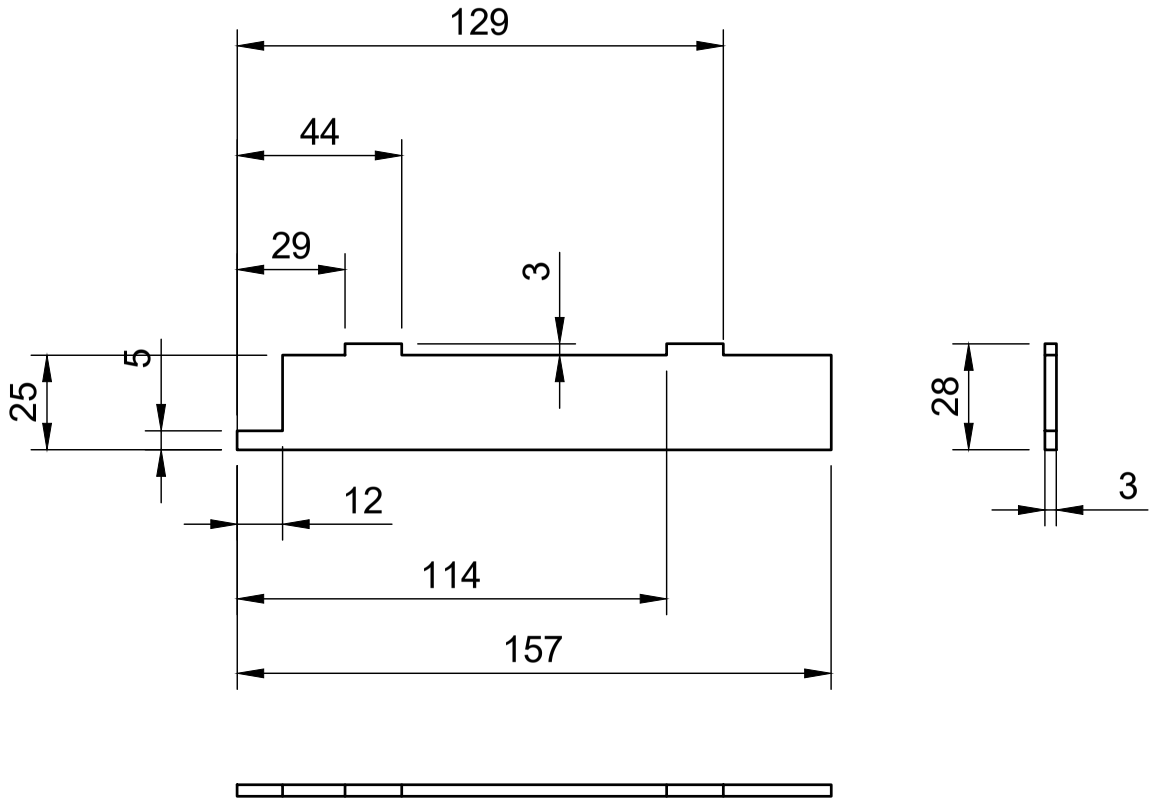
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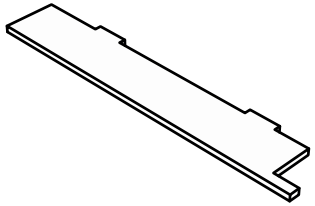


