Open Source Recycling

Developing an Open Source injection machine for recycled plastic

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Master Thesis Integrated Product Design
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September 2022
Integrated Product Design
Delft University of Technology

In collaboration with Precious Plastic

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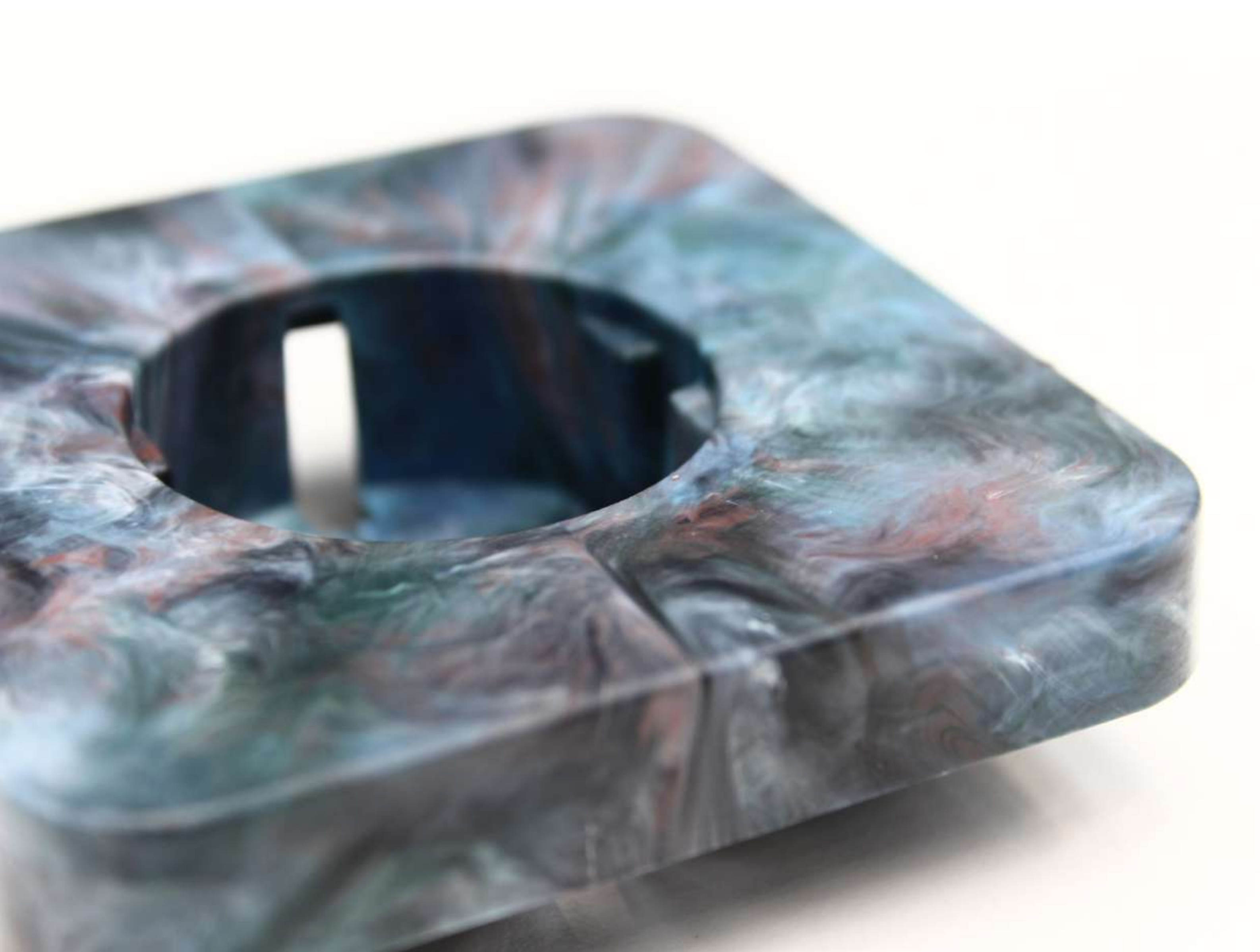

Acknowledgement

To everyone who was either directly or indirectly involved in this project, I would like to say ‘Thank You’.

To all the active members on the Precious Plastic Discord channel, for openly sharing your ideas, concepts and designs for me to inspire.
To all whom I interviewed and observed during the project, most notably Teun Zoetemeijer, Peter Bas Schelling, Friedrich Kegel and many other people.
To Carolina, Joseph and Yann, for their continuous support, expertise and advice as clients.

To everyone in the PMB at IDE, for teaching me how to operate practically every machine and their continuous stream of jokes.
To Bas, for his enthusiastic mentorship and helping me reflect on my ideas.
To Silje, for always supporting me in my ‘little crises’ and giving me her honest point of view.
To Jerry, for being the main enabler of the project and his supportive involvement as a coach

To everyone in Huize Ballenzicht, for distracting me with coffee, rooftop chillings and their enthusiasm for the project.
To my parents, brother and sister, for their continuous love and support.
To my friends, for the endless fun and their interest in my work.
And to Laura, for all her love and support.

Abstract

At this moment, the problem of plastic pollution does not need an introduction. Although recycling rates are slowly rising, plastic pollution remains one of the biggest threads to the global ecosystem. Especially in low-to-middle-income countries, industrial recycling systems are sparse due to their required investment.

Precious Plastic is an organization aiming to tackle plastic pollution, step by step. They openly distribute blueprints of recycling machines for anyone to use, which enables local recyclers to start their own informal recycling workshop. Over 40,000 people in 400 workspaces are connected through the Precious Plastic Universe, in which recyclers, designers and plastic collectors collaborate.

One of their machines is an injection machine, capable of injecting recycling plastic into a mold (figure 1). This machine is low cost, easy to build, and creates a beautiful marbled aesthetic that convincingly tells the story of the value of recycled plastic.

However, the design of the machine has quite a number of problems. Mainly, it requires an excessive amount of hand-force which exceeds human ergonomic limits. The machine also has a number of safety and buildability issues. Lastly, the machine does not easily enable tailoring due to its monolithic design. Next to the problems relating to the injection machine, Precious Plastic has noticed they often miss out on gathering improvements that builders implement in their machine. Due to this, valuable opportunities for development of the machine are not redeemed.

This project aims to tackle these problems through two design outcomes.

The first outcome is an online framework where users can tailor their injection machine based on their needs and upload their machine improvements. The concept aims to transform the current monolithic design sharing system into an inviting modular framework.

The second outcome is an advanced version of the injection machine. The goal aimed to develop, validate and document a functioning prototype of an advanced arbor injection machine. The design of the machine decreases the required input force by 70%, while producing a higher injection pressure and solving the prior safety and usage problems. The design of the machine was developed in active collaboration with a group of experienced machine builders and will be distributed throughout the Precious Plastic Universe.

In the end, both design outcomes contribute towards a more sustainable world, in which people are empowered through Open Source Hardware and plastic is in fact precious.

Figure 1: Injected parts in mold

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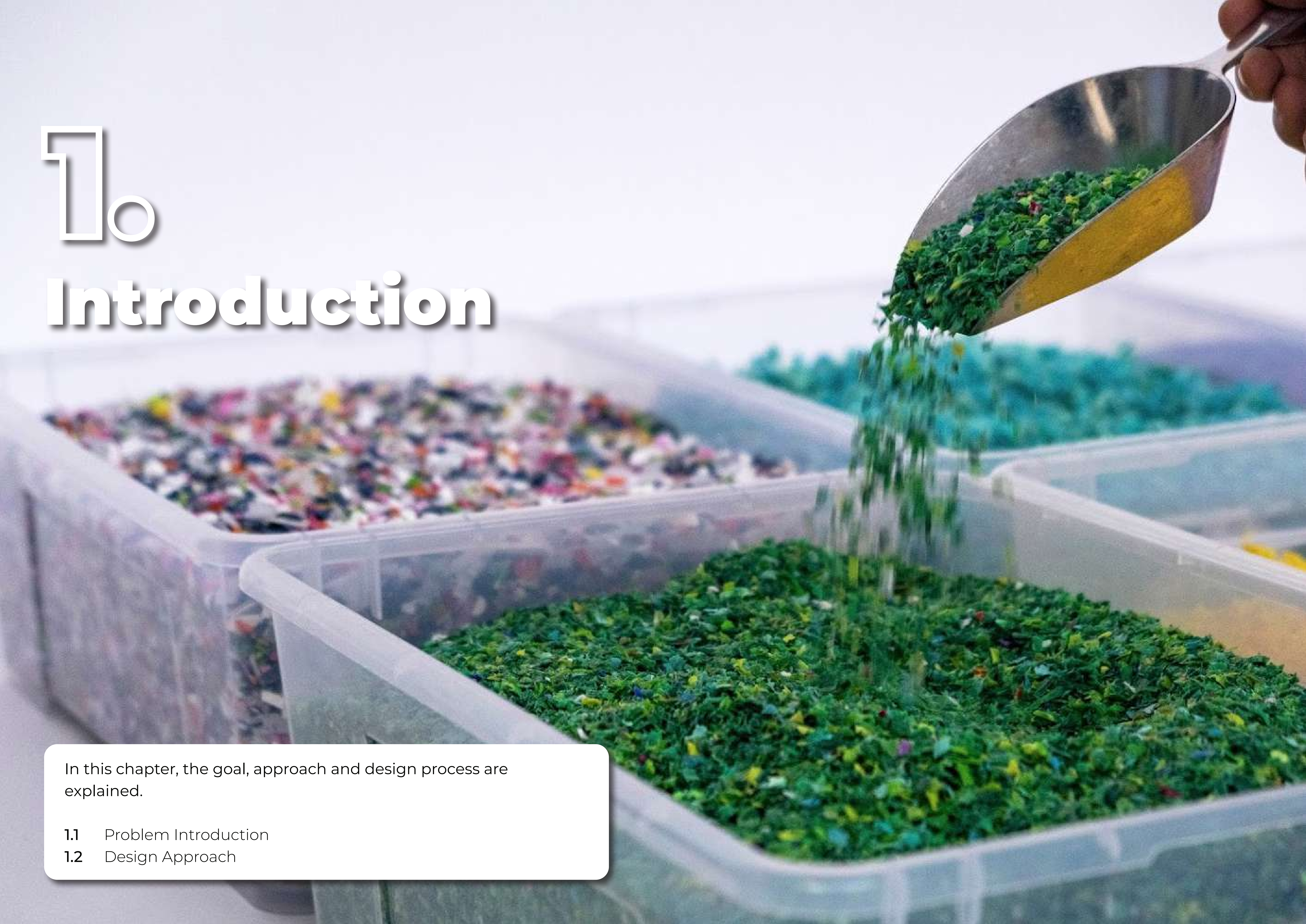


1. Introduction

In this chapter, the goal, approach and design process are explained.

1.1 Problem Introduction

Plastic pollution remains one of the largest global problems (Thompson et al., 2009). Although each year, more and more material is recycled in developed countries, a lot of plastic still ends up in landfills, in the ocean, or gets burned. This is especially true in Low-to-Middle-income-countries (LMICs), where sufficient recycling and collection systems are often non-existent.

Precious Plastic is an organization that designs multiple machines that are able to recycle plastic into new products. The blueprints and building guidelines for these machines are shared open-source online, enabling people all over the world to set up their own recycling workstations. Currently, over 40,000 people in 400 workspaces are connected through the Precious Plastic universe, in which recyclers, designers, producers and plastic collectors collaborate.

Their injection machine (figure 2) enables recyclers to heat and inject recycled plastic in a mold. In other words: a simple version of an injection molding machine. This machine is low cost, easy to build, and creates a beautiful marbled aesthetic that convincingly tells the story of the value of recycled plastic. It has become a popular machine within the Precious Plastic Community, and has been replicated many times around the world.

However, this machine is flawed in multiple ways. Mainly, it has an energy draining, time-consuming user experience for its operator. Besides the flawed machine design, Precious Plastic also faces another issue. As the existing injection machine is shared fully open source, the design has taken on a life of its own. Many builders have implemented hacks and modifications, often improving the core functionalities and solving existing problems of the machine. While this is encouraged by Precious Plastic, they often miss out on gathering the improvements and new features builders implement in their machine. Due to this, valuable opportunities for development of the machine are not redeemed.

Figure 2: Current Injection Machine

1.2 Design Approach

Design Approach

This project takes an integrated design approach based on the Double Diamond approach and methods described in the Delft Design Guide (Van Boeijen et.al., 2020). The Double Diamond approach divides the project into four phases.

Discover the problems, background and context principles that apply to the problem by researching the scope.

Define the problem area(s) that should be solved within the project (and which ones not)

Develop ideas and concepts that provide solutions to the problem areas.

Deliver a validated final design outcome.

Figure 3 provides a visual overview of where the different stages of the design process are presented in the report. Also, it highlights the applied methods and tools.

Methods and tools

Throughout the design process, a wide variety of design methods and tools were applied to methodologically perform research activities, deliver ideas and find solutions. Figure 3 provides an overview of these methods and specifies where they are applied.

The following methods were applied as overarching approaches throughout the project.

- **Co-Design** is an approach in which design work is executed in close collaboration with users, experts and non-designers. By actively working together with these actors, Co-Designing goes further than simply asking for input by enabling experts to fully immerse in the project. Its principles were mainly applied by close collaboration with machine experts within the Precious Plastic community.

- **User-Centered Design** is an approach that focuses on the user perspective to create a valuable outcome. Its principles were mainly applied through front-end user research and concept evaluations.

- **Design for Open Development** integrates the fundamental ideas of Open Source development into the design process. The approach opens up the design process by ensuring the public can study, modify, make, and distribute design content. Its principles were mainly applied in the development phase of the project.

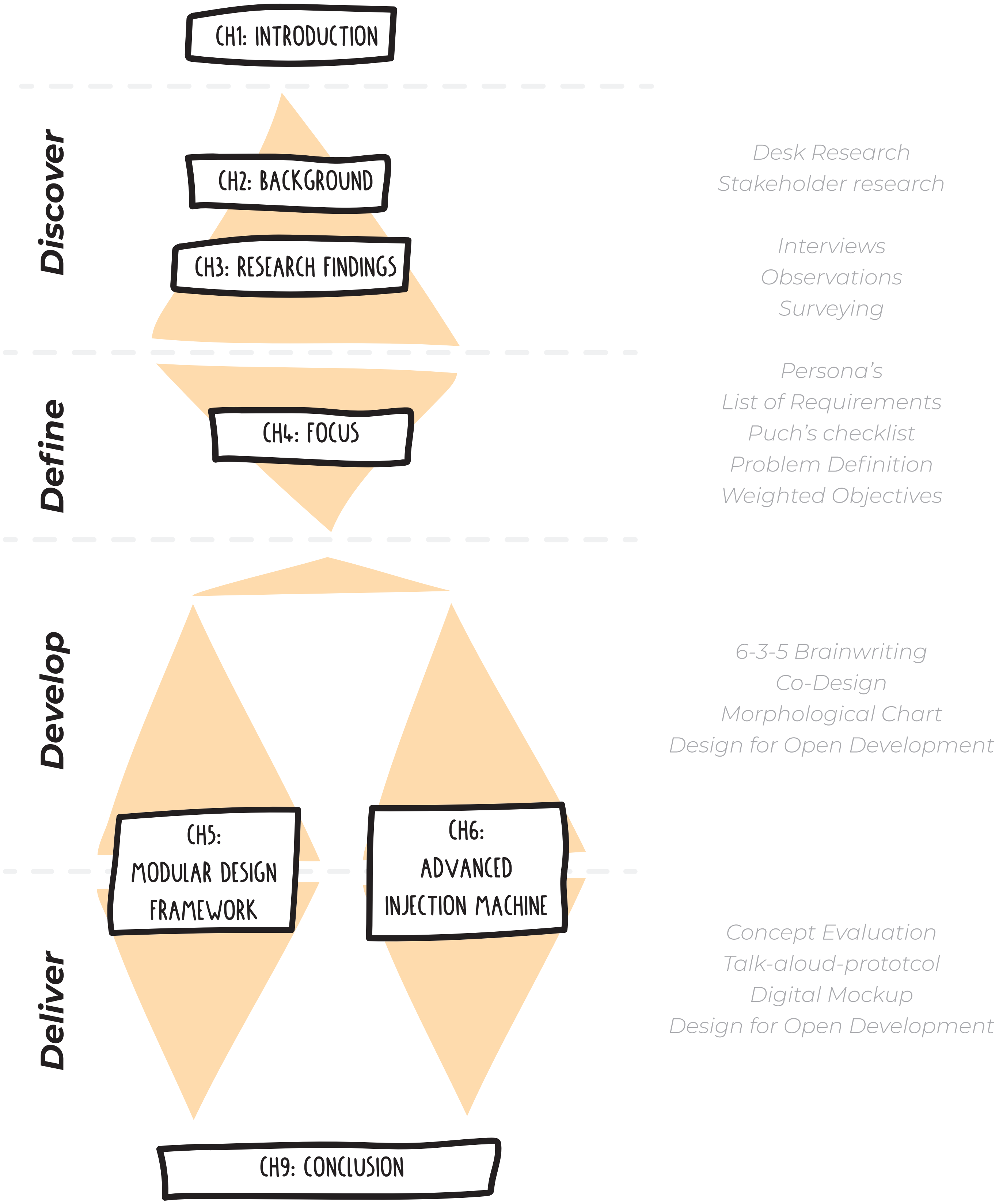
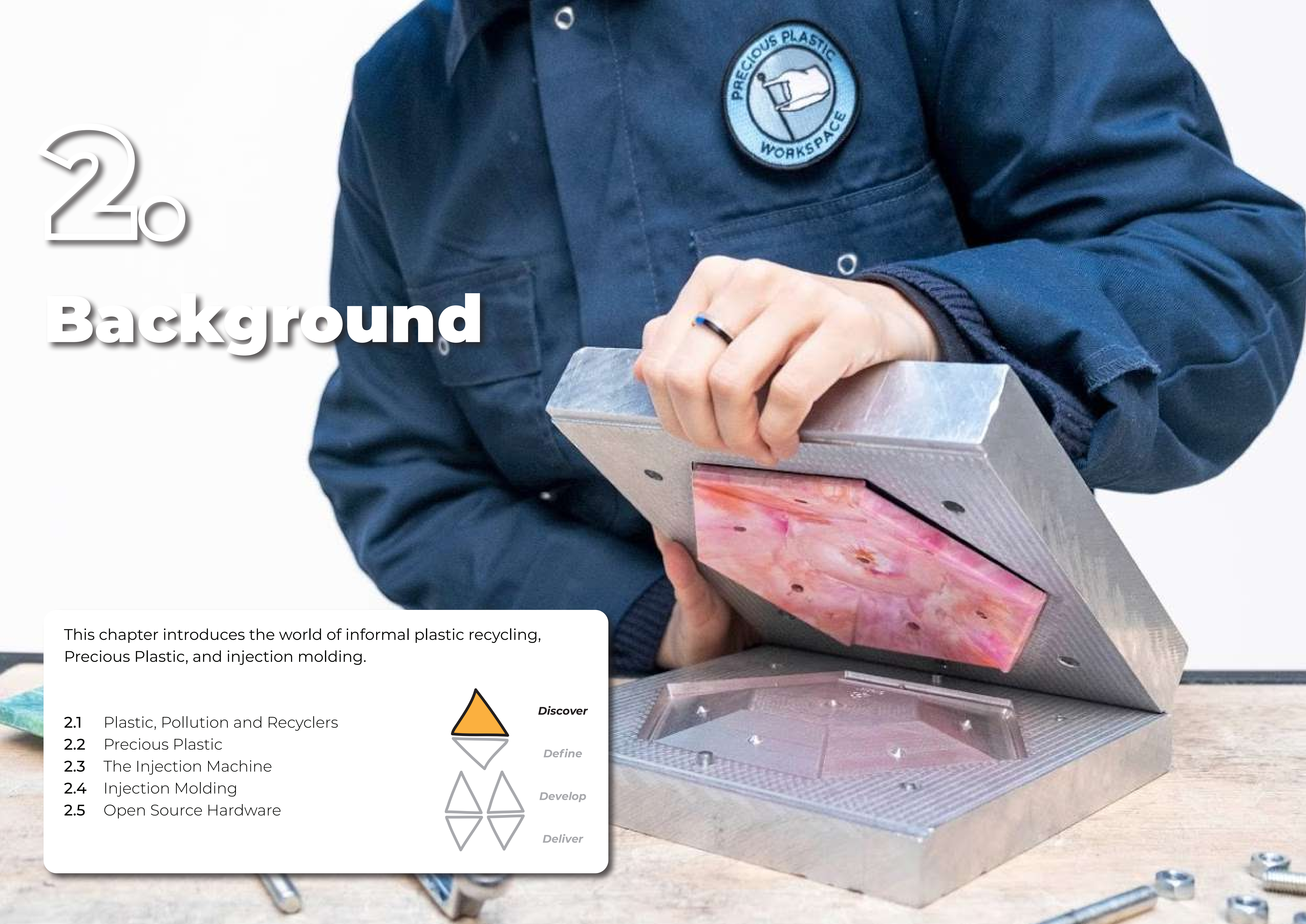


Figure 3: Projectstages and applied methods



2. Background

This chapter introduces the world of informal plastic recycling, Precious Plastic, and injection molding.

Discover
Define
Develop
Deliver

2.1 Plastic, pollution and recyclers

Introduction

By now, the global plastic problem does not require an extensive introduction. Plastics are used globally for a wide range of applications. As most plastics aren't biodegradable, the material accumulates in landfills or the natural environment due to poor waste management (Barnes et. al., 2009). Besides the obvious material-loss this linear end-of-life model ensues, plastic pollution has devastating effects on wildlife and global health (Chae et.at., 2018).
As this project aims to make a positive impact on global plastic pollution, it's key to understand the relevant context and characteristics of plastic pollution and recycling.

Context

Although virtually every country on earth generates plastic waste, the extent to which it is properly managed and recycled differs by a lot. Of the top 20 countries that produce plastic waste, 16 of them are Low-to-Middle-Income Countries (LMICs) where fast economic growth leads to a trailing waste management infrastructure (Jambeck et.al., 2015). This is mainly because effective waste management is expensive: It can take up to a third of municipal budgets (Karak et. al., 2012). Therefore, poor waste management features especially in low income countries, where up to 90% of waste generated gets disposed in unregulated dumps or is publicly burned (Kaza et. al., 2018, figure 4).