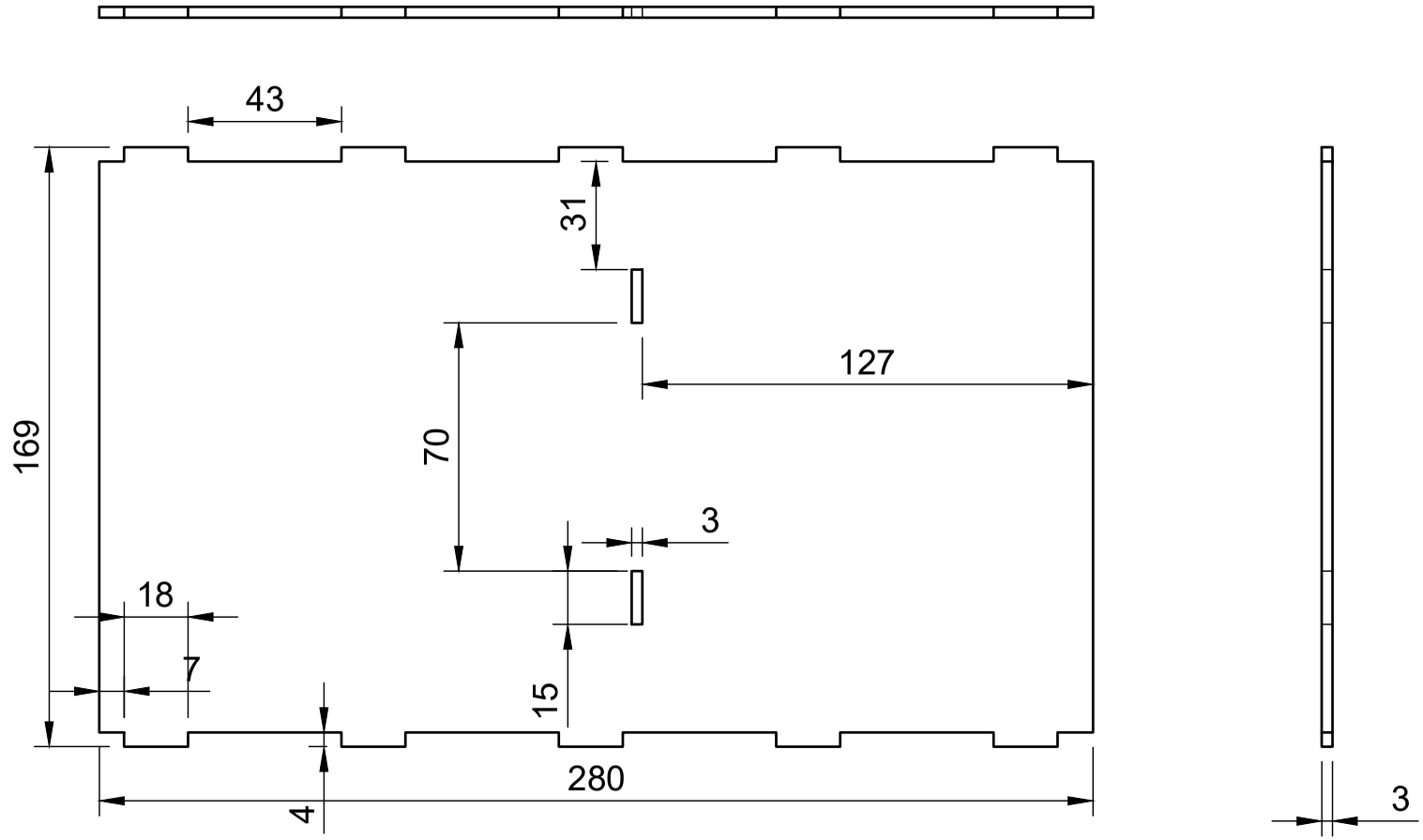


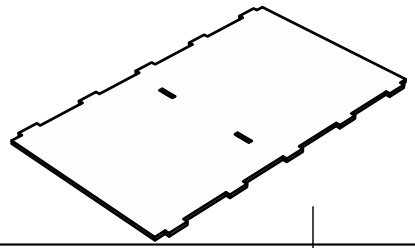


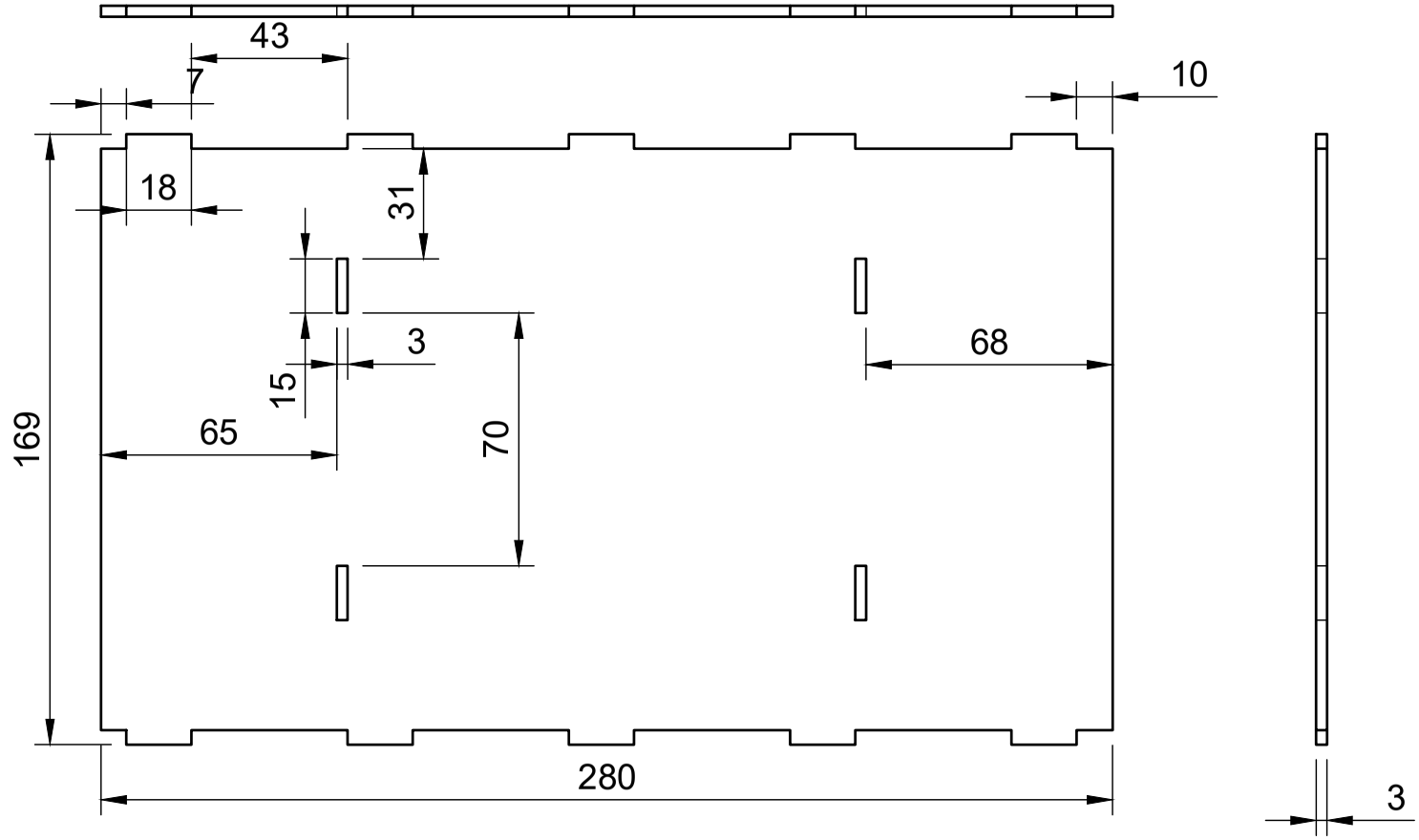
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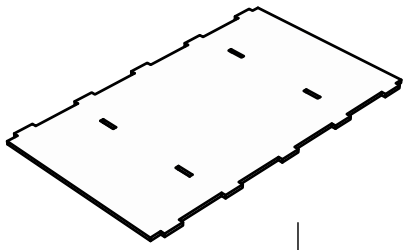
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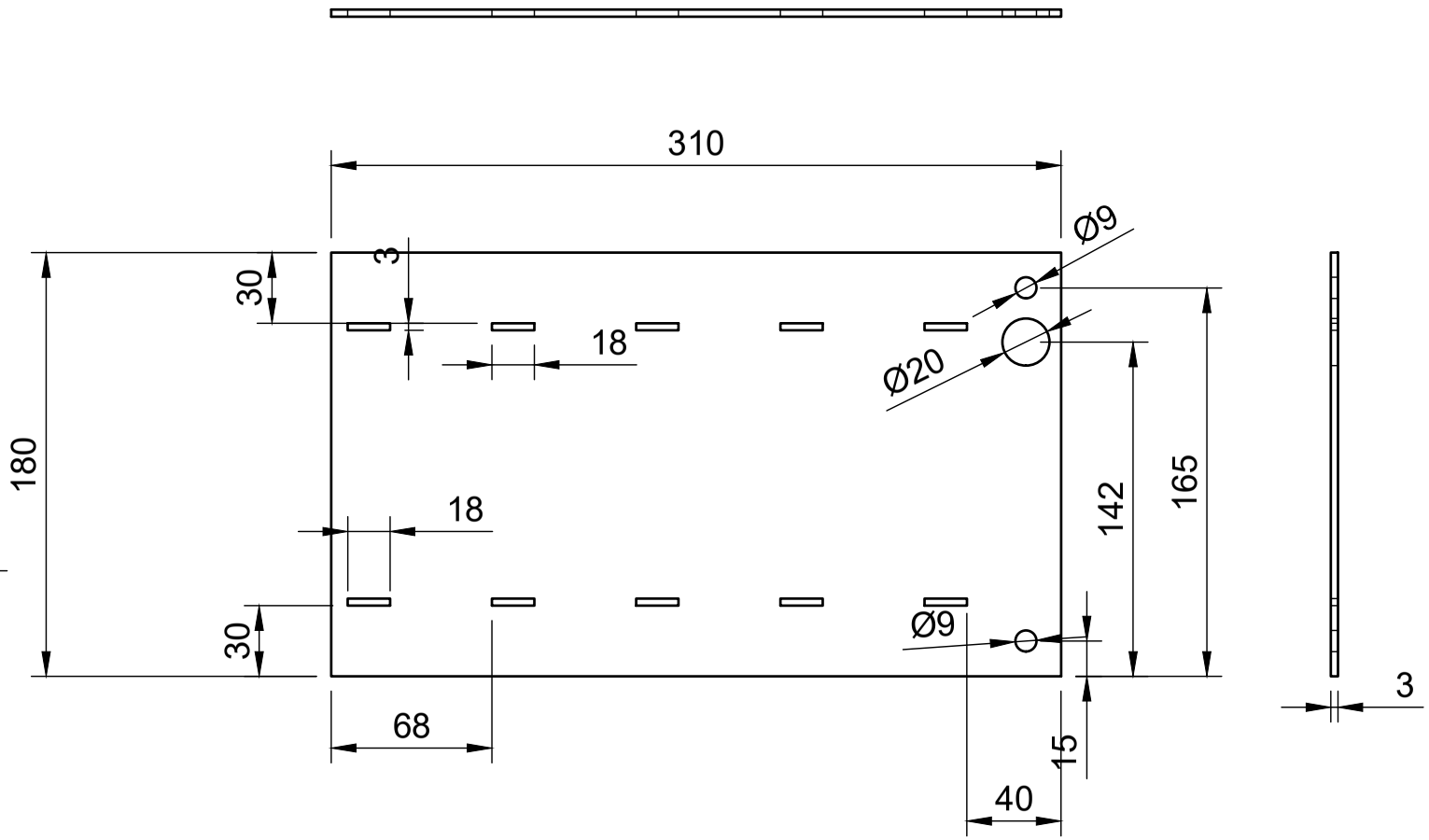
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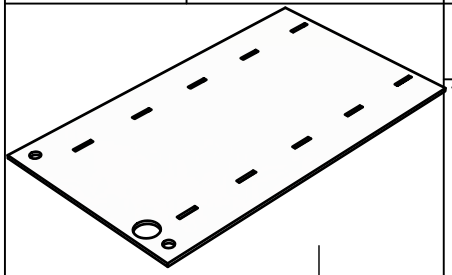
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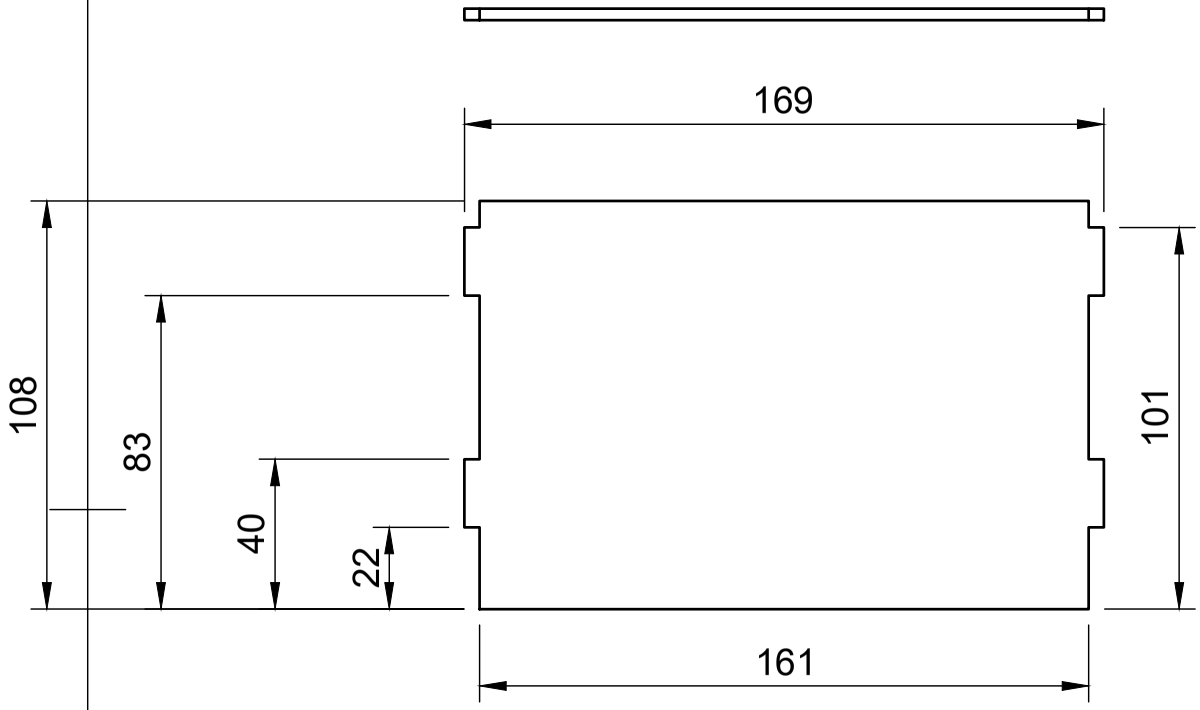
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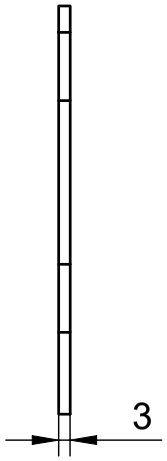
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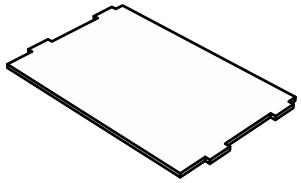
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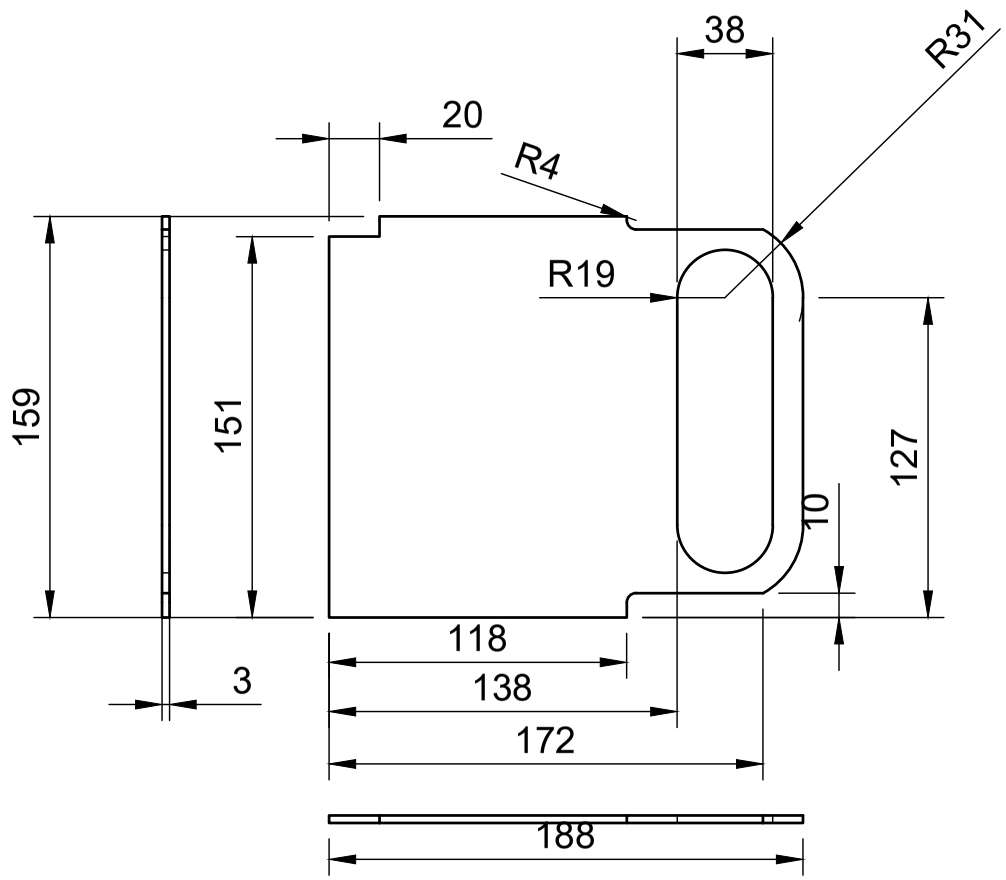