Besides financial hurdles, municipalities in LMICs lack skilled workers and advanced technology to set up circular waste management systems on a large scale. Instead, material recovery often relies on informal workers who collect and recycle up to 20% of generated waste (Kaza et.al., 2018). It is estimated that more than 15 million people earn a living in the informal waste sector, which is still increasing in size (Sida, 2004 & Medina, 2010). They are often a vulnerable group consisting of women, children, unemployed and migrants (Medina, 2010).
In these contexts, Precious Plastic machines can both be a part of the solution to the plastic problem, and making a societal impact as well.

Plastic 101

Plastic is one of the world's most diversley applicable materials. It is used from consumer products and medical applications to construction and clothing. To understand how to recycle it, a better comprehension of the material is needed.

Plastics are generally either a thermoset or a thermoplastic: The former cures irreversibly into a fixed structure, the latter can be molten and reshaped. Around 80% of the plastics around are thermoplastics. This is a good thing, as they are much easier to recycle. On an atomic level, plastics are long chains of basic atomic building blocks called monomers. These strands are entangled into a spaghetti-like structure, which gives the material quite a good base strength and durability. This makes plastic a popular material to make diverse products with.

Figure 4: Burning waste pits (picture by Eddy Mbuyi/Oxfam)

Recycled plastics

Recycling plastics is one of the obvious ways to prevent its environmental burden and is a pillar to the circular economy. Starting around 1980, plastic recycling rates in Europe have steadily risen up to 35% in 2020 (Plastics Europe, 2021). Of the plastic recycled, over 97% was recycled mechanically, meaning the remelting of collected plastic into new items (Alassali et.al., 2021). The other 3% is recycled chemically, which is currently not viable due to high cost and energy use (Manžuch et.al., 2021).

There are some limitations to mechanical plastic recycling. To get the best quality, plastics need to be separated by color and polymer type. Especially the latter is key, as mixing different types of polymers renders a weak and unreliable material (Rageart et.al., 2017). Apart from this, plastic is a material that will insurmountably degrade. During the production and usage of a plastic product, factors such as thermo-mechanical wear and photo-oxidation cause the material to degrade on a chemical scale (Schyns et. al., 2021). This leads to polymer shortening and tiny impurities on a chemical level, which causes decreased qualities once the material is recycled.

Key takeaways

- Most plastic waste is produced in Low to Middle Income countries as a result of non-existing or poor waste management systems.
- In these countries, plastic recycling mainly relies on workers in the informal economy.
- Workers in the informal economy are a diverse and vulnerable group, many of them women.
- Plastic is a tricky material to recycle, but does have outstanding mechanical properties.

2.2 Precious Plastic

Background

Precious Plastic is an organization that aims to reduce plastic waste. Through the creation of an alternative recycling system, they enable people anywhere in the world to individually start recycling and help solve the plastic waste problem. This recycling system is supported by open source recycling machines, such as shredders, extrusion machines, injection machines, sheet-presses and compression machines.

The organization was founded in 2013 following the graduation project by Design Academy student Dave Hakkens. Starting with a team of around 12 people, the initial recycling machines were gradually improved. The designs were released open-source online and build by people around the globe. In 2018, work started on the Precious Plastic Universe, which transitioned the concept into a platform-based system. This was released in 2020 and entailed among others a virtual map and the bazar (figure 5).

Figure 5: Precious Plastic Members

Key players and features

People and organizations create spaces that make up the Precious Plastic Universe. These spaces are interconnected and dependent on each other to function well. They form local networks that together create the alternative recycling system.

On the right, the relevant system components and their roles are explained.

At **Collection Points**, plastic waste is gathered from the local neighborhood, businesses and organizations.

In **Workspaces**, plastic is transformed from waste into valuable resources. These can either be raw materials or fully finished products made from recycled plastic. This is done using one or multiple recycling machines.

Community Points function as a hub to connect people and parties that are interested in plastic recycling.

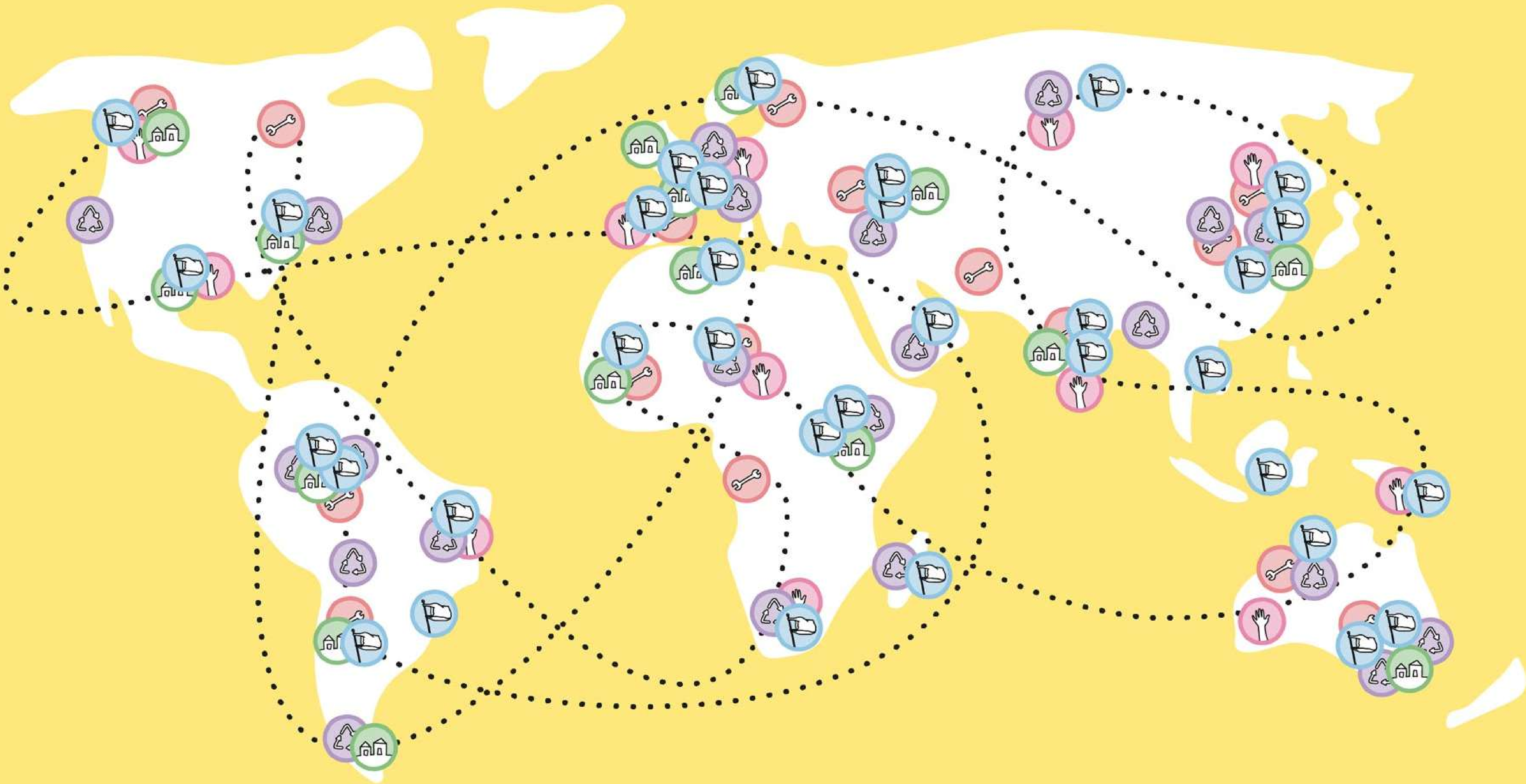
Machine shops are places where parts, assemblies and molds are manufactured. They provide the technical support within an local recycling network.

Individual **members** support the recycling network in some way, mostly through plastic collection and purchasing products. They usually don’t own or operate recycling machines.

The **online bazar** allows Precious Plastic members to sell machine parts and assemblies to each other. This way, expensive parts such as molds can be reused and costs can be lowered.

The **online map** enables Precious Plastic members to look up local collection points, workspaces and other members.

The Precious Plastic **core team** is a group of 7 people that manage and develop the Precious Plastic organization globally.



Precious Plastic Machines

There are two categories of machines, either basic or pro. Some machines only have either a basic or pro version, for others both versions are available. Below, each version is briefly highlighted (figure 6):

- **The shredder** (basic & pro) cuts up plastic waste and yields small pieces that can be used in the injection, extrusion and sheetpress.
- **The injection machine** (basic only) heats up plastic flakes and enables the user to inject them into a mold. It is mostly used for small precision products.
- **The extrusion machine** (basic & pro) takes in plastic flakes and outputs a consistent, mixed flow of extruded plastic. It is well suited to make extrusions, granulated pellets or filament.
- **The sheetpress** (pro only) is able to compress plastic into a flat sheet. These sheets can then be used in construction, laser cutting or as raw material.
- **The plastic scanner** (under development) which was developed in 2021 by IDE alumnus Jerry de Vos (who is also a coach in this project), uses infrared spectrometry to determine the plastic type.
- **The plastic washer** (under development) enables recyclers to clean plastic before it gets turned into a new product. This improves material quality by removing impurities.

Figure 6: Basic Machines

Mission, values and standards

Precious Plastic's main mission is to reduce plastic waste globally. To do this, they see individual people as the key element to reach this goal. Therefore, the organization is set up like a grass-roots movement, counting on the power of small steps made by millions of people. Their main way to reach this goal is by sharing and developing the open source machines described before. Besides actually recycling plastic, these machines are also used to educate people worldwide about plastic and plastic pollution, generating momentum and awareness to solve the waste problem.

The individual recyclers form an active community in which machine designs, best practices and other valuable information are shared. This has produced a large variety of other plastic recycling machines, which are shared next to the original designs. To somewhat guide the development of these machines, Precious Plastic have created a set of design values that create a foundation for designing new things within Precious Plastic.

Standard components
To make sure the Precious Plastic machines are buildable anywhere on the planet, the use of standardized and accessible materials is crucial. This way, the machines are as replicable as possible.

Modular design
As build contexts are often very different depending on their location, modular design ensures builders can use different components to suit their context and needs. Therefore, tight integration of specific components within the design should be avoided.

Design for disassembly
Often, machines are build in one place and transported for use in another. Therefore, the design should be optimized for easy dis- and reassembly.

Safety components
One of the goals of Precious Plastic is to teach people about plastic recycling. This means that wherever possible, the functional parts of the machine should be visible as much as possible. The only components that should be covered are hot elements and electric components to ensure safety.

Results to date

In 9 years, Precious Plastic has grown into a substantial network of recyclers with serious impact. Below, a summary of the main results can be found

- 500+ recycling workspaces in 100+ countries working with Precious Plastic
- 380+ tons of plastic recycled in 2019
- € 2m global annual revenue from all Precious Plastic workspaces
- € 5m recycling workspaces in 100+ countries working with Precious Plastic
- € 200k processed on the Precious Plastic Bazar in 2020
- 15m views on Youtube
- 800k annual visitors on our websites
- 90k users on the forums (discontinued)
- 7k users on the Community Platform
- 10k users on Discord
- 100k downloads of Precious Plastic kits

Key takeaways

- Precious Plastic is a network of individual recyclers sharing machine designs, knowledge and materials to upcycle plastic waste
- Precious Plastic sees individual people as the key element to in reducing plastic waste
- Standard components, a modular design, design for disassembly and use of safety components are cornerstones of Precious Plastic approveddesign.

2.3 The injection machine

Functionality and use

In 2013, Precious Plastic released the first version of the injection machine. Besides the Sheetpress and the Extrusion machines, it is one of three PP machines that transform cleaned, sorted and shredded plastic into new plastic parts. Compared to other machines in Precious Plastic's inventory, it is relatively cheap to build at around 131€. Quite a few parts can be found in scrapyards (see BOM in figure 7) and no heavy machinery such as electrical motors are required, which drives down the price.

BILL OF MATERIALS / INJECTION

DESCRIPTION	MATERIAL	DETAILS	QUANTITY	WHERE TO GET IT	REMARKS	PRICE
Machine parts						
Strip	Steel	20x3mm	18cm	Scrapyard	-	2
Strip	Steel	30x4mm	152.5cm	Scrapyard	-	5
Roundbar	Steel	26x680mm	58.5cm	Metal shop	accurate and smooth from the inside	10
Squaretube	Steel	30x30x3MM	569.1cm	Scrapyard	-	30
Tube	Steel	34x26x4MM	53 cm	Scrapyard/ Metal shop	-	1
Angle profile	Steel	30x30x3mm	16cm	Scrapyard	-	2
Wooden base	Wood	18mm		Leftover	Can also use another material	0
Sheetmetal	Steel	1mm		Scrapyard	-	5
Electronics						
PID Controller	-	0-400 Degree	2x	Ebay	-	20
SSR	-	2-24 V	2x	Ebay	-	8
Thermocouple	-	Type K	2x	Ebay	-	15
Bandheater	metal	35x45MM	4x	Ebay	-	25
Power switch	-	220V	1x	Scrapyard/Hardware store	-	3
Led indicator	-	220V	1x	Hardware store	-	3
Powercord	-	30x30x3mm	5M	Scrapyard/Hardware store	-	2

TOTAL 131.00€

Price varies depending on where you live

Figure 7: BOM Current Injection Machine

Design breakdown

Figure 8 shows an exploded view of the injection machine. Its main functionality is to melt plastic and to allow the user to press it into a mold. To do this, plastic is conductively heated up to its melting temperature by band heaters. Note that no reciprocating screws are used to melt and mix the plastic, which is common in most industrial injection machines. As the plastic remains mostly at rest during melting, the plastic grains remain intact and later form a beautiful marbled appearance in the produced part.

The shredded plastic can be inserted into the heating barrel through the hopper. Once it's melted, the user lowers the lever, which presses the plunger down in the barrel. The force exerted on the melt forces it down through the nozzle into a mold. Once the plastic in the mold is solidified, the final part can be removed.

The temperature PID controller functions as the brain of the machine. It allows the user to input a SV (set value), to which the controller will match the PV (point value) measured at the thermocouple. Depending on the plastic type, they are typically set to around 200C.

The band heaters fit around the barrel and transforms electrical power into heat. The current design uses 3 heaters for melting the barrel, and an additional one to heat up the nozzle. This is done to improve material flow and prevent clogs. Attached to the band heaters, thermocouples function as thermometers to measure the temperature of the assembly.

Two Solid State Relays (SSR) function as a bridge between the PID controllers and band heaters. They convert the low-voltage PID signal into a high-voltage current to the band heaters.

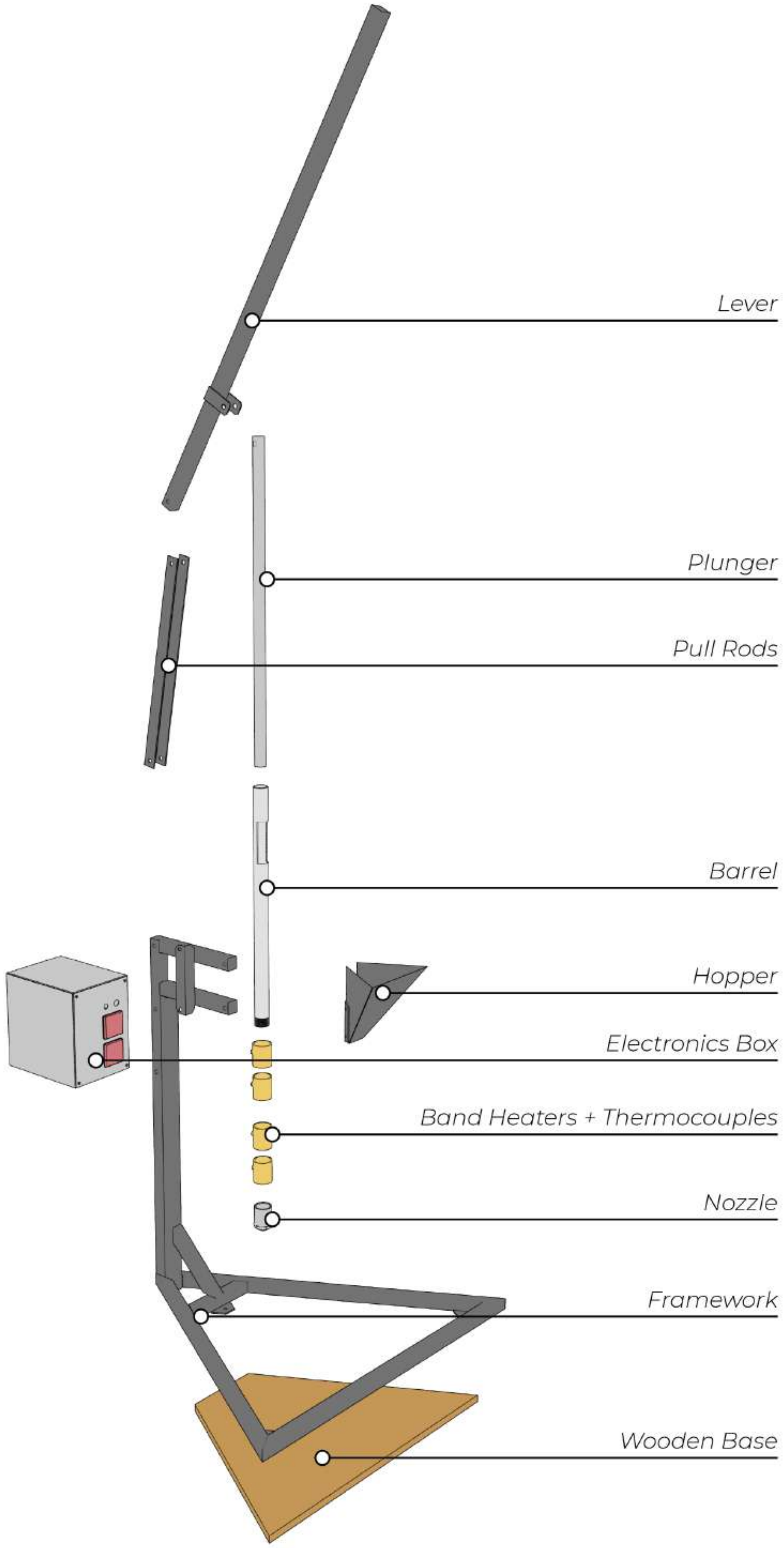


Figure 8: Exploded view Current Injection Machine

Applications of the machine

Figures 9 to 15 show examples of parts made with the injection machine.

Figure 9 to 15: Examples of injection molded products

Key takeaways

- The current injection machine is one of the simpler recycling machines in Precious Plastic's inventory.
- The machine is used to make small, detailed objects.

2.4 Injection Molding

Industrial injection molding

Injection molding is one of the key manufacturing processes on the planet, as injection machines can be used to create a wide range of complex parts.

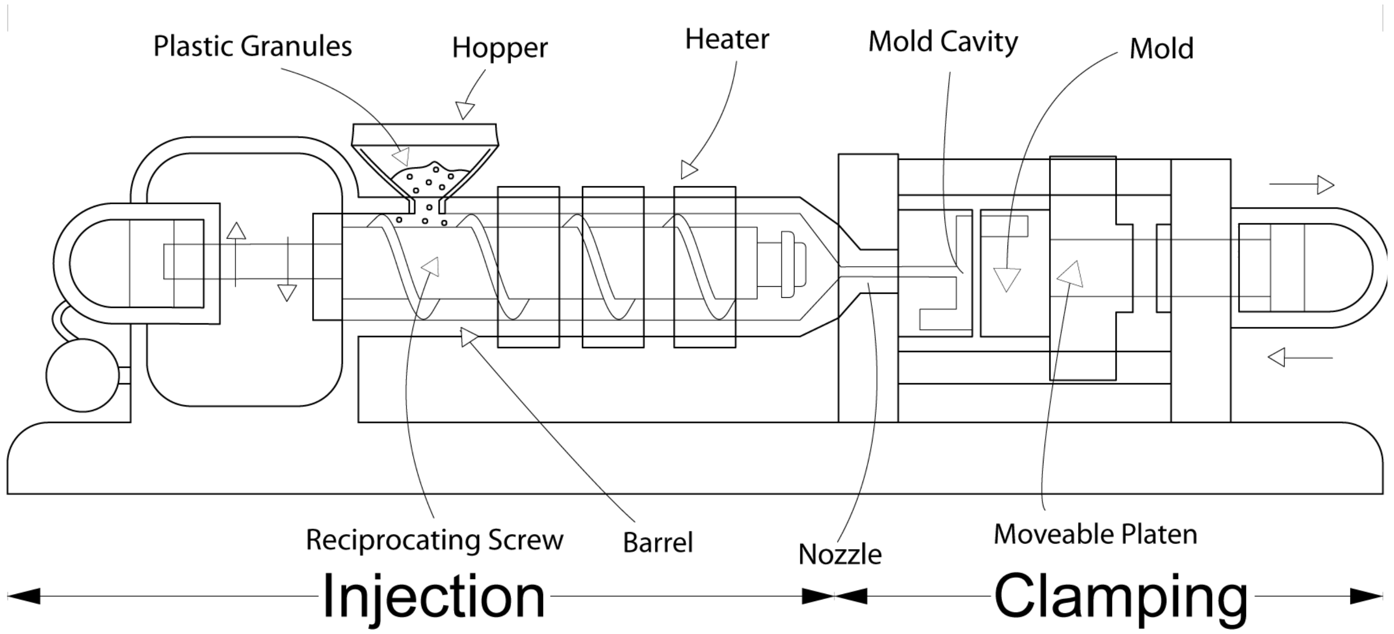
In principle, injection molding is simple:

1. Heat up material
2. Inject material in a mold
3. Let the material cool
4. Remove the part from the mold

In reality, it is however quite a delicate process. Industrial injection molding machines take care of this process and make it reliable, fast and efficient. The visual in figure 16 shows the basic modules of an industrial injection machine.

The injection unit melts and mixes the plastic and pushes it into the mold. Its main components are a reciprocating screw, a cylindrical barrel and band heaters. The reciprocating screw is a specially engineered part. It is made so the available space between the screw's core and the outside of the barrel gets smaller towards the end of the screw. This compresses the plastic and mixes it around thoroughly. At the end of the reciprocating screw, the distance between the band heaters and the screw is so little that the plastic heats up quickly and uniformly.