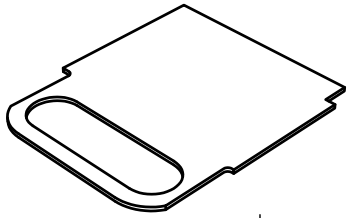
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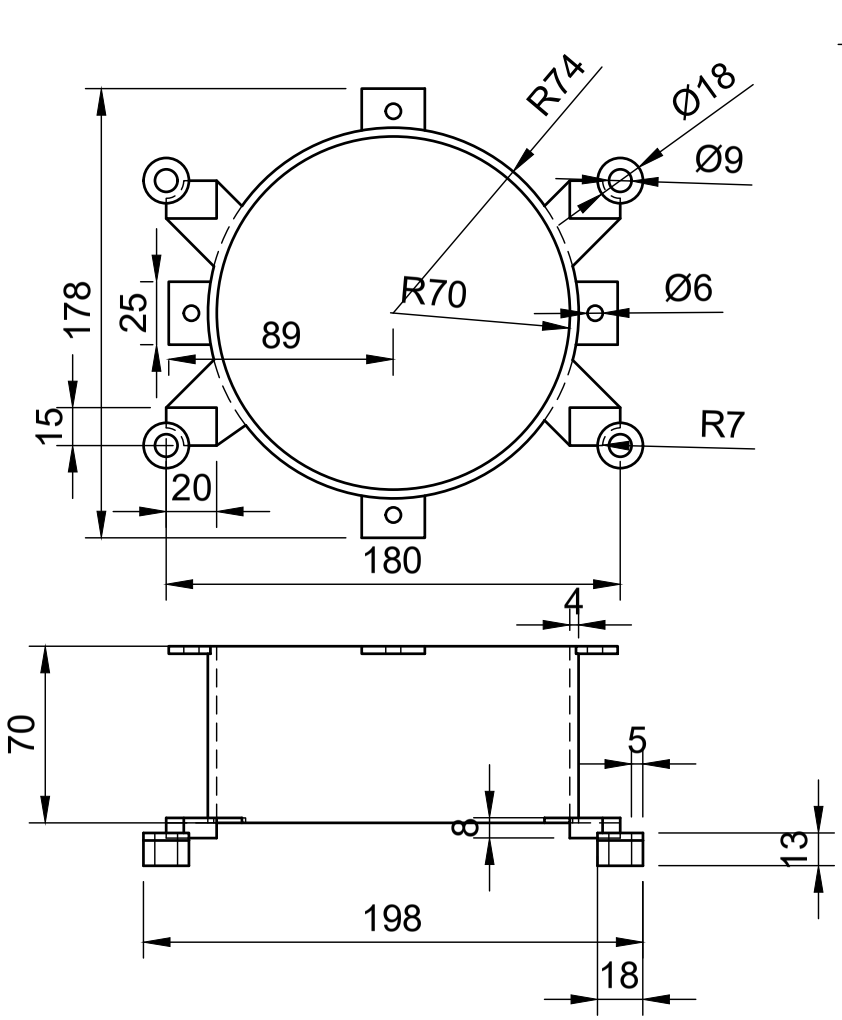


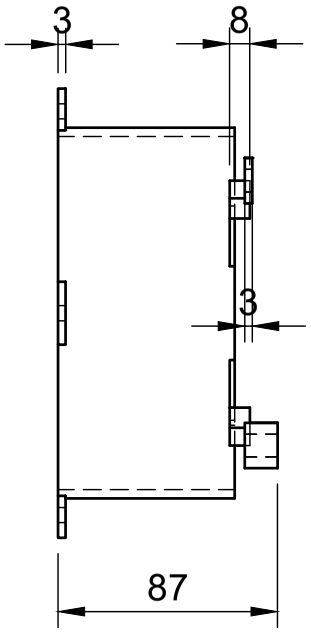


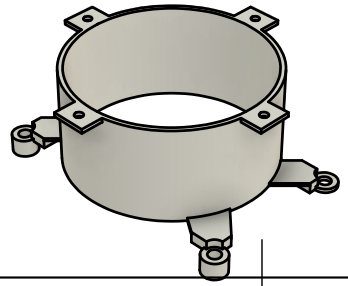
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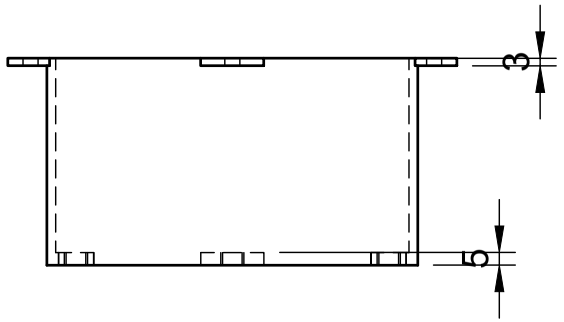