Figure 16: Injection Molding (graphic by Brendan Rockey)



To inject plastic into the mold, it needs to be heated up to its softening temperature or glass-transition temperature in semi-crystalline plastic (Tempelman, 2014). These temperatures differ per plastic type, but generally fall between 180 and 260 C° for most common plastics.

Once enough plastic is fully melted, it is ready for injection. By pushing the reciprocating screw forwards, it acts similar to the plunger of a bicycle pump and forces the melt into the mold. This mold usually consists of two mold halves that form a cavity in the form of the desired plastic product. Upon rushing in, the molten plastic pushes out the air within the cavity through very thin vent channels manufactured in the mold halves.
To properly fill the cavity, the plastic is injected at high pressures. To make sure the mold halves keep together during the injection stage, a clamping force firmly pushes the mold halves together.

Next, the material will start to solidify. The stages and pressures in this process are visualized in figure 17. Once the mold is completely filled with plastic, the packing stage starts. As melt starts to cool down and solidify, it begins shrinking. Therefore, the pressure on the melt is maintained as it continuously gets 'topped off' to counteract the shrinking. After some time, the solidification reaches the sprue, which is the part of the cavity where the plastic first enters the mold. Once this is solid, the injection pressure is released as no more plastic can enter the mold at this time. Once the plastic is cool enough to maintain its shape, it can be ejected. This is done through ejector pins, which force the shrunk part off the mold half. The molding process is now complete and can be repeated.

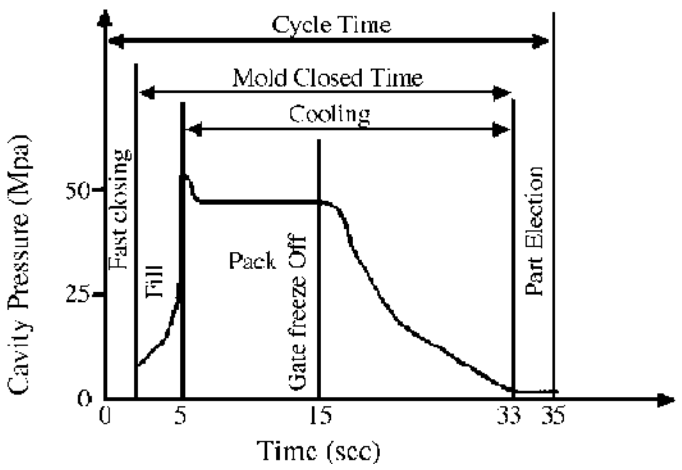


Figure 17: Injection Molding stages

2.5 Open Source hardware

OSH in general

The idea of 'Open Source' originated in computer software. In this field, a hugely successful project is the operating system Linux. This showed the potential for companies to harness the power of open source development by capitalizing on a community sharing and improving ideas. Gradually, this concept made the jump to the world of hardware, where the self-replicating RepRap printer is the most famous example (figure 18).

In 2020, a DIN SPEC was written to define a standardized definition of Open-Source hardware and to break it down into design criteria (Arndt et. al., 2020). Their definition of open source hardware is as follows:

"Hardware for which a free right of any use belongs to the general public and whose documentation is completely available and freely accessible on the Internet"

Arndt et. al., 2020

The open sharing of information and designs results in faster innovation and expert contribution (Goldberg et.al., 2019). It also enables the builder of an open source item to add personalization to the product. This does come with additional requirements to the project, as users have the right to study, modify, make, and distribute the information, which also holds for commercial uses (Bonvoisin et.al., 2017a).

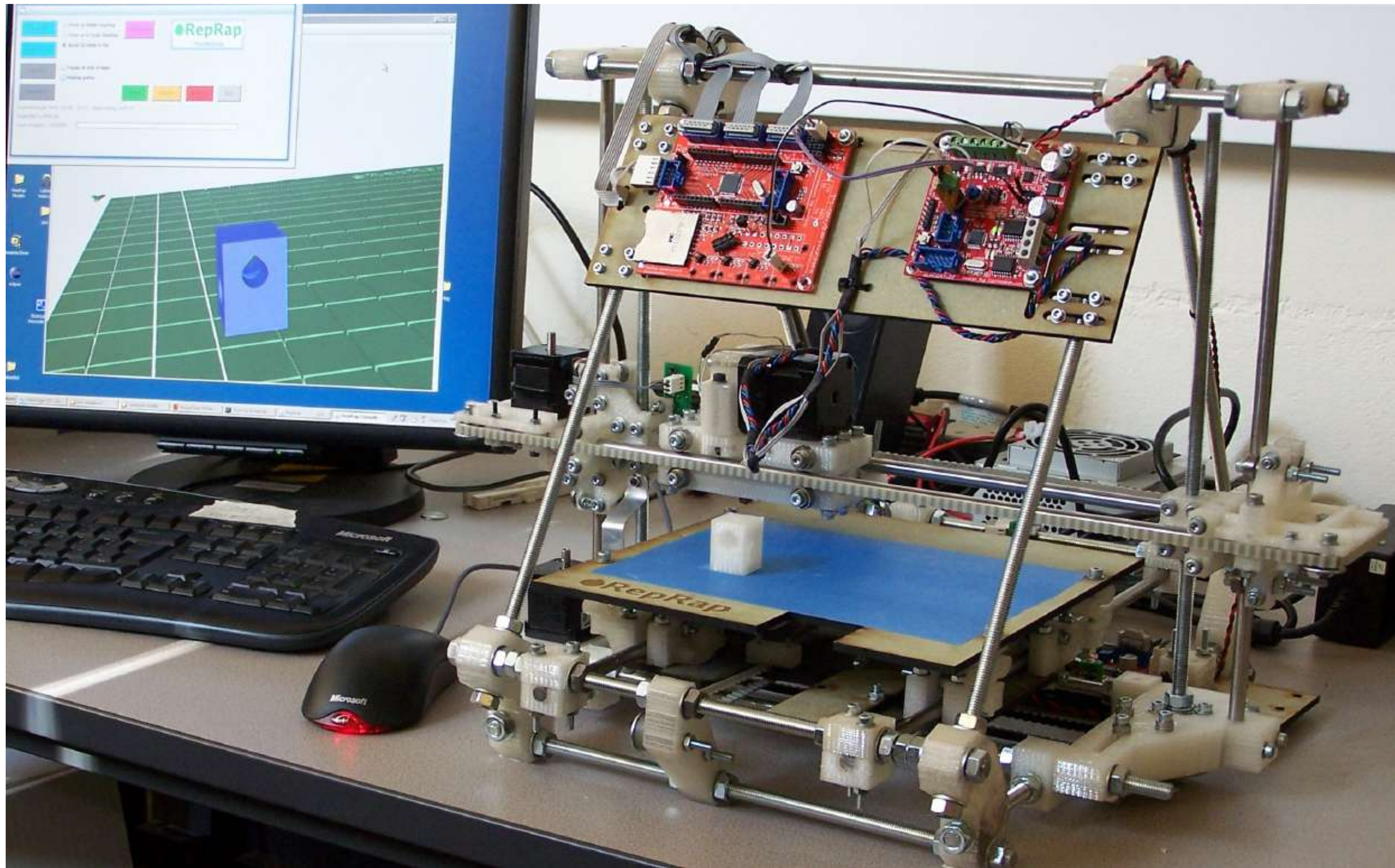
One big misconception about open source hardware is that the process is automatically open and collaborative. In fact, there are two main approaches to open source hardware (Bonvoisin et.al., 2018):

1. Private development, in which a product is privately developed and later shared openly with the world.

2. Open development, in which the product is developed openly with and the design converges into a stable version.

The large majority of OSH products remains the result of private development.

Figure 18: RepRap printer (picture by RepRap)



OSH at Precious Plastic

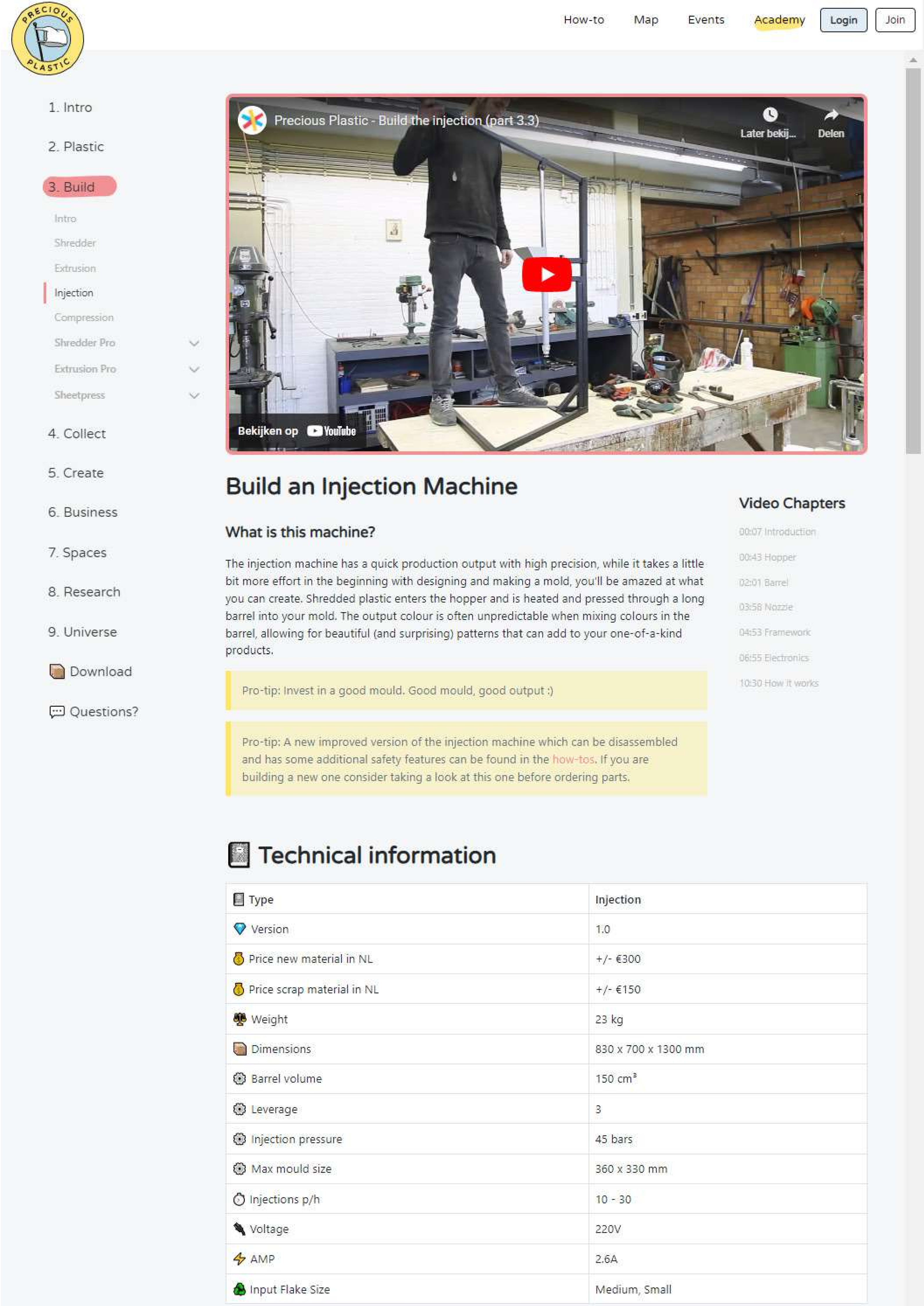
Open source hardware is at the core of Precious Plastic's activities. The key platform in the Precious Plastic universe is their community website, which is set up as a guide to everything you might need as a recycler (figure 19). Here you can find, among others, machine blueprints, general knowledge about plastic, advice on running a business and ongoing open research. There are download kits available, which recyclers can download to get all necessities for starting a workshop such as a bill of materials, blueprints for the parts and assembly and CAD files in multiple formats. The website also includes links to building tutorials on YouTube, where the building process is explained step by step.

Precious Plastic mostly follow a 'private development' approach, in which designs are developed by the core team and later shared openly online. However, the development process is not completely private: The website also features a tab where individuals can share their redesigns, modifications and improvements on the design. These can be seen and implemented by anyone and are implemented in newer official machine versions from time to time.

Key takeaways

- For Open Source Hardware, users have the right to study, modify, make, and distribute hardware.
- Open Source projects are often privately developed.
- The hardware shared by Precious Plastic was originally developed privately, but they are searching for a better way to openly develop their machines.

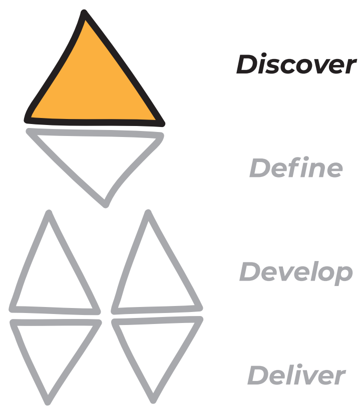
Figure 19 (right): Screenshot of Precious Plastic community webpage



3.

Research Findings

This chapter presents the key research findings of the initial analysis of the project scope.



3.1 Research approaches

Research Questions

To deliver an end-result that is desirable, feasible and viable, research activities were conducted on the current injection machine, its use cases, the building process and other relevant themes. This research yielded key insights that could be used in the design process. The main research questions within this project are as follows:

- **How is the current injection machine being used?**
- **What are the barriers in the building process?**
- **What is the impact of the local context on the machine design?**
- **What are the main legislative factors to consider?**
- **What are the best practices in designing Open Source Hardware?**

Research Approaches

To formulate answers to the research questions, 5 different research approaches were taken. As the insights from these approaches are quite diverse and overlapping, they are discussed in 6 themes in the following sections. On the right, the research approaches are presented. Figure 20 gives an overview of how the insights in each theme originate in the research activities.

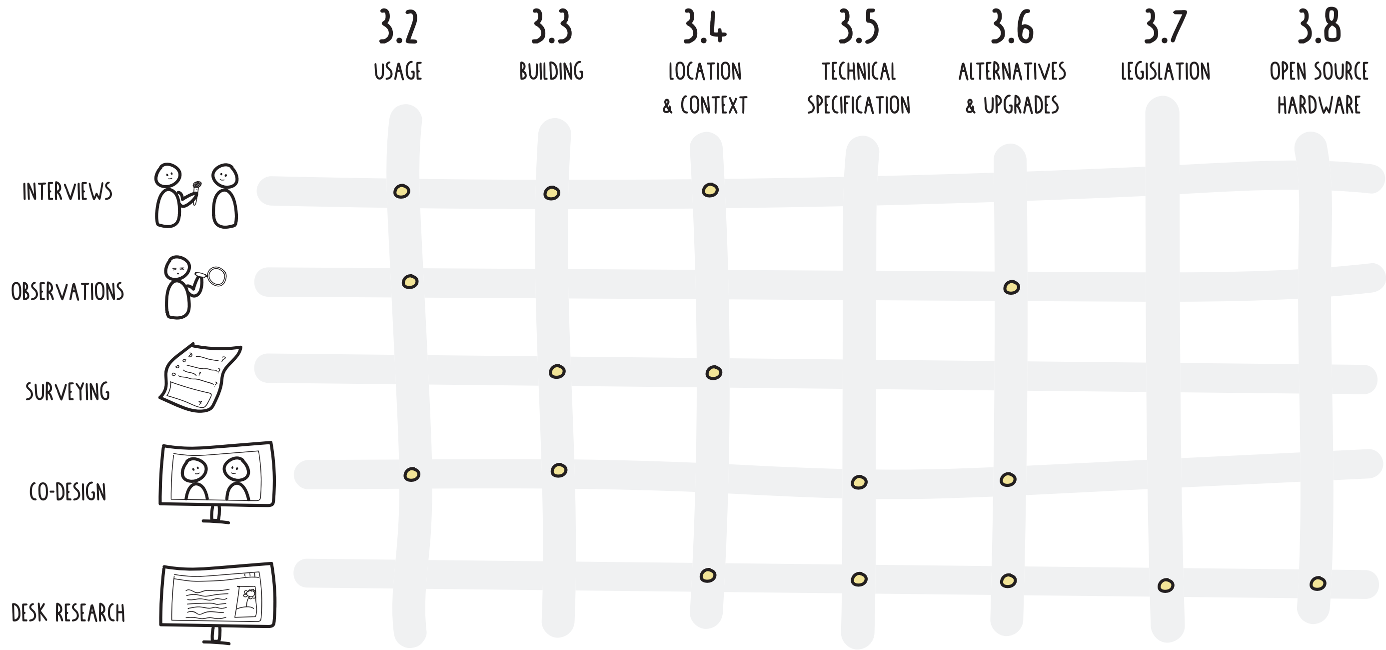


Figure 20: Research Overview

Interviewing machine builders and users in different contexts online. In total, 5 online interviews were conducted with machine builders. They were specifically selected to aim for a good spread among high, middle and low income countries. The following 5 injection users were interviewed:

- Mitchell and Debrah, working at Limpi in Curacao
- Suleiman, the founder of Chako Recycling on Zanzibar
- Ramdhan, a machine builder and user in Indonesia.
- Blake, a machine builder working in Melbourne
- Guenther, a machine builder working in Barcelona

Observing the usage of the injection machine in their context. To this end, 2 observations were done with Teun from Plasticworkshop in Haarlem and Peter-Bas from PBS machinery in Zwolle.

Surveying the accessibility of building materials and resources on different contexts online. To evaluate the accessibility and buildability of both the Precious Plastic injection machine and popular alternatives, a survey was sent out to every workstation with an Injection Machine found on the Precious Plastic map. Also, it was shared on the Precious Plastic discord server (900 members) and the Slack (300 members). The raw data can be found in Appendix A.

Co-Designing on Discord with expert machine builders. During the research phase of this project, a Discord channel was created on the Precious Plastic server to discuss the development of the injection machine. This channel has grown into a channel with 39 injection machine users sharing ideas, design directions and insights.

Desk research on various topics. This included the Precious Plastic online network, their YouTube tutorials and reading research papers.

3.2 Usage insights

Usage Experience

To get an overview of using the current injection machine, the usage procedure of Teun from Plasticworkshop in Haarlem was mapped. Teun has made his machine a few years ago and currently gives workshops to local schools and children parties (figure 22).

He also has a team of people in his neighborhood in Haarlem who help him out in collecting plastic.
Figure 21 shows an experience map, which gives an overview of the steps in the process and highlights the experience of the user.

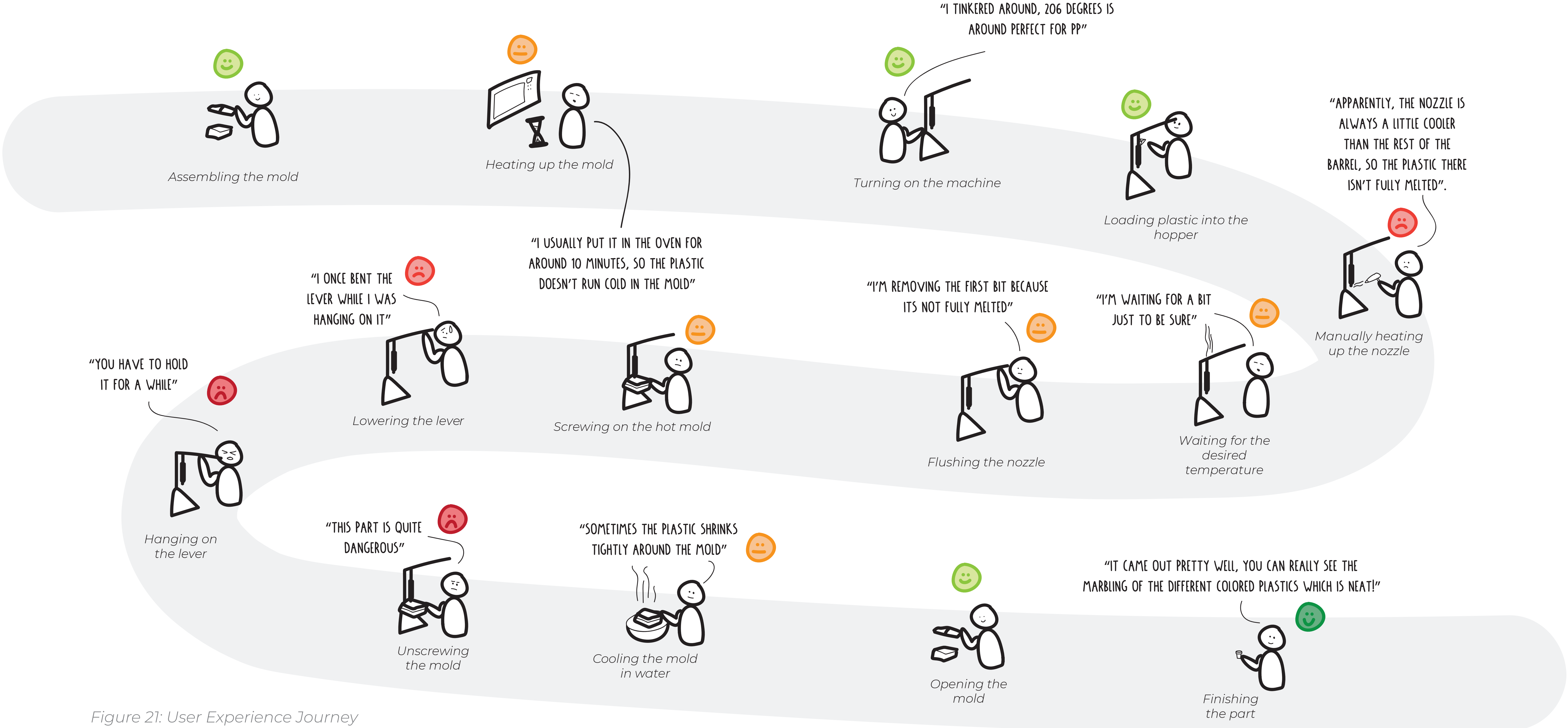


Figure 21: User Experience Journey

Below, the insights from Teun's experience map were summarized and supplemented with insights from other observations and interviews.

- **The current method to apply force is insufficient.** Every interviewed user mentioned they need to use their full body weight to inject plastic, which is especially inconvenient when needing to inject multiple parts. Ramdhan: "Injecting [the plastic] is quite heavy, I actually bent the lever a bit while hanging on it".
- **The barrel volume is quite small.** Teun: "The volume is a serious limitation: one plant-pot of around 60 grams can easily be made, but the second one definitely not" The small barrel volume firstly limits the part size, but also has another implication: To repeatedly use the machine, the user continuously needs to refill the barrel and wait for the plastic to melt, which extends the cycle time of the part by a lot.
- **Attaching the mold is not user-friendly.** The current method of screwing the mold onto the injection nozzle is a tricky process, as it needs to happen fast while temperatures are high. Survey Respondent 1 from France writes: "It's hard to attach the mold, easy to get burnt, very stressful because if you are not fast enough the nozzle can get clogged with plastic"
- **The machine is not safe to use, for a range of reasons.** The barrel and mold can reach temperatures up to 250 C°, which can easily cause burns if users are not careful. Also, plastic flakes tend to accidentally fall on the exposed band heaters, which releases unhealthy fumes users breathe in. Lastly, the machine is a bit unstable, which is especially dangerous while users use their full body weight during injection.
- **The injection process is not time-efficient.** A lot of time is spent waiting on parts to either heat up or cool down. Suleiman: "Sometimes, people turn on the machine and then start working on other projects. Then they forgot they turned it on, which creates a big mess". Therefore, it is in its current form not viable as a production tool.
- **The machine does not produce consistently.** Ramdhan: "It is difficult to get a consistently well filled mold, as you have no idea what is actually happening in the machine"
- **Having a transportable machine would be a big plus.** Teun: "I sometimes take [the injection machine] to schools, but it barely fits in my car"

Figure 22: Teun's Injection Machine

Use Case Personas

By analyzing the responses of the interviewees, two prominent use cases emerged. On one side, there is the Industrial use case. Machine users in this use case aim to run a workplace that is able to recycle as much plastic as possible and selling high quality products. Their key preference in an injection machine is having an advanced, highly automated machine with a quick cycle time. A persona of the 'industrial' use case can be seen in figure 23 and the full use case is described in Appendix B.

On the other side, there is the Educating use case. The aim of machine users in this use case is substantially different from the Industrial use case, as the focus is on educating people and spreading awareness on plastic recycling. For them, the most important factor in the machine is the possibility to show the recycling process to others as clearly as possible. A persona of the 'educating' use case can be seen in figure 24 and the full use case is described in Appendix B.

THE INDUSTRIAL RECYCLER

Recycling as much plastic as possible by making and selling high quality products

Fast
The goal is to produce quickly, so they aim for low cycle-times (2 - 4 min)

High Quality
They aim for high quality, finishing, durability and aesthetics

A lot of products
They make a wide range of different products

Expected cycle time (1 minute – 10 minute)

Building skills (basic – advanced)

Degree of automation (manual – machinal)

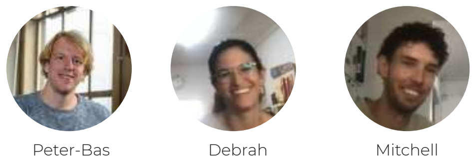


Figure 23: Industrial Usecase

THE EDUCATOR

Practically teaching people about recycling

Show the process
Having a long cycle-time (8 - 15 min) leaves plenty of time to explain the process

Buildable
They aim for a simple machine without expensive fancy parts.

Teach about recycling
They want a machine with a clear, self-explanatory working principle

Expected cycle time (1 minute – 10 minute)

Building skills (basic – advanced)

Degree of automation (manual – machinal)

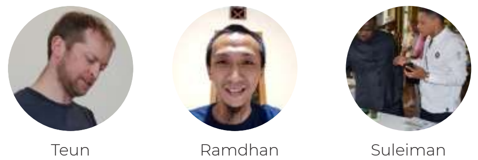


Figure 24: Educating Usecase

By mapping these use cases as opposites on an axis, a spectrum of use cases emerges (figure 25). This spectrum reflects the actual usage of the current injection machine fairly well, as most users find themselves to be somewhat of a combination of both of these use cases.

The current design of the injection machine mostly fits the 'Educating' use case, as it cannot achieve the low cycle time and high part qualities the 'Industrial' users desire.

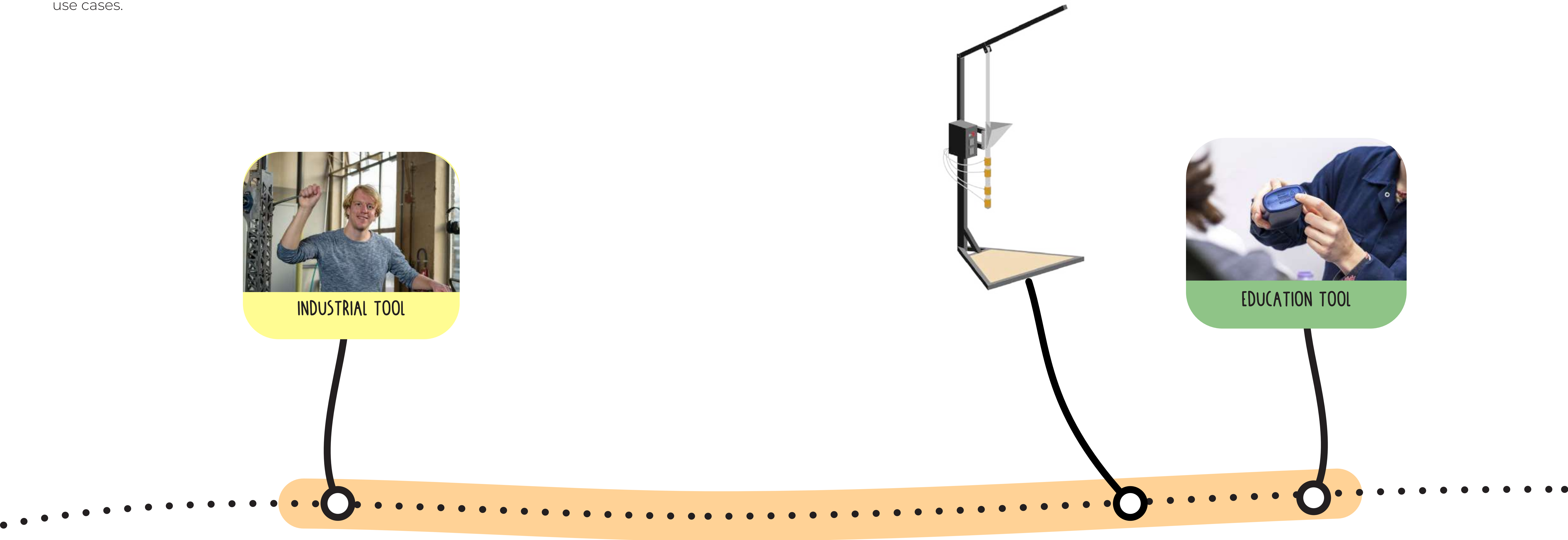


Figure 25: Usecase Spectrum

Ergonomics

As indicated by all interviewees and by the Precious Plastic core team, the ergonomics of the injection stage is one of the main issues of the machine. Using the machine dimensions, the currently required manual injection force is estimated around 720N.

Therefore, desk research was done to dive deeper into this topic.
Ergonomie fur design und entwicklung (Burandt, 1978) provides extensive data on maximum applicable forces by human hands in a variety of different positions and locations compared to the torso. To better interpret the data, figure 13 shows the 3 anatomical planes in humans.

Interpreting the data found by Burandt (pg. 53, table 53.1), the following trends are apparent:

- Perpendicular to frontal plane at multiple heights, rather pull towards than push away. For example, pushing at shoulder height results in an average force of 130N, while pulling gives 200N.

- Perpendicular to transverse plane (figure 26), rather exert a force downwards than upwards. The highest forces can be achieved by pulling downwards between head-height and shoulder height.

- The closer the force is applied to the body, the higher the maximum force achieved.

- There are only small differences in the maximum forces applied in front, diagonally or on the side of the torso, which is true for any height, direction and proximity.

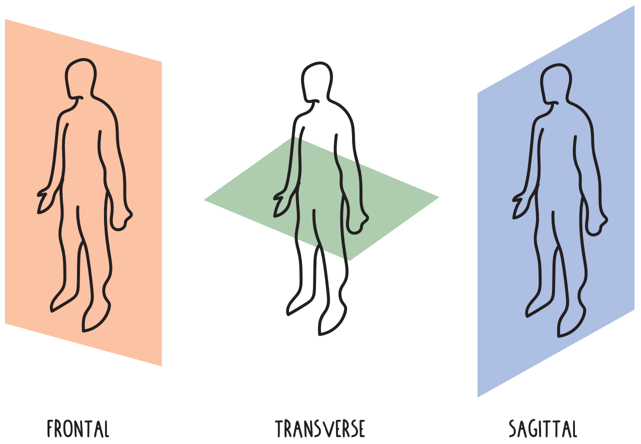


Figure 26: Human anatomy planes

Based on these trends, Burandt predicts the maximum ergonomically permissible force to be around 540N. Figure 27 visualizes the position in which this can be achieved.

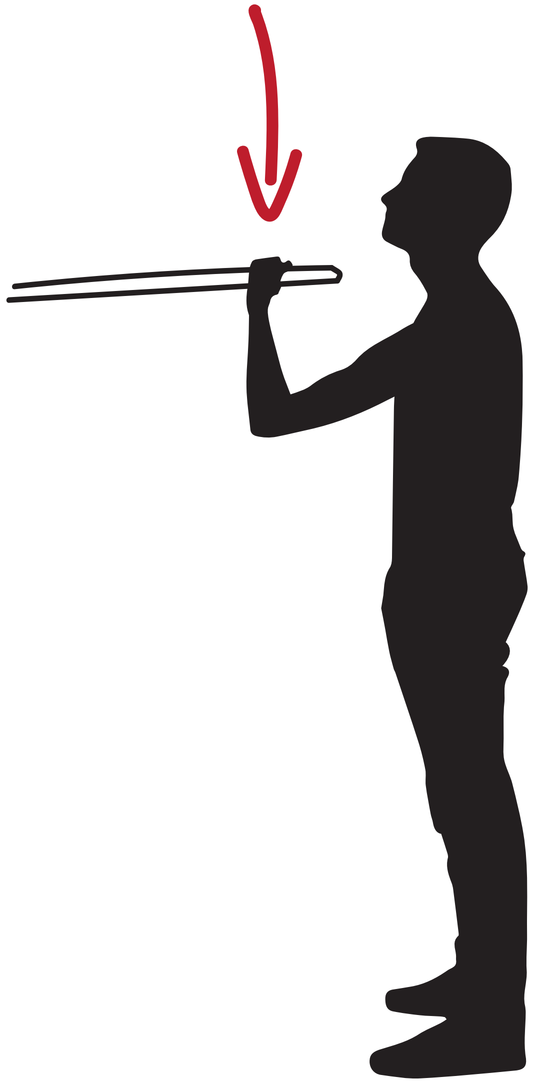


Figure 27: Human anatomy planes

However, this value does not take into account the variation over time. This is an important omission, as Burandt shows that the maximum force exerted decreases over time due to fatigue (pg 57, figure 57.1). The observations within this project showed that pressure needs to be applied for a maximum of 30 seconds, which is similar to conventional industrial injection times (Goodship, 2004). For this duration, a reduction of around 40% of the maximum ergonomically permissible force is expected.

This results in a maximum user force of around 350 Newtons.

Key takeaways

- The current injection machine is tedious and timeconsuming in use.

- The current machine can be dangerous to use. During the process, there are a lot of steps in which the user is put at risk.

- There are different use cases with diverse users having quite different wishes for the machine.

- The current force application method is insufficient and not user friendly. Ideally, the user would need to exert a maximum of 350 Newtons.

3.3 Building insights

Building Timeline

As discussed in chapter 2.5, the building process starts on the Precious Plastic website where builders are able to download a kit with all required blueprints and CAD models. The kit also features a building tutorial on YouTube, which provides a good picture of the building process of the current injection machine.

The main steps are visualized in the experience timeline in figure 28 and are based on the builder interviews and buildability survey. Appendix C provides an extensive description of the building steps.

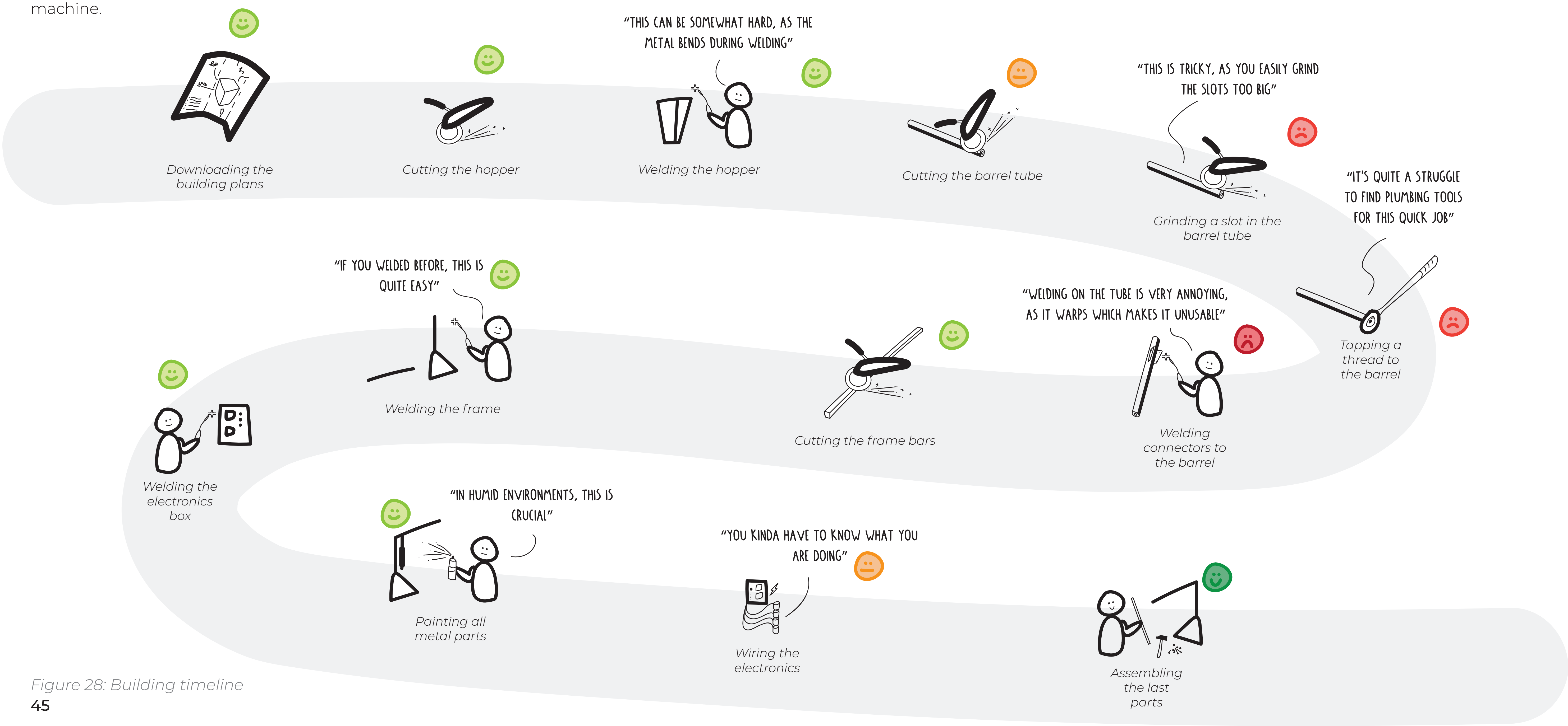


Figure 28: Building timeline

Part Accessibility

In order to develop an injection machine that can be built in different contexts, it is important to look at the accessibility of different parts around the globe. This was mainly done through analysis of the accessibility survey's results and supplemented with interview insights. Within the survey, participants were asked to rate parts of the Precious Plastic injection machine on a 1 to 7 scale, ranging from 'very easy to find' to 'very hard to find'. Besides these parts, key components of alternative designs were also evaluated to learn about their buildability. These are the gear and rack. Figures 29 and 30 give an overview of the survey results, the raw data can be found in appendix A.

	Part name	Mean (1-7 scale)	Standard Deviation	% used in build	Number of responders
Frame parts	Square tubes	1.4	1.06	94	18
	Metal strips	1.1	0.35	94	18
	Angle profile	1.3	0.58	100	18
	Sheet metal	1.7	1.25	81	18
Injection Unit parts	Metal round bar	2.4	1.54	100	18
	Metal tube	3.3	1.88	100	18
	Insulation	2.7	1.16	63	18
Electronic parts	PID Controller	2.0	1.21	100	18
	Solid State Relay	1.8	1.22	100	18
	Band heater	2.4	1.30	94	18
	Thermocouple	1.9	1.34	100	18
	Cabling, Power switch and LED	1.3	0.62	94	18
Alternative design parts	Rack	2.5	2.12	100	2
	Gear	3.0	1.41	100	2

Figure 29: Survey Results

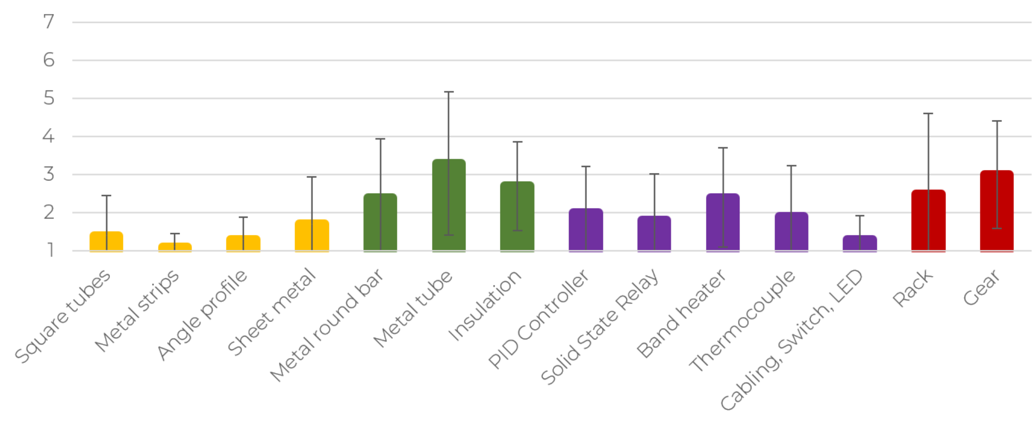


Figure 30: Survey Results

The results clearly show a number of patterns.

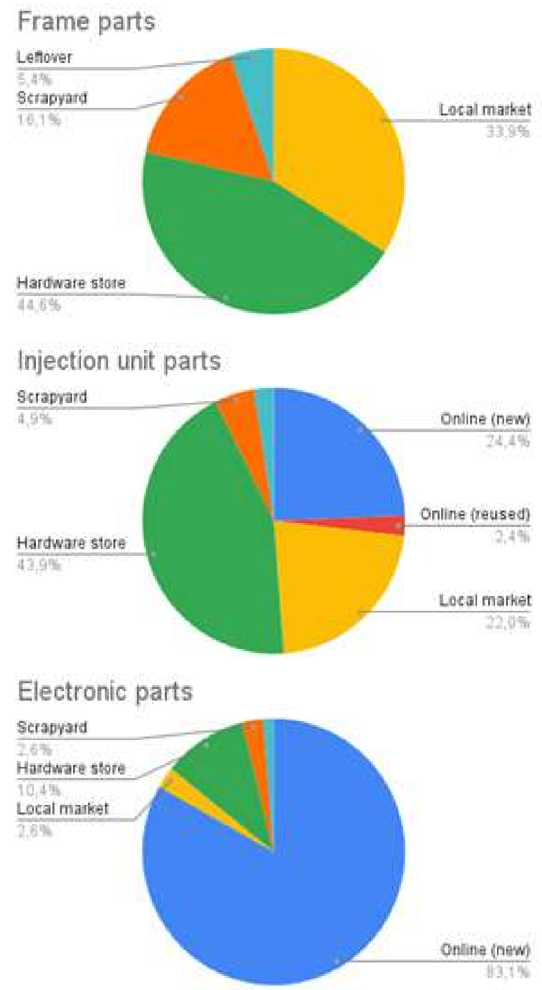
First, it is apparent that on average, survey responders experience all parts to be very to medium accessible. Between part categories, frame parts (orange) are very easy to find (μ = 1.1 .. 1.7), electronic parts are reasonably okay to find (μ = 1.3 .. 2.4) and injection unit parts are the hardest to find (μ = 2.4 .. 3.3) similar to the alternative design parts (μ = 2.5 .. 3.0). The values for the alternative design parts are, however, hard to judge due to the low number of respondents. The metal tube from the barrel is rated as the hardest part to find (μ = 3.3), which respondents explain is due to the unclear dimensions and the specific fit with the plunger.

Another interesting result is that globally, large differences exist between countries in accessibility to online markets. As participants indicate:

"In Argentina it is very difficult and expensive to bring things from other countries, especially from Asia"

Respondent 5, Argentina

In addition to the accessibility score, the survey yields interesting results on where people get their parts. Figures 31 to 33 show these results divided per part category.



Figures 31 - 33: Survey Results

The first pattern within these figures is the role of online part ordering: A large majority of electronic parts are ordered online, whereas frame parts are bought locally. Next to this, the results show that recycled materials are not used often. The parts for the metal frame have the highest chance of being reused (about 22%, n= 4 of survey responders), while electronics are almost exclusively bought new.

Building resource Accessibility

Next to the accessibility of parts, the accessibility of building resources such as welding and lasercutting are also important factors for machine design. Figures 34 and 35 show the results of the accessibility study for these building resources.