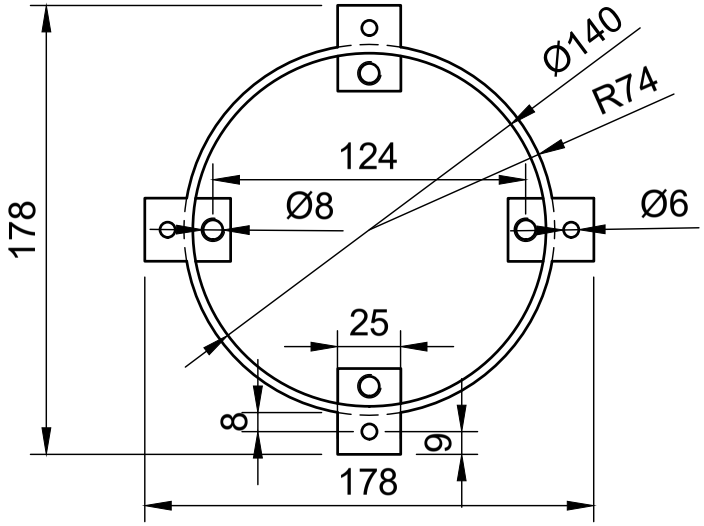
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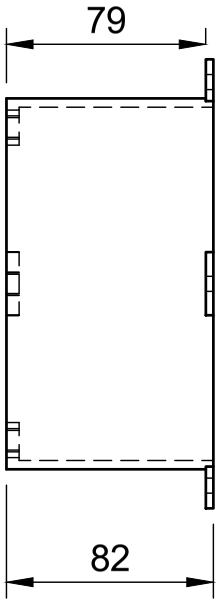


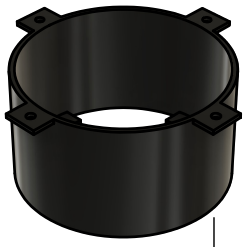


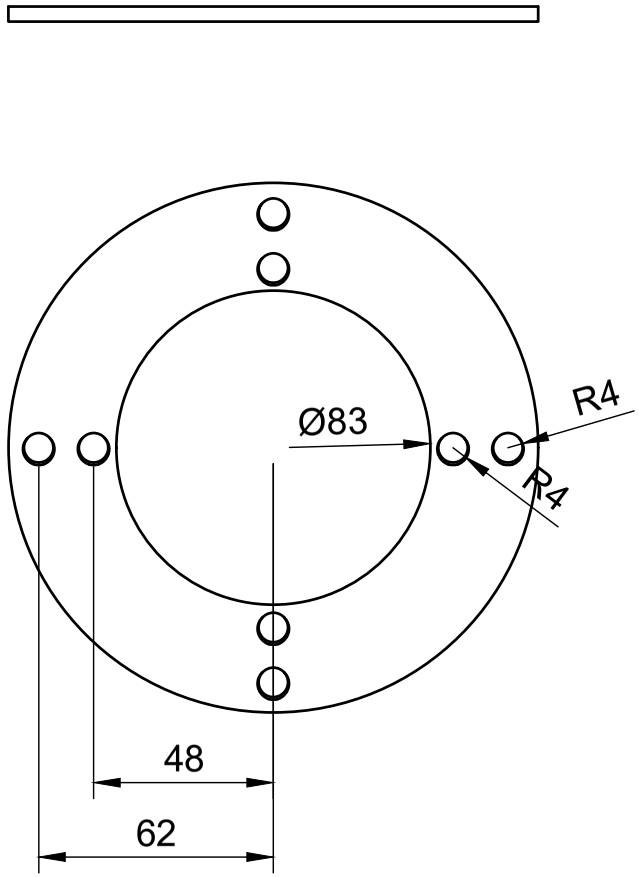
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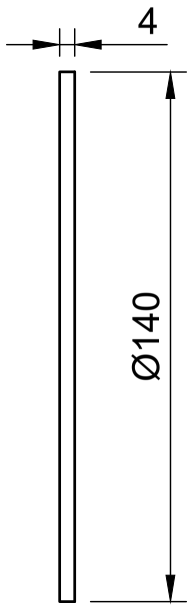