Manufacturing technique	Mean, 1 - 5	SD	% of respondents that applied this technique	% of respondents that outsourced this technique
Cutting metal parts	1,9	0,62	100	11
Welding	2,4	0,93	100	6
Boring holes	2,1	1,16	100	0
Bolting things together	1,7	0,84	100	0
Wiring electronics	2,6	1,20	100	0
Fitting parts together	2,7	1,19	100	0
Painting	1,6	0,85	100	0
Laser cutting	1,4	0,53	50	11
Milling/lathing	2,7	0,82	67	11

Figure 34: Survey Results

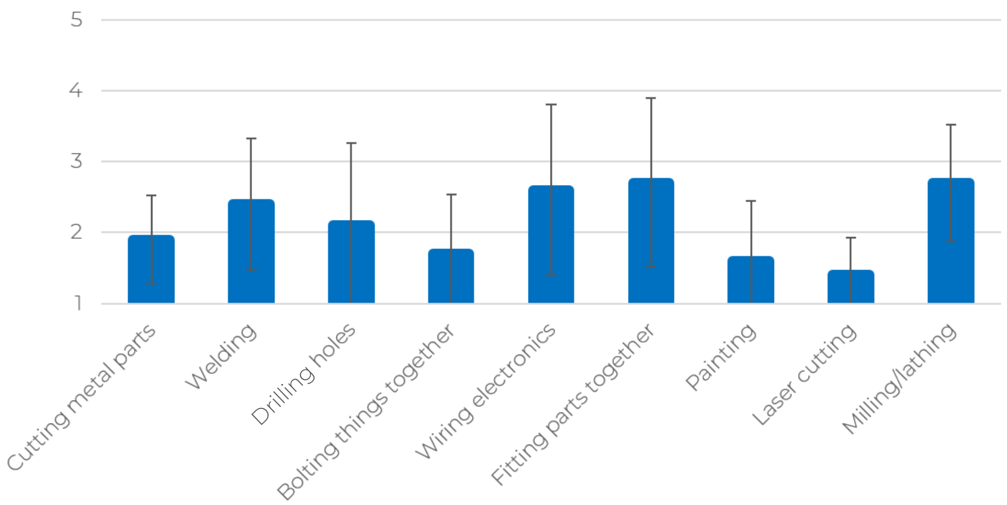


Figure 35: Survey Results

The results show that, similar to the part accessibility, most building resources are on average between very easy and medium accessible. For the building resources required to make the Precious Plastic injection machine, fitting parts together, wiring electronics and welding appear the hardest to do. Also, laser-cutting and milling/lathing are used far less than other techniques, which makes sense as they are not required to make the standard version of the machine.

Choice criteria on machine style

In choosing their preferred design of a machine, the builder's envisioned usage case is one of the key choice criteria as described in chapter 3.2. However, there are also certain building criteria that come into play in making this decision.

The availability of manufacturing techniques seems to be the most important factor. In general, 'industrial' users have access to more advanced manufacturing techniques such as milling and lathing, whereas 'educating' users tend to pick basic tools for their build. However, there seem to be many exemptions to this rule. By outsourcing certain parts, 'educating' users can get access to advanced parts, while not all 'industrial' users might own a milling machine. Therefore, this factor is very dependent on the personal situation of the builder.

Another important factor is the builder's **allocated budget**. Again, this factor seems to align somewhat to the two use cases, although this does not apply to every case.

Also, **the amount of time allocated** to the machine build can be a factor for choosing a specific style of machine. For builders with little time to spare, buying a machine from a machine builder on the bazar can be a viable option.

Lastly, the amount of **building experience** can also come into play.

Building Experience

After analyzing all data from the accessibility survey, supplemented with the online interviews, the following key insights into the building experience are determined:

- **The building instructions are unclear**. While watching the video, the absence of any explanation to the steps made immediately sticks out. As many interviewees and survey responders point out, this leads to confusion and costly building mistakes. Without a technical background, building the machine is even harder.
- **Welding is hard and can damage the machine.** Multiple survey respondents and interviewees mention that in welding the hopper to the metal barrel tube, the barrel bends slightly causing the plunger to get stuck.
- **It is difficult to fit the barrel and plunger together.** These parts need a tight fit to prevent plastic from flowing anywhere else but through the nozzle, while they should also be low on friction. Next to this, Survey respondent 16 from Colombia mentions: “It has to be [...] an extruded tube, because here a tube is made by bending and welding so it has a weld line in the inside”
- **Threading is tricky.** The thread on the bottom of the extruder is hard to make: It requires specialist thread making tools, which are common for plumbers but not often found in a regular tool shops.
- **Most people build some form of isolation**, although it is not a regular part of the build. 60% of builders surveyed (n=10) mention adding it, although there are many ways to insulate and it is hard to choose without proper guidelines.

Key takeaways

- There are quite some building steps that are very difficult or impossible to do right, such as welding parts on the barrel, cutting the hopper hole in the tube and threading the barrel.
- Most parts used in the current injection machine are reasonably accessible for builders.
- The key choice criteria on a machine style include the usage case, access to manufacturing techniques, allocated budget and amount of time allocated.

3.4 Location and Context insights

Injection machines are used and build everywhere around the world. However, the number of machines in high income countries is far higher than in middle and low income countries. The online interviews, accessibility survey and expert interviews provide insights to the significant differences to these building contexts in relation to the Precious Plastic universe.

Figure 36: Precious Plastic at GIVO in Nigeria

High-Income countries
Here, advanced materials and machining options are available, although often at a high price. In return, parts are often of quite high quality. There are quite some regulations, especially when moving goods through customs.

Middle-Income countries
In these contexts, manual labor and machining prices are lower. People often buy their parts on local markets or online. Often, recycling is done as a side business for some extra profit. Also, waste collection systems are typically non-renewable or absent.

Low-Income countries
In these contexts, builders often lack access to high-quality materials and machines. Especially ordering parts online is difficult. Therefore, machines are often build in other countries and then transported to the usage location (figure 36). Often, people work in larger groups within a recycling station.

In the context of Low-Income countries, the main value of Precious Plastic workplaces comes in the form of social work by enabling underprivileged people to work. Recycling spaces can enable especially women to work and earn an income.

In general
In all contexts, it is apparent that recycling spaces are mostly located around urbanized places, which has multiple reasons. Firstly, urbanized places have a higher concentration of people and therefore waste produced. Secondly, the availability of machine and material shops allows builders to keep cost down. Lastly, urbanized places make it possible to sell recycled products easily.

Key takeaways

- There are large differences in use cases, available materials and building facilities globally. The current design is not tailored for this.
- Precious Plastic-enabled workspaces have the potential to enable underpriviledged women to work.

3.5 Technical insights

Conceptual units

On a conceptual level, the Precious Plastic injection machine can be subdivided in 5 conceptual units with distinct functions. In the following sections, the minimal technical specifications underlying the injection machine are explained. Also, the different sub-functions of the machine and its units are described.

Together with the experts on the co-design discord channel, the minimal specifications of these functions are defined (figure 37). The reader should note that these minimal specifications do not constitute a complete list of requirements for the injection machine, but merely form a starting point for development.

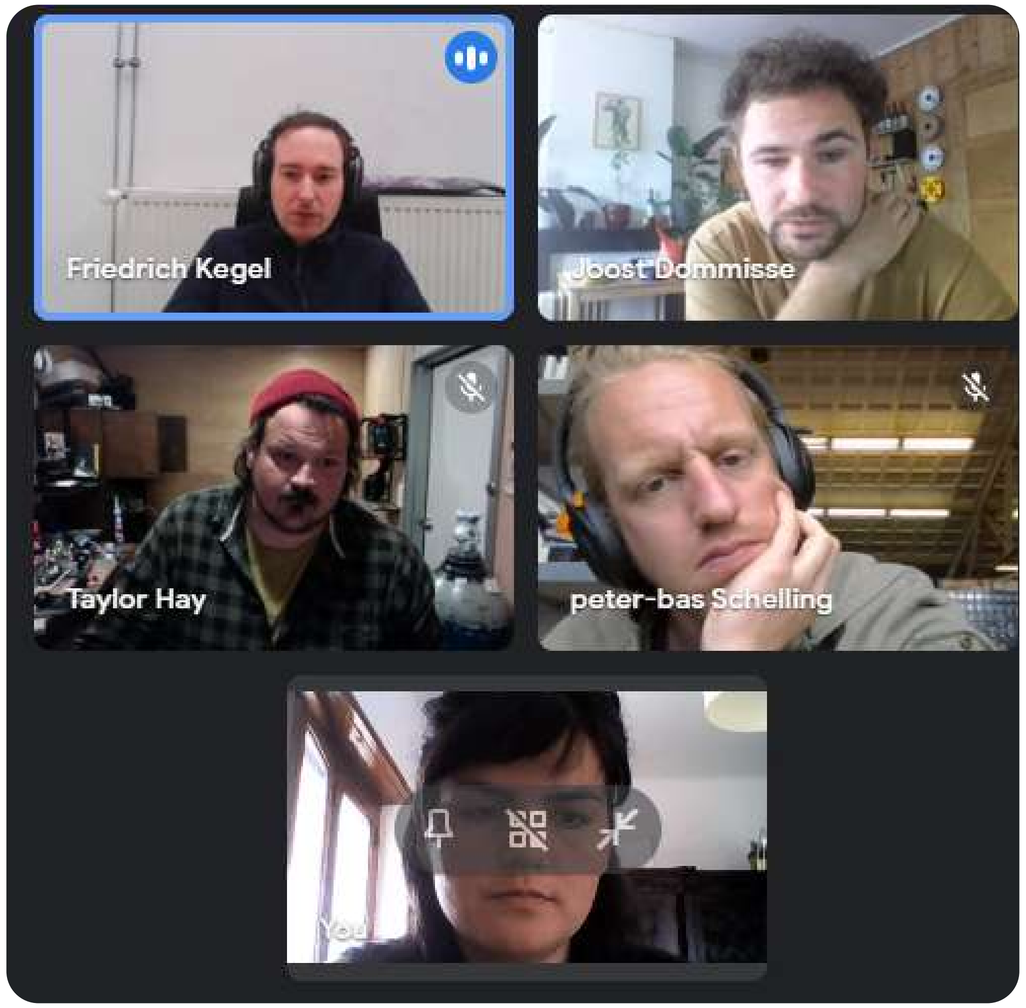
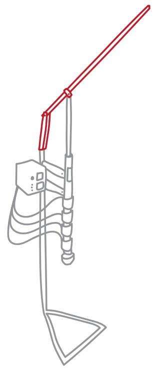


Figure 37: Collaborating with machine builders



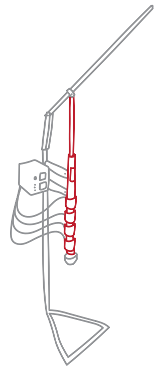
Force Application Unit

The Force-Application Unit acts as a system that takes the human power input and transforms it into pressure and movement onto the plastic melt. To successfully do this, it requires the following minimal specifications:

- It should produce a minimum pressure of around 42 bar in the barrel to successfully inject plastic. Given the current barrel diameter of 26mm, this means it should apply a minimum force of 2250N on the plunger. This force is dependent on the geometry of the barrel, as a larger barrel diameter would decrease the force needed to reach the minimum pressure via the following formula:

$$Pbarrel = Fplunger / Rbarrel^2 \times \pi$$

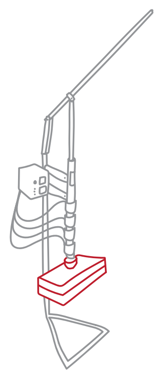
- It should be able to move the plunger at least 38cm to successfully inject all the plastic in the barrel, given the current barrel diameter of 26mm. As with the minimum pressure, changing the barrel diameter would change this value.
- It should induce a minimum travel speed of 5cm/s on the plunger to successfully inject plastic. According to literature and practical experience, having a lower travel speed could result in short shotting due to early solidification (Goodship, 2004).



Injection Unit

The Injection unit has multiple functions. Primarily, it holds the plastic flakes and heat them to their melting temperature. Besides this, it makes sure the pressure from the Force application unit can be built up and is applied to the plastic. To successfully do this, it requires the following minimal specifications:

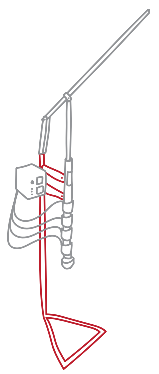
- It should be able to heat the input plastic flakes to a maximum temperature of 250C°. This is the melt temperature on which the most commonly used recycled plastics (PP, HDPE and PS) are melted.
- It should have a minimal volume of 150 cm^3. As the shotvolume of the existing injection molds in the Precious Plastic Universe are based on this figure, decreasing it would severely limit the injection machines applicability.
- It should have a maximum internal radius of 15mm. According to multiple experts, further increasing this radius would prevent the plastic from thoroughly melting.



Mold Unit

The Mold unit also has multiple functions. Mainly, it keeps the nozzle and mold engagement together. Also, it holds the mold in place and stable during the injection process. To successfully do this, it requires the following minimal specifications:

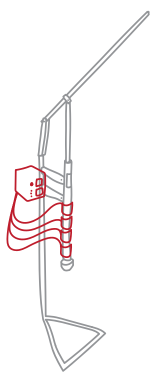
- It should minimally have an working area with a diameter of 380mm and a height of 170mm where molds can be successfully injected.
- It should minimally keep the nozzle and mold engagement together during the injection process. A loose or weak connection could endanger the user and cause the shot to fail.



Frame Unit

The Frame unit's key function is to provide structural support to all other units. To successfully do this, it requires the following minimal specifications:

- It should remain stable under the applied forces during the injection process.
- It should minimally withstand the forces applied through the force application unit, injection unit and mold unit.



Electronics Unit

The Electronics Unit's main functions are to regulate the temperature of the barrel and to enable the user to set the desired temperature. To successfully do this, it requires the following minimal specifications:

- It should properly run on a voltage of 220V. This enables the machine to be used on the regular power grid instead of requiring a less accessible three-phase electric power connection.

Key takeaways

- On a conceptual level, the injection machine can be subdivided into 5 conceptual units with their own sub-functions and minimal requirements

3.6 Alternatives and upgrades

Besides the injection machine made by Precious Plastic, there are many alternative designs that circulate in the builder community. These designs often improve the existing design in a number of ways.

Trough discussing on the co-design channel on Discord, an overview of existing alternatives was made with the help of expert machine builders. This section provides relevant examples of a number of these alternatives.

Appendix D provides an extensive overview of all alternatives found.

Figure 38: The Plastic Preneur machine

Arbor Mechanism

Arbor mechanism based designs are one of the most popular design alternatives out there (figure 38). At their core, they function through an interlocking spur-gear and rack-gear. The key improvement compared to the lever-style design is the way the minimum plunger force and distance are achieved: The gear allows both for a high transmission of force and continuous movement of the plunger. Within the lever-style design, there is always a trade-off between the force transmission and plunger movement, as increasing either will decrease the other.

Figure 39: Insulation material

Insulation

Insulation is added by many users (figure 39). This greatly reduces the amount of energy loss within the system, while also speeding up the melting process.

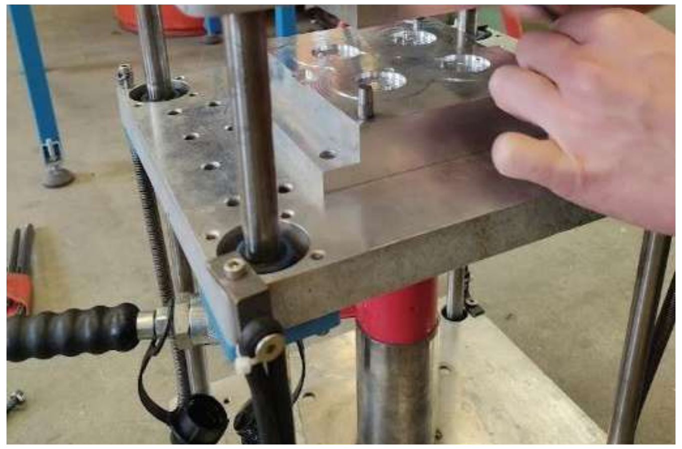


Figure 40: Piston clamp

Hydraulic Pistons

Using a piston, some advanced machine are able to directly clamp the mold halves together without an internal clamping system (figure 40). Although it makes demolding much faster, its quite advanced to install.

Figure 41: Movable Barrel

Movable Barrel

A movable barrel (figure 41) allows the user to effortlessly connect and release the mold to the nozzle, without screwing it on. In this design, the entire barrel is suspended by a spring and is forced down a few centimeters by the plunger force until it engages with the mold gate.

3.7 Applicable Legislation

Globally, there are many directives and requirements that machines like the injection machine should adhere to for legal use. As it is impossible to collect all requirements in every country, the CE Requirements from EU legislation are chosen as benchmark as they are among the strictest in the world.
An interesting point in these requirements is the fact that only the builder of the machine is responsible for the CE certification of this machine. Although Precious Plastic has a moral obligation to share safe design plans, they are not the responsible party. Moreover, the 'design' of a machine cannot be CE certified in and of itself: only a finished, physical machine can be tested.
To ease the certification process for the builder, the key requirements that should be met CE certification are used as guidelines in development.

General directives

For machines like the injection machine, the following EU Directives should be met:

- EN 60204-1:2018 Safety of Machinery general Requirement
- EN 61000-6-2: Electromagnetic Compatibility Part 6-2:Generic Standard-Immunity for industrial environment
- EN 61000-6-4: EMC Part6-4: Generic Standard-Emissions for industrial environment.
- EN ISO 12100:2010 : Safety of Machinery-Basic Concepts, general principles of design-Risk Assessment

Key Requirements

The directives provide plenty of requirements on general safety, machine wiring, physical aspects and many more. The key requirements for the design of the machine are mentioned below.

The reader should note that this list is not a complete rendition of all the CE requirements applicable to the machine, but it merely forms a starting point for the development of the machine.

- The user should be protected from Mechanical hazards such as crushing, shearing, cutting or others.
- The user should be protected from Electrical hazards such as burns and electrocution.
- The user should be protected from Thermal hazards such as burns.
- The user should be protected from Material hazards such as poisoning or explosions.
- The user should be protected from Ergonomic hazards such as fatigue or stress.

According to the EU Directives, the advised method to reduce the hazards above is as follows:

1. Eliminate the hazard by a suitable choice of design. If this is not possible, then:
2. Apply appropriate protective measures.
3. Provide stickers with information for use.

Key takeaways

- The builder is responsible for the safety of their machine, not Precious Plastic.
- Potential hazards should mainly be eliminated, or else be protected as thoroughly as possible by design.

3.8 Open Source Hardware

This project is meant to be shared in an open source environment. This section describes the best practices in OSH found within the community and through desk research.

Best practices

In 2017, the Open Source Hardware Association published a list of best practices for developing OSH (Bonvoisin et.al., 2017b) Below, the main practices that are relevant for this project are described.

- **Enable others to study** the project results. This mainly entails that this project results should be accessible online for free. Within the Precious Plastic universe, this is already good practice. As a general guideline, the design files should be understandable by someone with no prior experience.
- **Enable others to replicate** the project results. The OSHA advises offering a design kit containing CAD models, a bill of materials, blueprints and clear building instructions. As mentioned, the latter is a point of improvement for the current design.
- **Enable others to contribute** to the project. The project results should be shared through Open Source CAD software applications. Precious Plastic's practice is to share the design files in multiple CAD formats to make the design as accessible as possible. Besides this, a general description of the purpose should be added to the design package.

Open Source at Precious Plastic

Comparing the best practices of Open Source Hardware to the Precious Plastic Universe shows where Precious Plastic can improve. The main issue is the way in which people are enabled to contribute to a project. Although the Precious Plastic website features a How-To page on which builders can upload their own ideas, Precious Plastic indicates people actually rarely do this. This is a common problem among open source hardware and has been described in literature (Bonvoisin et.al., 2017a). Precious Plastic acknowledges this problem on their website:

> ***"[..] We haven't found a way to fully involve everyone in the creation of knowledge yet."***

Precious Plastic

The interviews with builders and analyzing the How-To page show where the community engagement could improve.

- **The main issue is the lack of structure** in which the How-To's are presented to the builder. They come in many shapes and forms: a lot of uploaders implement small improvements to parts, whereas others share a full machine redesign. Especially to a builder who is new to a machine, it's hard to find upgrades or design changes suited to them.
- **Another issue is the way in which the how-to's are shared.** They are presented as upgrades that can later be added to the machines, whereas this is not always the case. Some redesigns uploaded by builders require for example an enlarged frame dimension, which cannot be changed later on. The fact that builders are not presented with this choice at the moment they start planning their machine renders these larger improvements useless.
- **Lastly, the design of the injection machine is shared in quite a non-modular way.** Both expert input and existing literature agree that a more modular design would be more inviting for users to make their own improvements.

Clark et.al. (2002) show how a more modular design would improve builder engagement.

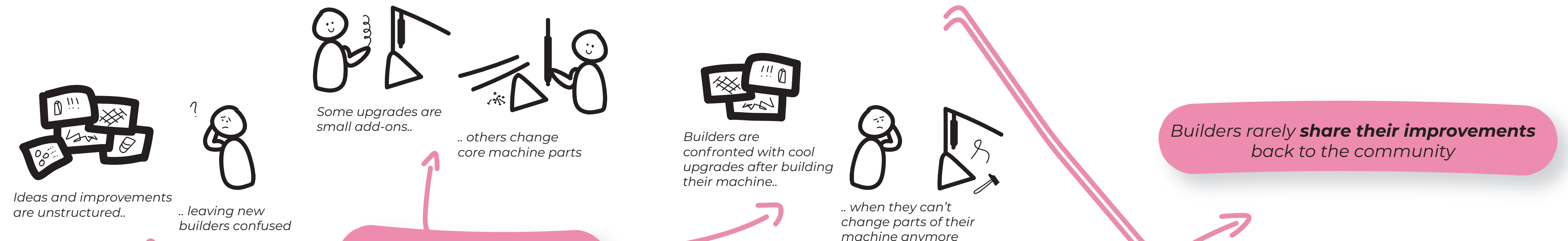
1. 'Modularity makes complexity manageable': Complex problems can be decomposed into simpler subproblems.
2. 'Modularity enables parallel work': Working on independent modules can be done by independent working people, whereas an undivided monolithic system can only be worked on by a closely collaborating team.
3. 'Modularity is tolerant of uncertainty': Within a modular system, incorrectly functioning components can be altered easily without damaging the whole system.

Key takeaways

- Builders rarely share their improvements with Precious Plastic.
- The How-To's-system on the Precious Plastic website is chaotic and unclear to new builders.
- The how-to platform is uninviting to new ideas due to a lack of structure
- The design of the injection machine is quite monolithic and not very flexible to changed parts.
- A modular approach to design could improve on these issues.

3.9 Visual Overview of Key Insights

The research outcomes of this chapter were analyzed into key insights into the design scope. To conclude this phase of the design process, a poster was made to give a visual overview on the most important insights and issues. This poster can be seen in figure 42.



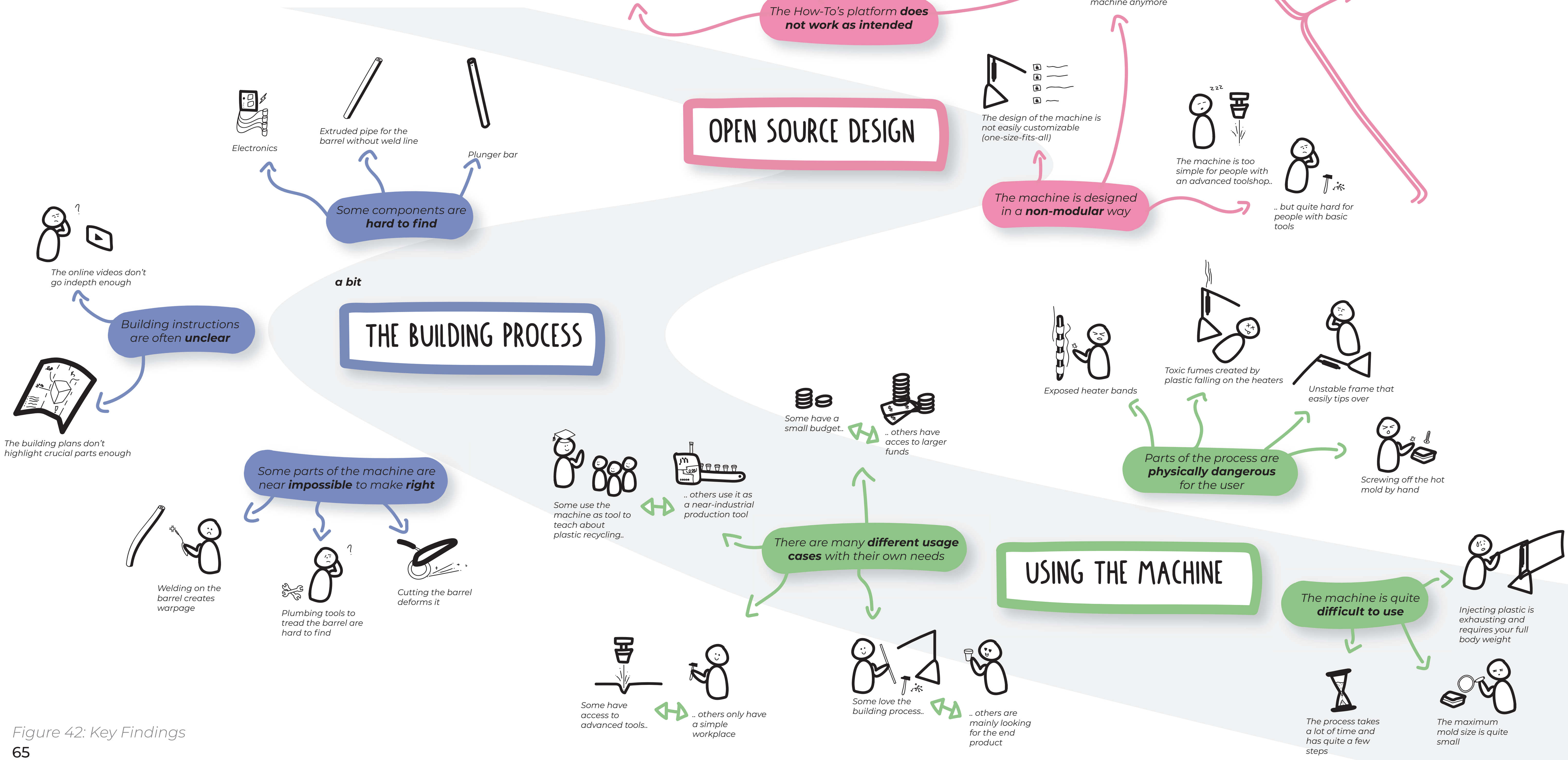


Figure 42: Key Findings

4 Focus

This chapter describes the redefined focus of the design project and presents the initial stages of the design process.

4.1 Project Goals

Based on the key insights, two project goals are developed to provide clear targets for this project. These goals are defined in consultation with Precious Plastic and the discord community.

Goal 1:

Transforming the ***current monolithic design sharing system*** *into an* ***inviting modular framework*** *for builders to actively* ***compose their bespoke injection machine***

Current monolithic design sharing system?

In the current situation, the injection machine is shared online as a single, inseparable monolithic design. This prevents it from being tailored to its users usage case and builder criteria. Also, it prevents any significant upgrades and makes it harder to repair.

Inviting modular framework?

A modular framework would be a system of independent modules that together constitute the injection machine. As concluded in chapter 3.8, a modular system could be the solution to the issues coming from the current monolithic sharing system.

Compose their bespoke injection machine?

Composing would be fitting together the modules into a functioning, tailored machine. This would be done by the builder themselves based on their use cases and building criteria.

Goal 2:

Developing, validating and documenting *a functioning prototype of an* ***advanced arbor injection machine***

Developing, validating and documenting?

These steps are necessary create an Open Source-design ready for sharing online and are part of the basic design process.

Advanced arbor machine?

The envisioned injection machine will be an advanced build and would be aimed at 'industrial' usage case (chapter 3.2). This strategic decision was made in consultation with Precious Plastic to offer a more industrial-capable machine next to the current 'educator'-machine. Chapter 4.3 provides an indepth description of the requirements on the advanced machine.

An Arbor-style mechanism is chosen as the main Force Actuating Mechanism. Compared to other mechanisms, an Arbor-style design performs best on evaluation criteria of both the 'educating' and 'industrial' use cases. Also, it performs best on additional criteria such as achievable pressure, injection time, cost and accessibility. Appendix E goes into detail on the weighted objectives method which was used to make this choice.

4.2 Design Criteria for Project Goal 1

This section discusses the List of Requirements and Wishes (LoR/W) for the framework as described in project goal 1. A LoR/W is a set of criteria that can be used to evaluate design solutions.

As there is no predecessor to a choice-tool like this, the development of the modular framework remained in a conceptual stage. Therefore, the LoR/W developed for the frameworks contains only conceptual criteria, which are not all defined with quantitative criteria.

The list contains two types of criteria: Primarily, there are Original Requirements and Wishes (OR/OW) that were found through the insights on the research from Chapter 3 and form the basis of project goal 1. Secondly, there are Development Requirements and Wishes (DR/DW) that were found during the development of the framework. They are discussed within the section on framework development in chapter 5.5.

Requirements

Original Requirements

OR1: The framework should provide structure to machine variants.
This is based on the insight that machine variants are currently presented in an unstructured way (the How-To's) as concluded in chapter 3.8.

OR2: The framework should enable builders to tailor their machine
This is based on the insight that the sharing method of the current injection machine is currently very much 'one-size-fits-all' as concluded in chapter 3.8.

OR3: The framework should help builders understand the impact of their choice
This is based on the insight that the buildability of machine variants is currently unclear (the How-To's) as concluded in chapter 3.8.

OR4: The framework should stimulate builders to return improvements
This is based on the insight that the current Precious Plastic website does not stimulate actively sharing back improvements as concluded in chapter 3.8.

Development Requirements

These criteria emerged during the develpment and are discussed in chapter 5.4.

DR1: The framework should enable a builder to meet all their criteria in the machine without concessions

DR2: The framework should only present feasible, viable and desirable solutions

DR3: The framework should invite builders to submit their own improvements and add-ons.

Wishes

Original Wishes

OW1: The framework would be as easy as possible to maintain for Precious Plastic
This is based on the insight that Precious Plastic is an organization with a limited budget and resources.

OW2: The framework would be as easy as possible to implement for Precious Plastic
This is based on the insight that Precious Plastic is an organization with a limited budget and resources.

Development Wishes

These wishes emerged during development and are discussed in chapter 5.4.

DW1: The framework would be as understandable as possible to a new builder as possible

DW2: The framework would enable as much customization as possible

DW3: The frame would quickly guide builders in their choice as much as possible

4.3 Design Criteria for Project Goal 2

This section discusses the List of Requirements and Wishes (LoR/W) for the advanced injection machine as described in project goal 2.

To provide structure, the LoR was divided among technical (TR/TW), safety (SR/SW), usage (UR/UW) and building (BR/BW) criteria. The criteria arose from the key insights from chapters 2 and 3. The list was checked with the help of Puch's checklist, which is a method for verifying the completeness of a LoR/W.

Below, the key criteria that differentiate the Advanced Injection Machine from other machine compositions are presented. These criteria arise from the insights in the 'industrial' usage case and research on building tool accessibility.

The complete LoR/W for the Advanced Injection Machine can be found in appendix F.

Key Requirements

TR 1.1: The machine should be able to exert a minimum pressure of 42 bar on the plastic melt.
This is the minimum pressure needed to successfully inject conventional molds within the current Precious Plastic system as concluded in chapter 3.5.

TR1.8: The machine should not allow the nozzle and mold engagement to disconnect during the injection process.
This is to ensure the users safety during injection as concluded in chapter 3.5.

UR3.1: The machine should require a maximum human input force of 350N to reach the minimum pressure on the plastic melt.
This is the maximum ergonomic human limit in applying force for around 30 seconds as found in chapter 3.2.

UR3.2: The machine should be able to successfully inject cold molds.
This is based on the insight that mold heating currently takes a lot of time from chapter 3.2 and on insights on the advanced use case as described in chapter 3.2.

Key Wishes

TW1.1: The machine would produce around 60 bars of pressure upon application of the 350N of human input force.
This value was determined as the desirable injection pressure through expert input on the co-design discord channel. Next to this, this wish is based on insights on the advanced use case as described in chapter 3.2.

UW2.2:The machine would enable the user to engage the mold onto the machine with as little effort as possible.
This is based on user insights as described in chapter 3.2

UW2.3: The machine would enable the user to produce parts as quickly as possible.
This is based on insights on the advanced use case as described in chapter 3.2.

BW3.2: The machine could use advanced building techniques such as lathing and milling.
This is based on insights on the advanced use case as described in chapter 3.2.

4.4 Project Structure

Figure 43 presents an overview of the project timeline after the project goals were defined.

A key takeaway from the timeline is the structure of the development process. After the definition of the two project goals, each goal launched its own development trajectory. However, it should be noted that these two trajectories are not fully independent from another. The described project results in the next two chapters will therefore occasionally refer to eachother.

In total, 4 client meetings (CM) are organized in which the development was evaluated. These client meetings were organized on the Precious Plastic Discord channel and were open to any interested contributors.

CM1

- Presentation of key findings
- Overview of common upgrades
- Choice for Arbor Mechanism
- Discussion on Project goals

CM2

- Feedback on 1st CAD Models
- Choice on focus on Advanced Arbor Machine
- Discussion on 1st version of Modular Design Framework

CM3

- Feedback on 2nd CAD Model
- Presentation of ongoing prototype

CM4

- Presentation of final prototype
- Prototype testing
- Discussion on Implementation

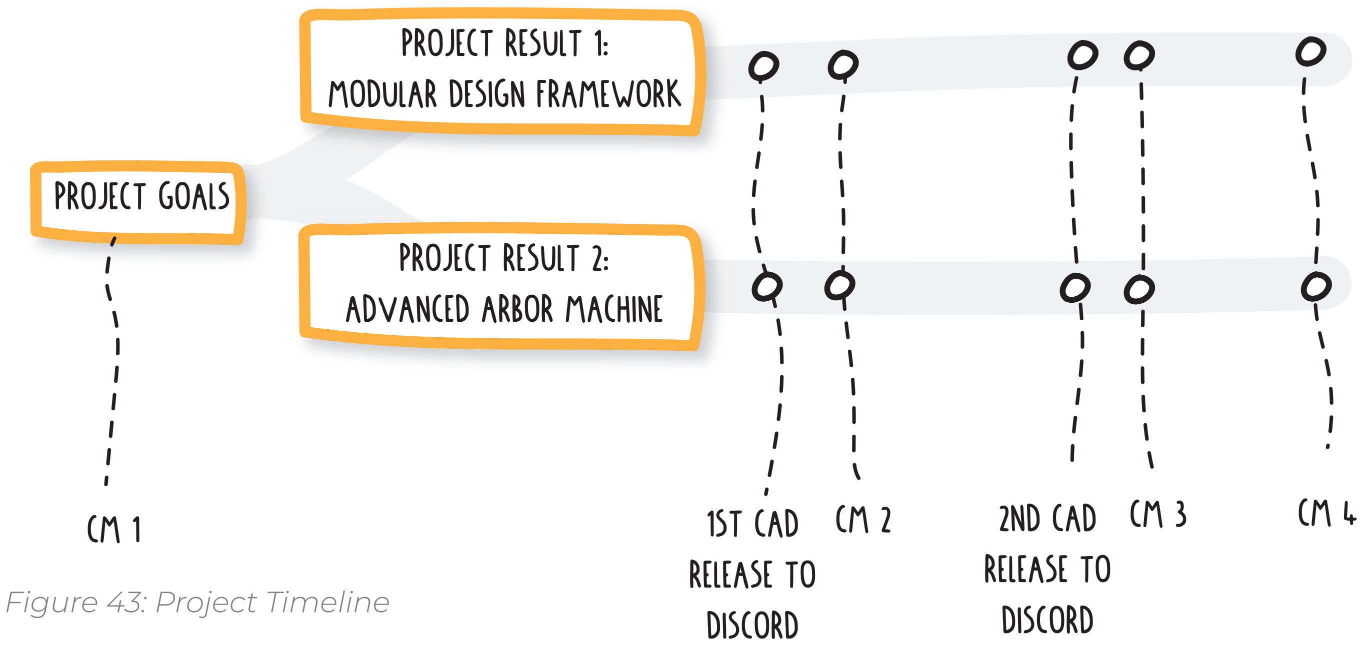


Figure 43: Project Timeline

5. Modular Design Framework

The Modular Design Framework is the first outcome of this design project and is the direct result of the first project goal defined in chapter 4.1.

5.1 Introduction to system elements

Introduction

The Modular Design Framework has the following 4 key functions:

1. Provide structure to the many possible variants within the design of the machine
2. Enable builders to tailor their machine
3. Help builders understand the impact of their choice
4. Stimulate builders to invent improvements and share them back with the community

A good analogy for this framework can be found in the racing game Mario Kart (figure 44). Before starting a race, users can combine cars, tires and gliders into their ideal racing combination through a structured, understandable process.

Figure 44: Mario Kart (screenshot, ©Nintendo)

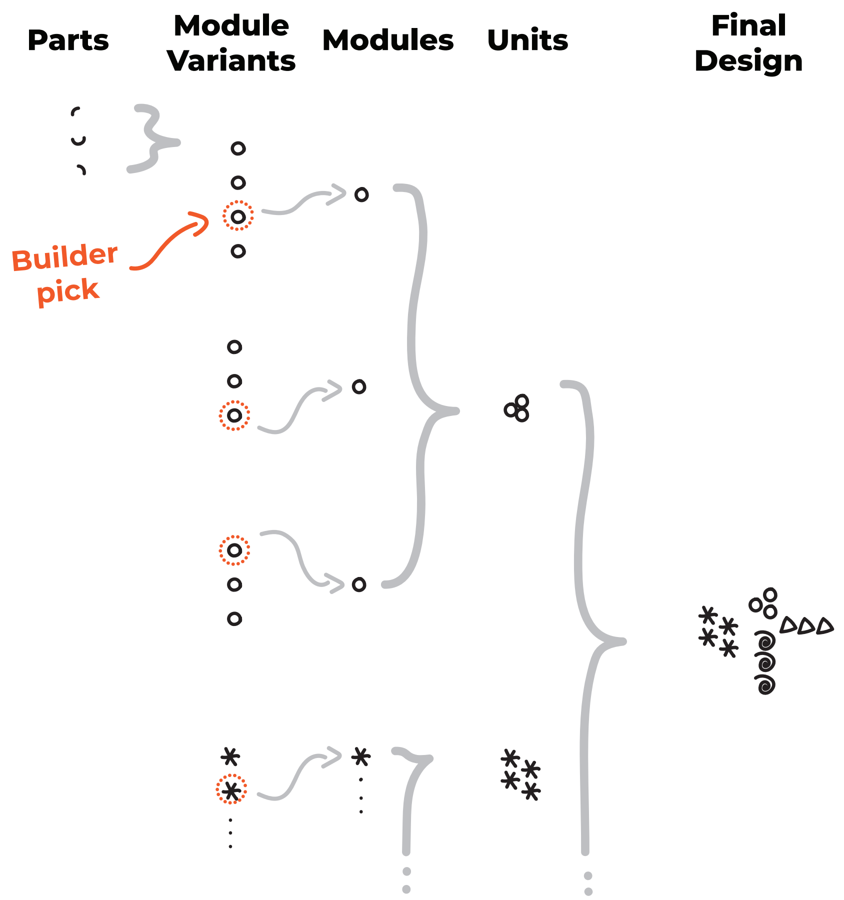


Figure 45: Framework Elements

Elements in the framework

Figure 45 provides an overview of the main elements within the developed framework.

To start at the most elementary level, any product is made up of parts.

Going up one layer, parts can be combined in a module variant which has a few specific subfunctions within the design. However, there are different ways to pick and combine parts into a module with more or less the same functions, dependent on resources, budget and preferences of the builder. To give an example: When making the piston in a car engine, there can be multiple feasible designs. All of these designs result in a functioning piston, but could be made up of different parts and materials. Therefore, each module can be made by choosing a specific module variant to build.

This is where a builder has to make a choice based on their specific needs: If they want to build a machine with limited resources, they can pick an inexpensive module variant. Alternatively, if they have access to advanced manufacturing techniques, they can pick a module variant that makes use of these tools.

Going up another layer, multiple modules are combined into units, which have transcending function. To stick with the car example: A unit would be the engine, which is a combination of modules such as pistons, electronics, a motor block and others. A unit can consist of any number of modules. Arriving at the final layer, the different units all combine into the final design. To stick with the previous analogy, this would be the car. By going through this hierarchical framework, builders can customize their design based on their needs.

Presets

One obvious deduction from this framework is that there will be combinations of module variants that make sense together. For example, it is sensible to combine module variants that are all designed to be lightweight. These 'logical' combinations are called pre-sets and are based on general trends on builder needs. Figure 46 visualizes this idea.

For builders, these pre-sets are the starting points to help them in their choice process. They indicate that there are different ways to configure their machine and end up with a tailored design.

Composer tool

Although these presets provide a good initial foundation, they will not be perfect for every builder. Therefore, after choosing a preset, builders are able to customize their design in a composer tool. In this tool, they can see details about all the variants and fully understand the philosophy behind them. If they want to, builders can swap module variants proposed in the pre-set for others and thus customize their build. This composer tool forms the backbone of the Modular Design Framework and will be further elaborated on in the next chapter.

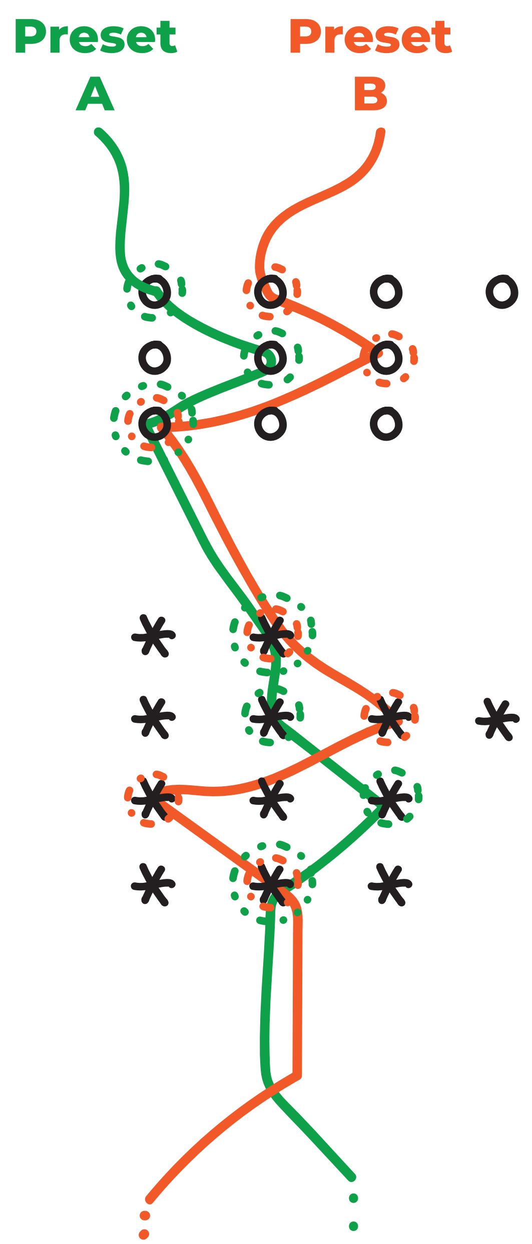


Figure 46: Presets

5.2 Developed Framework

Basic Units

The following section showcases the complete Modular Design Framework as it is developed in this project.
The injection machine contains 5 basic units, which are largely based on the conceptual units (chapter 3.5) and the initial ideation session (described in chapter 6.3).