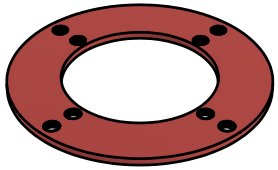


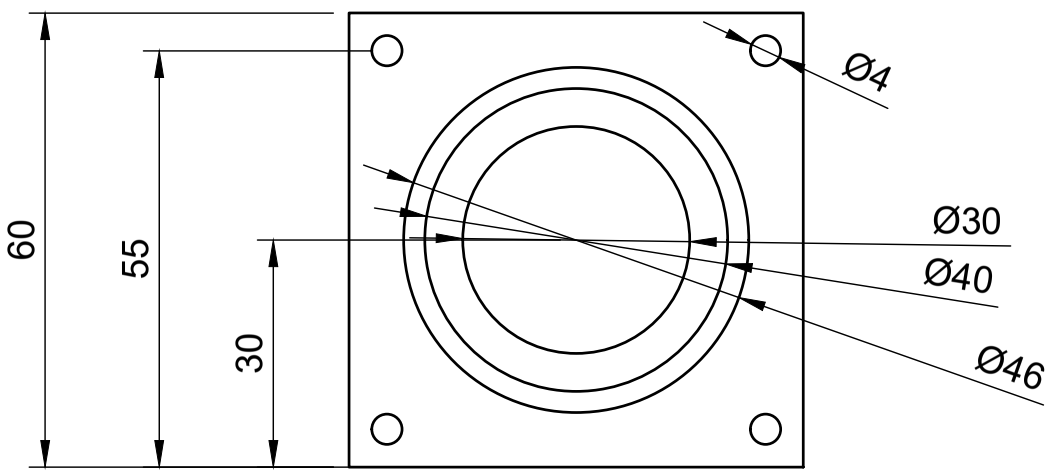


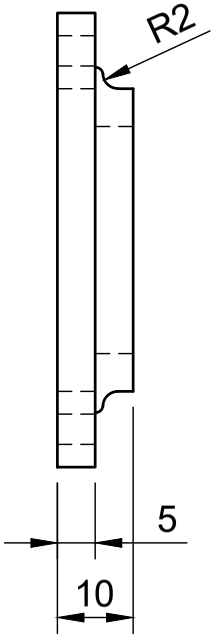
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			Rev. / Date of issue / Sheet 1/1



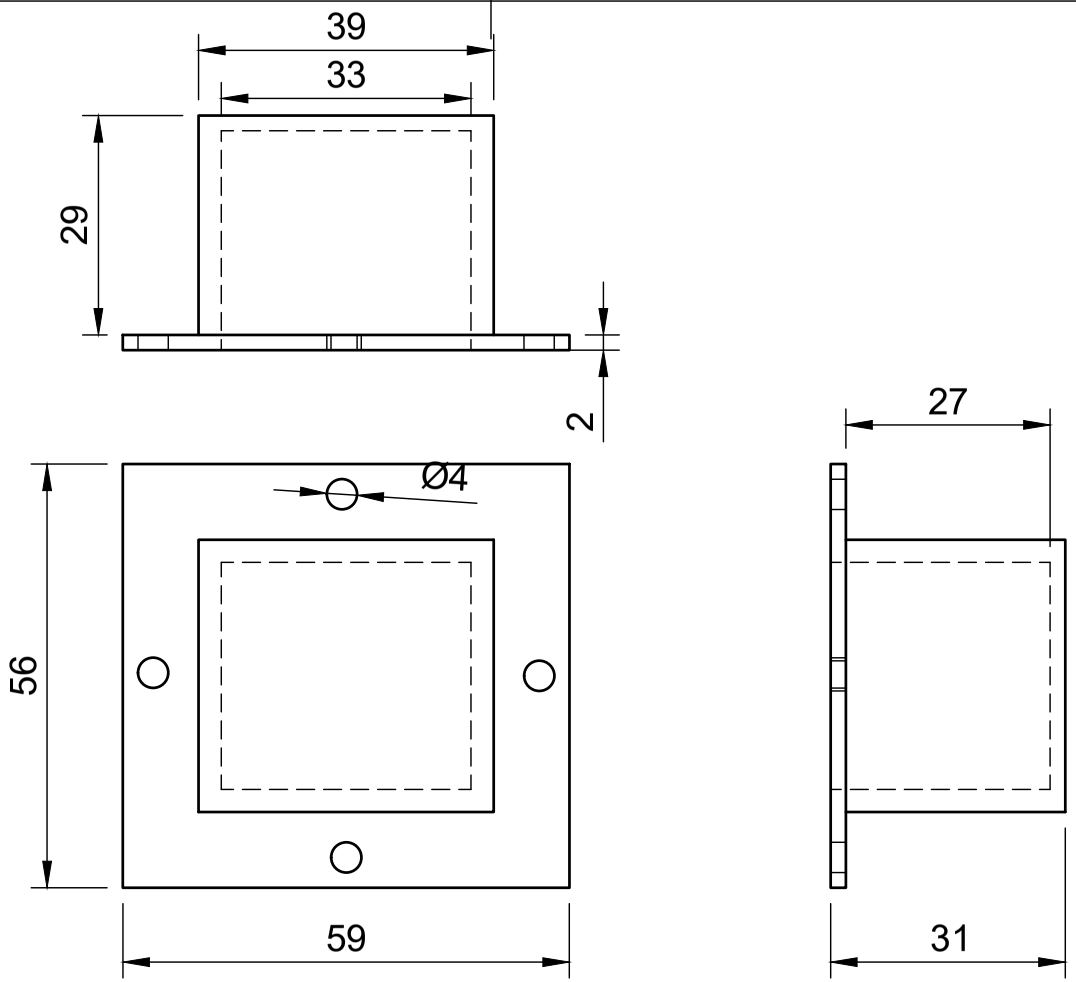


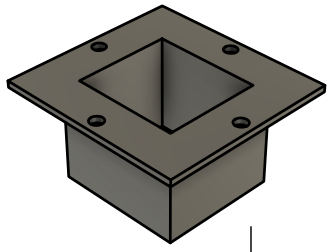
Dept.	Technical reference	Created by Gil Wagenaar 24/12/2024	Approved by
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		Title Rondelle reducer	DWG No.
			Rev. / Date of issue / Sheet 1/3