An Arbor unit, which translates human force into usable pressure through an arbor mechanism

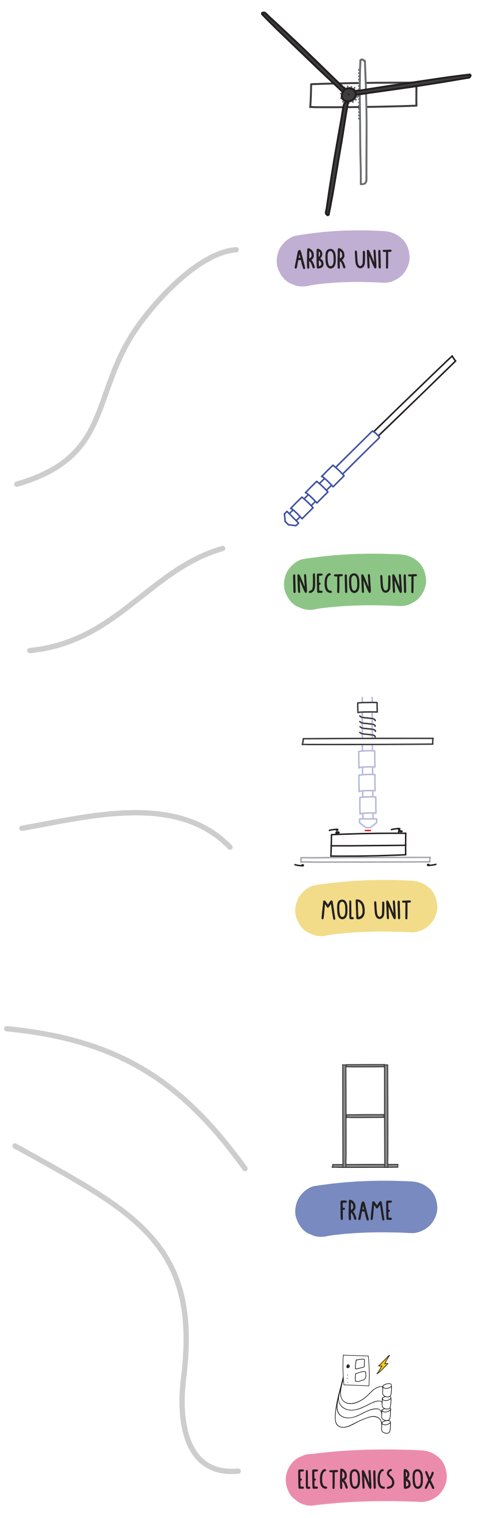
An Injection unit, in which plastic flakes are compressed, molten and injected through a nozzle

A Mold unit, which facilitates every aspect around connecting, holding and clamping the mold

A Frame unit, which provides the skeleton on which all other components are attached

An Electronics box, which controls the heating process

Next to these units, a 6th unit is called Add-ons, in which miscellaneous modules without an indispensable core function are gathered. These can be added to the build at the builders wish.



Injection Machine Module Variants

During this project, a total of 35 conceptual module variants are defined and are based on the initial ideation. Figure 47 shows a snapshot of these modules.

The reader is advised to view the high resolution poster in appendix G.

All module variants presented in the framework have been successfully implemented by a builder once and are based on the ideation presented in chapter 6.3. However, due to the limited time in this project, not all modules have been developed into validated concepts. Only the modules highlighted in green were fully prototyped and tested into publication-ready module variants. As discussed in Chapter 4.1, the 'Advanced build' pre-set can be made from the developed module variants and is therefore currently the only fully complete pre-set. Chapter 6 eludes on the engineering development of these modules.

Next to the module variants necessary for this pre-set, some other variants were developed and are also marked in green. These are mostly part of the 'Basic version' pre-set and are also publication-ready. They originated in exploring other concept directions in the design process and are also further explained in chapter 6.

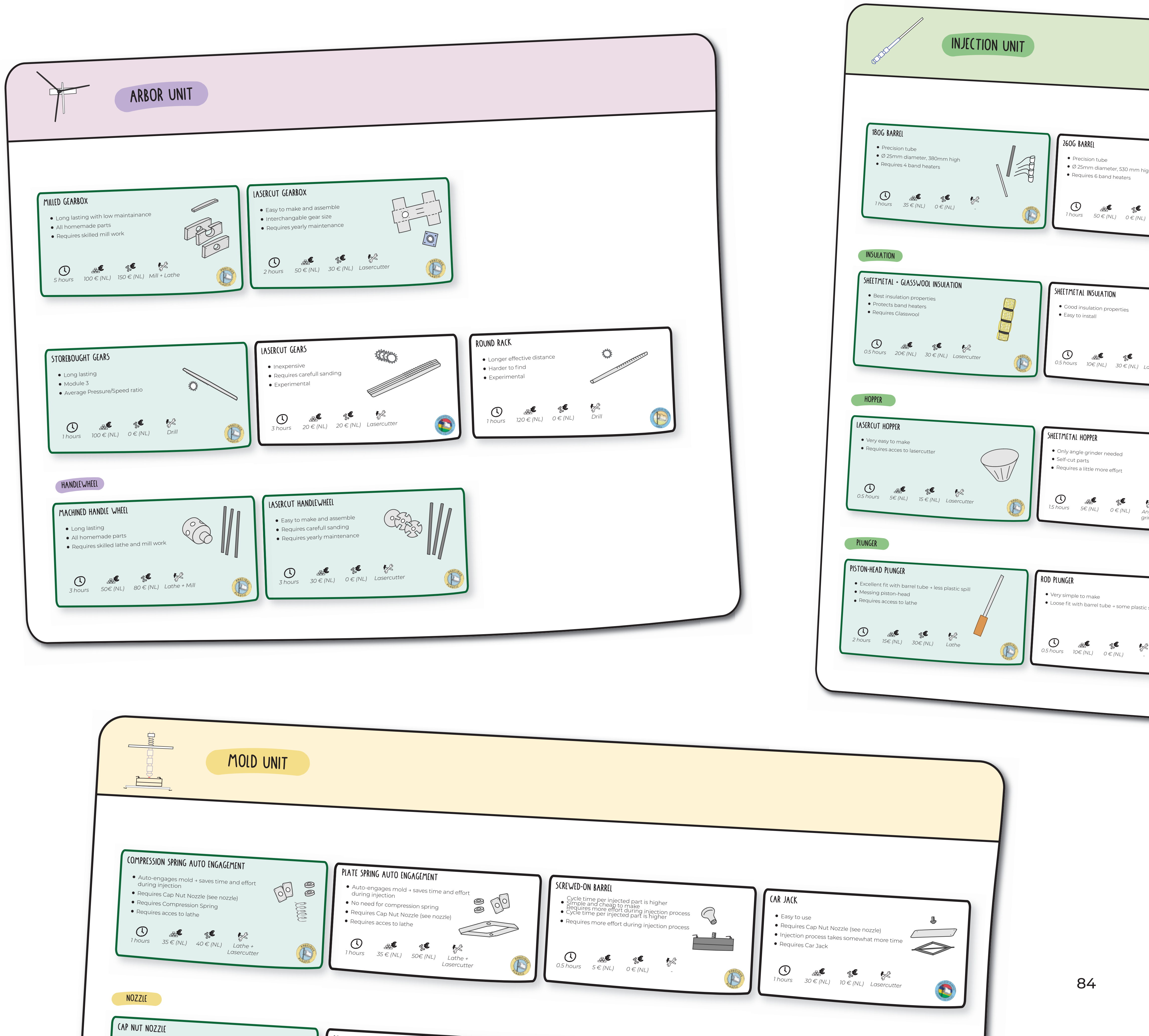


Figure 47: Module Variants

Presets Overview

Figure 48 shows a snapshot of the Morphological chart that is made to give an overview of the developed presets. Of this chart, a high-resolution poster can be found in appendix H which the reader is highly advised to view.

The pre-sets are mainly defined based on the usage cases (chapter 3.2) and building criteria (chapter 3.3). The colored line emerging from a pre-set touches all module variants that compose this pre-set.

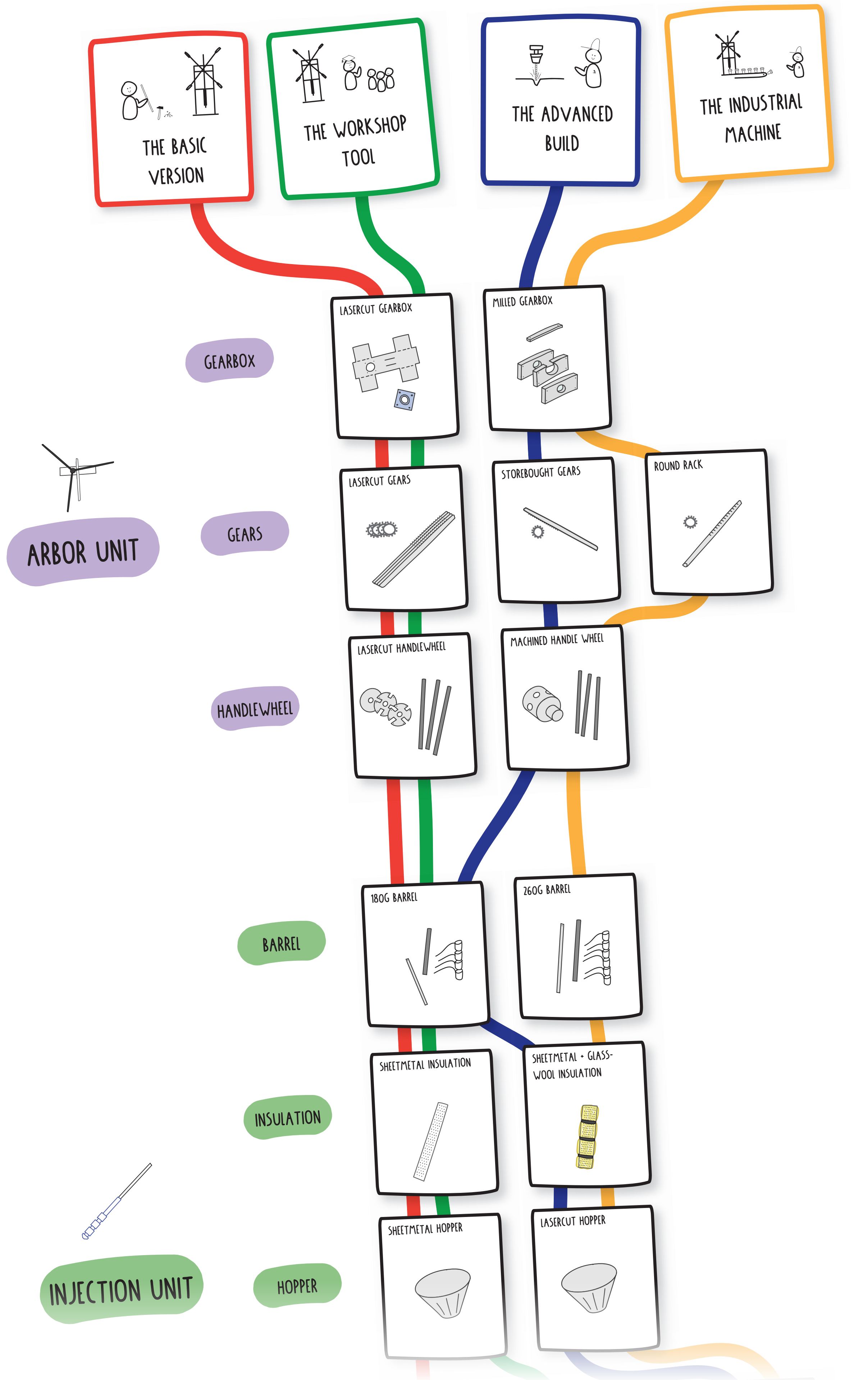
The Basic Version is aimed at builders looking to build an Arbor injection machine with the simplest tools and lowest budget. It entails module variants that are easy to make, as parts from these modules are generally lasercut or found in common hardware stores. Its total cost is estimated around 350€ . This pre-set uses basic joining techniques such as bolts and nuts instead of welding, which enables an easy build. The downside from some of these module variants are their need for maintenance and lower durability.

The Workshop Tool is aimed at the educating use case as this pre-set is perfect for educating others about plastic recycling. To this end, this preset is made to be easily transportable to other locations and is childproof. The required budget is still quite low at around 350€.

The Advanced Build is aimed at builders looking to use and build the injection machine in a professional way. This preset requires a somewhat bigger budget of an estimated 500€ and access to more advanced manufacturing techniques such as a mill and lathe. In return, the machine has a lower cycle time, requires less maintenance and can inject more complex molds. The module variants from this pre-set are fully developed within this project as part of the second project goal, which is further discussed in chapter 6.

The Industrial Machine is aimed at industrial builders looking for a professional production tool. It is optimized to have the shortest possible cycle-time. In return, this pre-set is the most expensive machine, estimated 900€.

Figure 48: Presets



Upload Form

One of the key functions for the Modular Design Framework is to stimulate builders to invent improvements and share them back with the community. To this end, an upload form is developed on which a builder can describe, document and share their own module variant. This upload form is presented in figure 49. After uploading, Precious Plastic could review the addition and integrate the new module variant in the system.

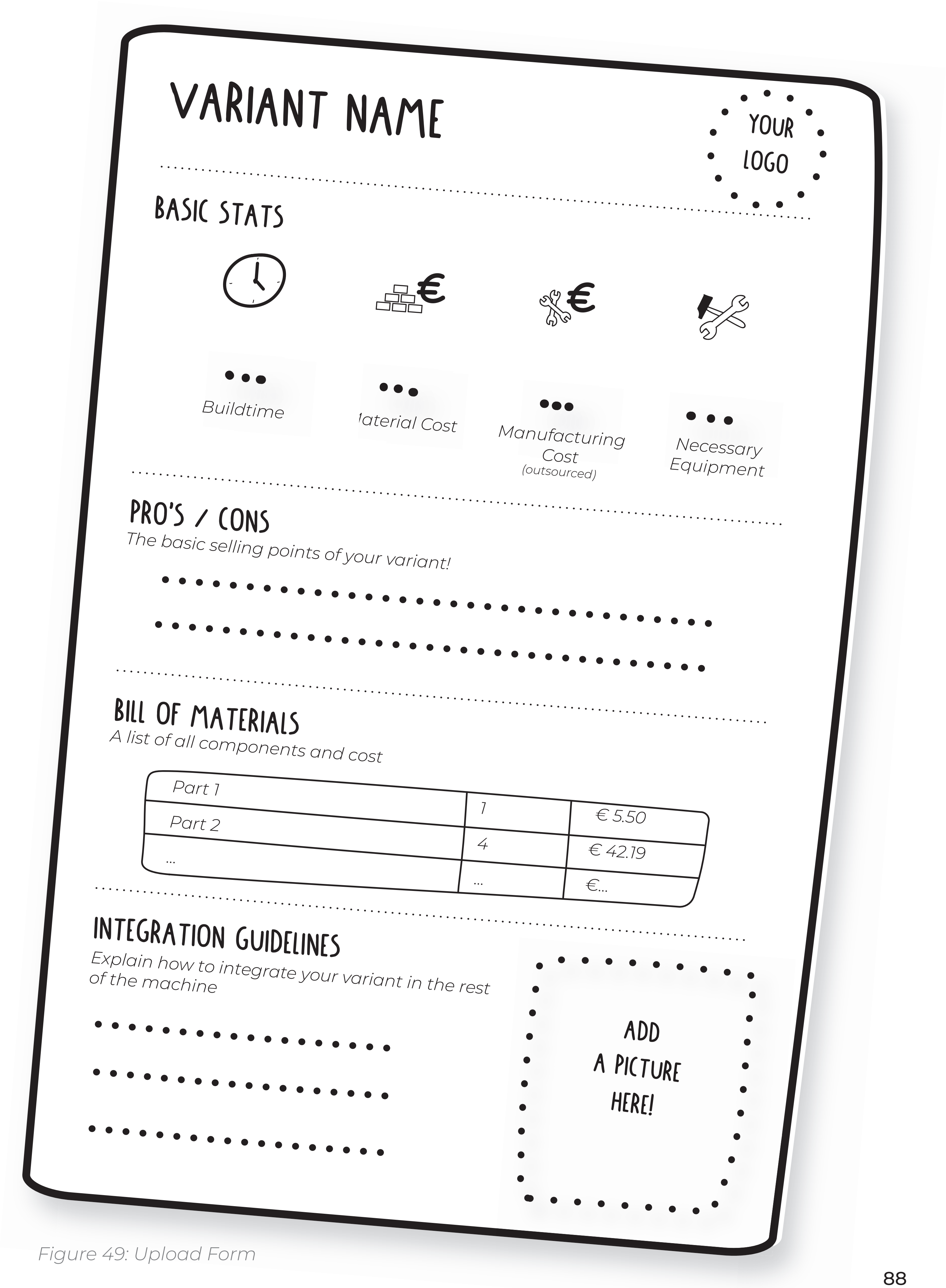


Figure 49: Upload Form

5.3 Envisioned User Interaction

Demonstrator

This section demonstrates how the builder would interact with the Modular Design Framework. As this interaction takes place online, the reader is highly advised to open the demonstrator website at [tinyurl.com/ppdesignframework]() along to reading the next section.

The builder first encounters the framework on the buildpage of the injection machine on the Precious Plastic website. Instead of being directly send to the download page for the build plans and CAD model, the builder is guided on a separate page through the choice process in the following three steps.

Stage 1: Introduction

As this system will be a new feature for builders, they first encounter an introduction page explaining the function and basic elements of the tool. It provides context and explains the added value of tailoring the machine. It uses informal language and provides understanding through a clear visual (figure 50).

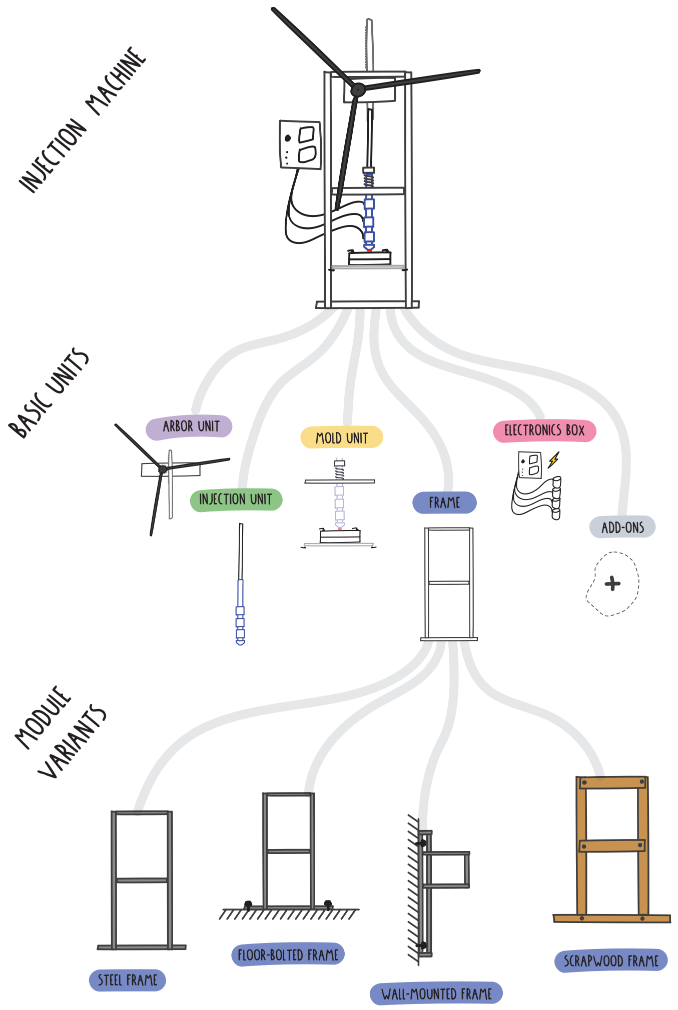


Figure 50: Introduction

Stage 2: Pre-sets

Next, 4 pre-sets are introduced (figure 51). Each pre-set is briefly introduced with a text that highlights its advantages, appealing to the builders with the matching choice factors such as their envisioned usage case or building criteria. The builder is able to select one pre-set to continue with by clicking it.

Figure 51: Presets

Stage 3: Composer tool

As a final stage, the builder is introduced to the composer tool (figure 52). In this interactive section of the page, the overview of all different module variants is presented. Based on their selected pre-set, the corresponding module variants are aligned to the left of the screen and highlighted in green. To their right, the alternative module variants are listed. If a builder prefers one of these alternative module variants over the proposed variant from the pre-set, they are able to click and select them.

Each module variant block has the same basic elements. In a few bullet points, its main pro's and con's are highlighted. Below this, some basic statistics are shown to quantify the variant. These are (from left to right) the estimated build time, the raw material cost, the outsourced manufacturing cost and the necessary equipment. On the right of the block, a picture of the module is shown to give the user an idea of the end result. Also, the designer of the module is credited by showing the logo of their workplace. In case the module is developed by Precious Plastic, their logo is shown.

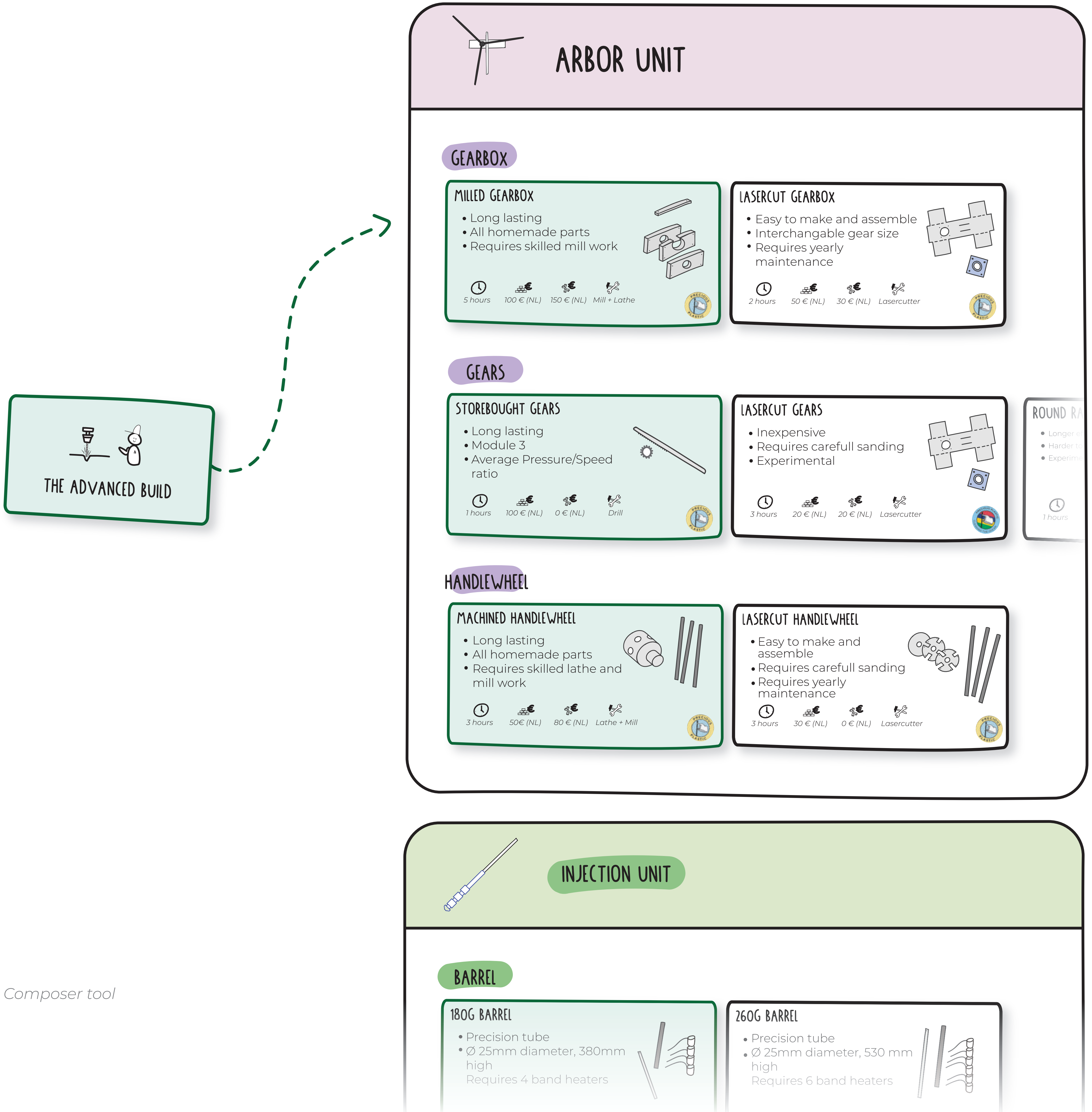


Figure 52: Composer tool

Stage 4: Download and Upload

Once the builder is happy with their selection, they continue to the Download & Upload section. Here, they are able to download a .zip file with all necessary drawings and models (figure 53).