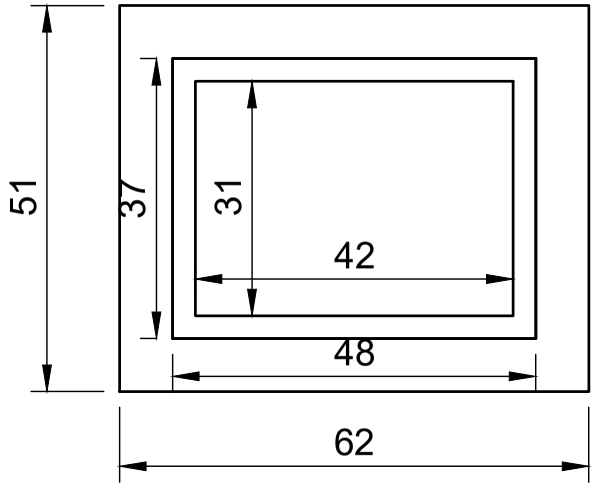


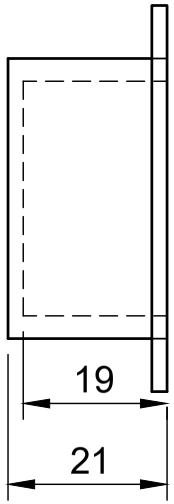


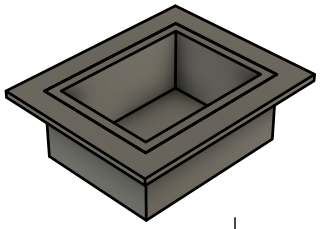
Dept.	Technical reference	Created by Gil Wagenaar 24/12/2024	Approved by	
		Document type Precious Plastic	Document status Scale 1:1	
		Title Switch integrator	DWG No.	
			Rev.	Date of issue / Sheet 1/1

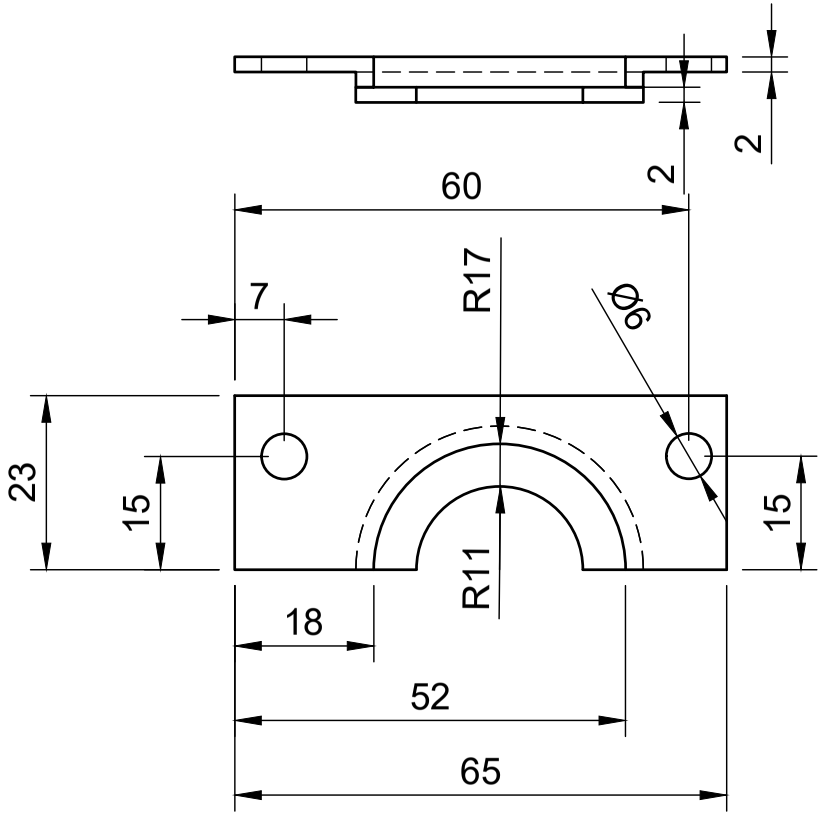


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		Gil Wagenaar 24/12/2024	
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			Rev. / Date of issue / Sheet: 1/1

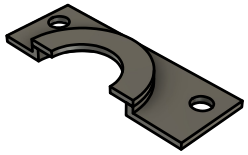




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		Document type Precious Plastic	Document status Scale 1:1
		Title Switch integrator Behind part	DWG No.
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		Document type	Document status Scale 1:1
		Title Switch integrator Front part	DWG No.
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