Also, they are notified of the option to share back modules they might develop themselves while building the machine. Through the clickable Upload form (figure 54), they are able to upload their tested module variants for Precious Plastic to verify.

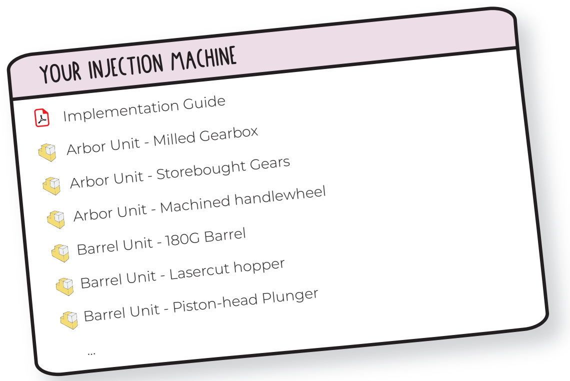


Figure 53: .zip download button

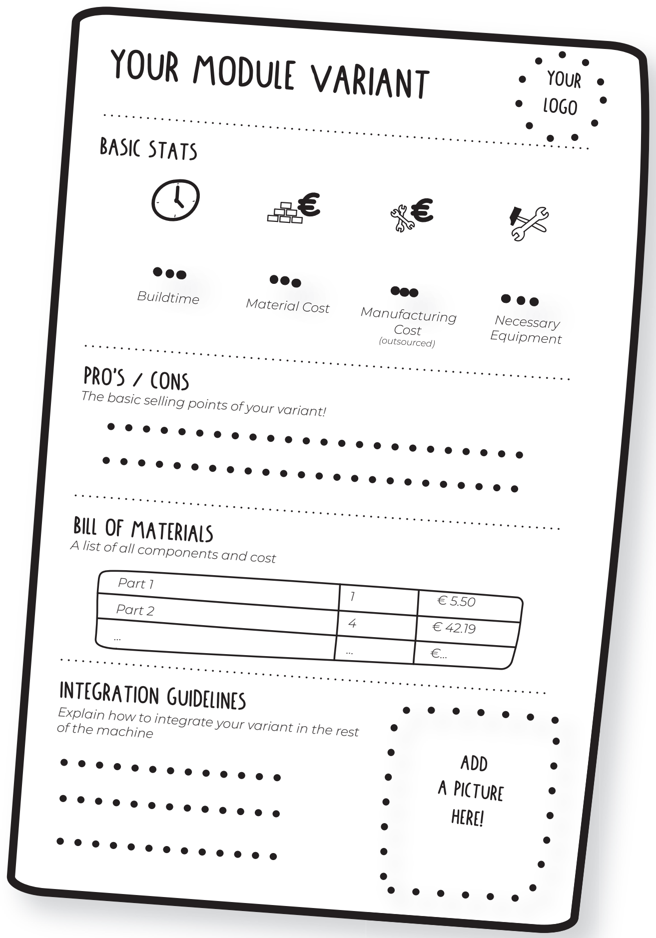


Figure 54: Upload Form

5.4 Unique Selling points

The Modular Design Framework has a number of advantages over the current design.

- The key difference is the shift in constraining the builder to the design of the publisher (Precious Plastic) to **stimulating the builder into active choice-making**. The current injection machine, which can only be downloaded as a single monolithic design package, is difficult for the builder to tailor.
- The Modular Design Framework gives this **control back to the builders,** without overwhelming inexperienced builders with a chaotic sea of choices.
- Next, the framework opens up the OSH development of the machine from private to **truly open development** to which everyone can contribute. The framework provides a fresh playground for development collaboration and does so in a way that is new to the OSH community. Ultimately, this would stimulate development of new module variants from which everyone benefits.
- The framework also generates **valuable data** on builder choices and preferences. Precious Plastic can use this to analyze builder needs and further enhance machine design.
- The framework enables builders to easily **sell modules on the bazar**, which enables used module variants to be easily reused.

5.5 Concept Development

The Modular Design Framework is the end-result of an iterative design process. This section describes the key steps in the development and presents the Development Requirements and Wishes (DR/DW) derived in each step.

Kick-off

The Original Requirements and Wishes (OR/OW) as discussed in chapter 4.2 were used as a starting point of the development process. To further develop the list of requirements and wishes for the Modular Design Framework, an iterative approach was taken by generating ideas, requirements and wishes in tandem.

Initial approach

One of the main goals of the Modular Design Framework is to enable tailoring the machine design to the builders specific usage case or building criteria. Therefore, a good starting point of the development process is the spectrum of use cases found in Chapter 3.2 and the range of building criteria found in chapter 3.3.

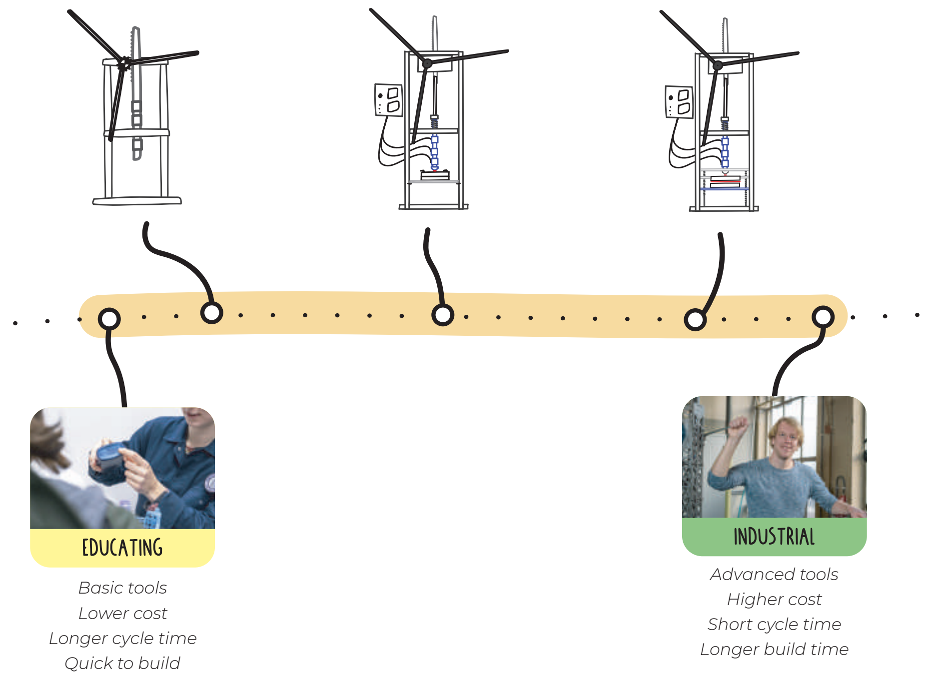
The initial approach to creating a choice-tool was to map the 'industrial' and 'educating' use cases on an axis opposite to another and to use different points on this axis as starting points for machine versions. Here, the assumption was made that the building criteria could be merged with these use-cases in a 'logical' way: For example, it would make sense to allocate 'advanced tool accessibility' to the industrial tool, as this version would likely require milling and lathed parts. Figure 55 provides a visual overview of this choice-tool.

Although this approach would be easy to understand and did enhance machine tailoring, it would still limit the builder in their choice: Assuming that the choice criteria would always fit the use-cases in this way meant that many builders would not see their situation reflected in the tool. For example, an educating user who happens to have easy access to a mill and lathe would have to either have to build an educating machine without using their advanced equipment, or build an industrial machine that did not fit their desired usage aim.

From the initial approach, the following Development Requirement could be devised:

- ***DR1:*** The framework should enable a builder to meet all their criteria in the machine without concessions

Figure 55: 1st Approach



Secondary approach

To improve on the flaws of the single-axis choice tool, the next approach was to expand the system by adding multiple axes with the building criteria to the usage case-axis. Within this system, the quadrants formed in between the axes would result in possible versions of the machine. Figure 56 provides a visual overview of this version.

Although this approach did improve upon previous flaws, this system would mainly cause other problems: Mainly, many of the versions derived from the quadrant would be quite illogical or impossible. For example, a high-cost, industrial version is quite impossible to be made with basic tools. Next to this, the system presented in figure 56 only factors in three axes, while in reality there are much more building criteria than this (i.e. desired build time, material accessibility etc.). Adding in these would only increase the complexity of an already incomprehensible system.

The main insight following this version is that any tool attempting to map machine versions on a scale would result in an enigmatic framework producing illogical outcomes.

From the insights on the secondary approach, the following Development Requirements and Wishes (DR/DW) could be devised:

- ***DR2:*** The framework should only present feasible, viable and desirable solutions
- ***DW1:*** The framework would be as understandable to a new builder as possible

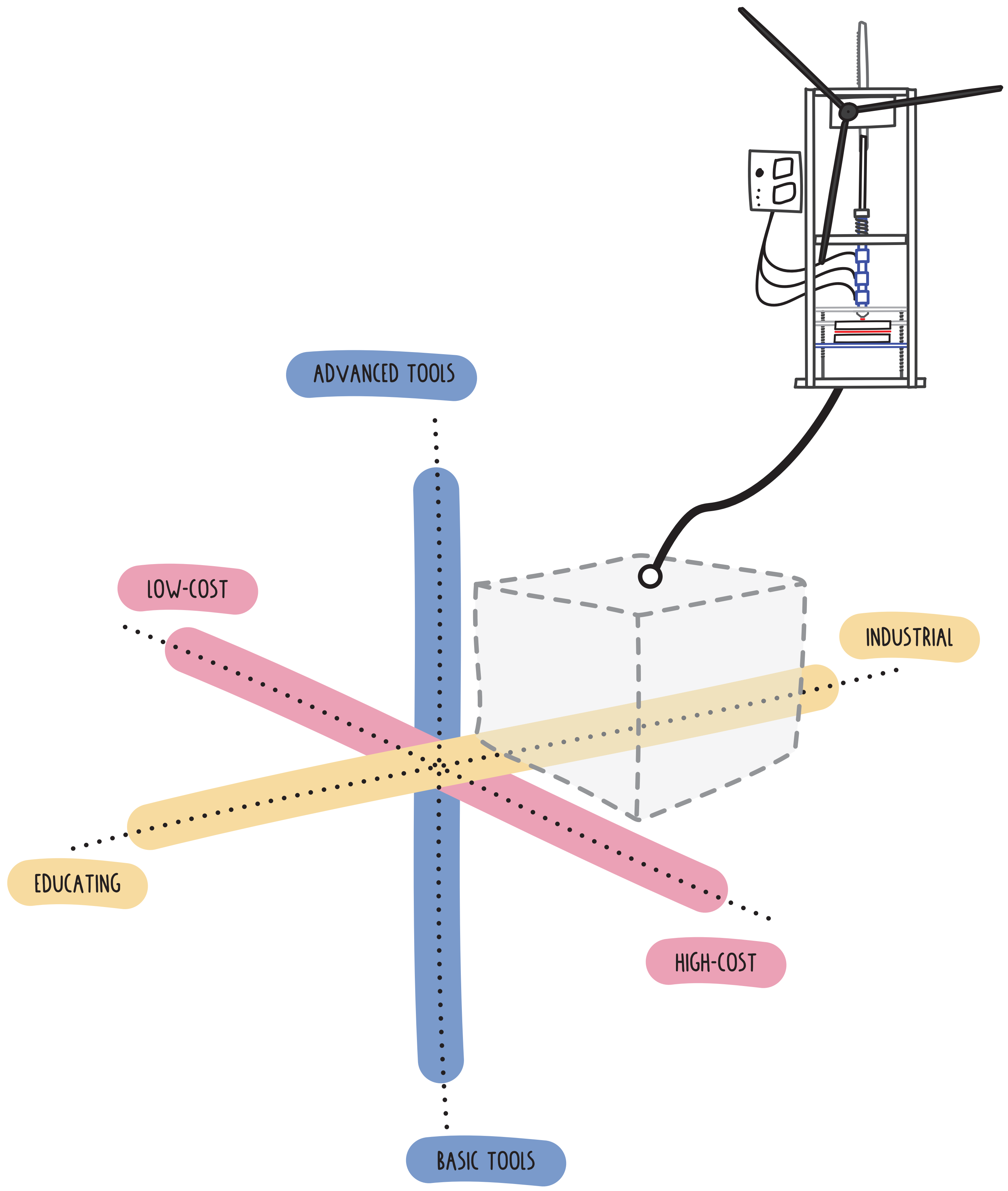


Figure 56: 2nd Approach

Tertiary approach

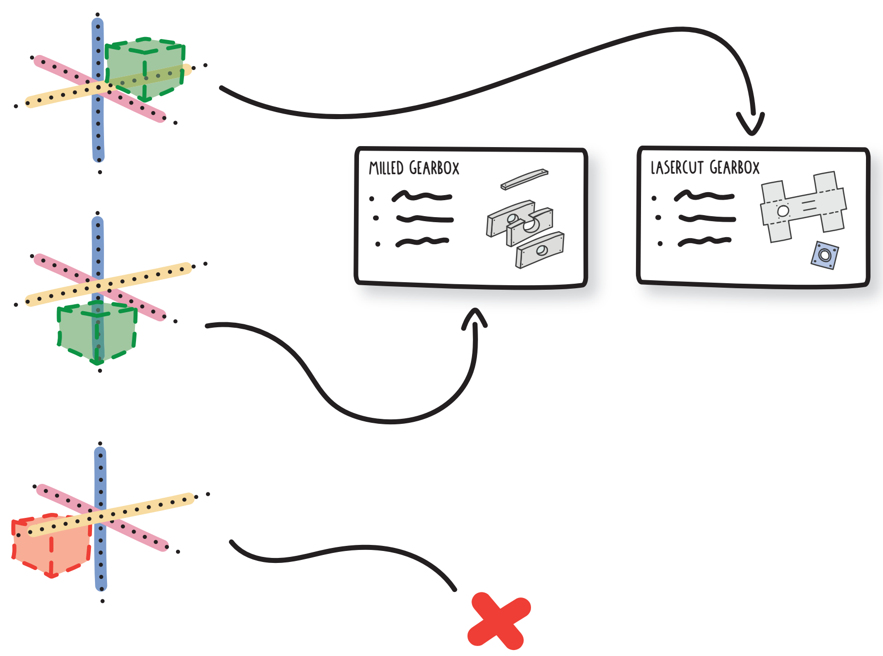
The tertiary approach was a direct result of the above insights. Instead of developing a rigid, analytical framework derived directly from usage and building criteria, the focus shifted to mapping the feasible ideas found in the ideation as presented in chapter 6.3. These ideas were grouped in different modules and resulted in the initial module variants. This approach resulted in the initial version of the presented Modular Design Framework. Here, the insights from earlier approaches were not left in vain: New module ideas were generated based on the promising quadrants from the secondary approach (figure 57)

However, the framework of module variants alone would still present a new builder with a confusing choice to make. Also, the framework developed in this approach does not yet stimulate builders in sharing back improvements.

From the insights on the tertiary approach, the following Development Requirements and Wishes (DR/DW) could be devised:

- ***DR3:*** The framework should invite builders to submit their own improvements and add-ons
- ***DW2:*** The framework would enable as much customization as possible
- ***DW3:*** The frame would quickly guide builders in their choice as much as possible

Figure 57: 3rd Approach

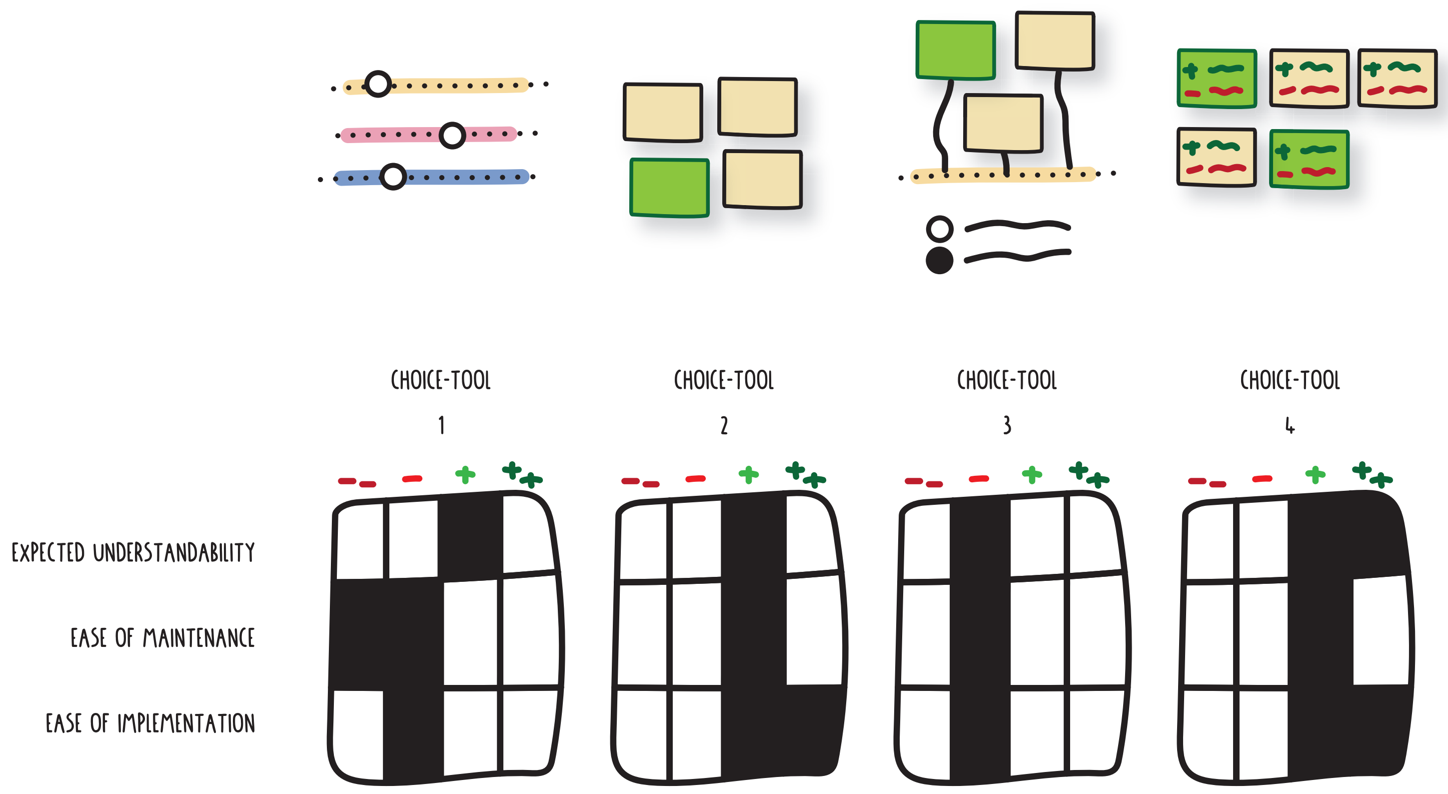


Quartenary approach

Within the vast field of options, some form of structure would be needed to make the choice for a builder easier. To this end, 4 different choice-tools were devised, which can be found in appendix I. To chose the optimum choice-tool, Harris-profiles were made using the relevant wishes from the LoR/W. Figure 58 shows the final Harris Profiles, from which choice-tool 4 is clearly the most promising idea.

By developing a small number of pre-sets based on usage cases, the builder is presented with a good starting point for their design. Next, they are enabled to diverge from the presets and tailor to their machine, while the implications on doing so are clearly explained. Therefore, this version is developed into the final Modular Design Framework.

Figure 58: 4th Approach



5.6 Concept Validation

Introduction and Approach

To validate the functioning of the Modular Design Framework concept, a qualitative user test was performed online with multiple machine builders. The aim of this test was to evaluate the main envisioned functionalities of the machine.

The following research question and sub-questions were answered through the validation:

RQ: To what extent does the Modular Design Framework stimulate the builder into active choice-making of their injection machine?

1. ***How well do participants understand the functionality of the Modular Design Framework?***
2. ***How do participants appreciate the possibility of tailoring their machine?***
3. ***To what extent the participants understand the impact of their choice?***

The research questions are based on the key envisioned functions of the Modular Design Framework as described in the introduction of chapter 5.1.

Methodology

To generate insights on the research questions, a qualitative usability test was conducted with a representative group of participants. In an online setup, participants generated data by interacting with a digital prototype through a talk-aloud session followed by an accompanying interview.

The test consists of two sections: In the first section, participants are asked to interact with the digital prototype while following a talk-aloud protocol (figure 59). A talk-aloud protocol is a form of usability testing in which participants are asked to simultaneously perform a task and verbalize their thoughts (Lewis, 1982). In this setup, the interviewer does not intervene in any way, neither by advising the participant nor by asking questions. This method ensures a higher chance of an honest rendition of the user experiences, with a lower risk of unintentionally steering towards a prejudiced outcome. Also, it enables the emergence of unexpected insights. This can also form a limitation of this method, as it is not possible to directly ask questions on the research questions.

To counter this limitation, the second part of the test consists of a short interview with questions based on the research questions. This interview can be seen as a backup in case the participants don't mention anything about the research topics during the talk-aloud protocol.

Test setup

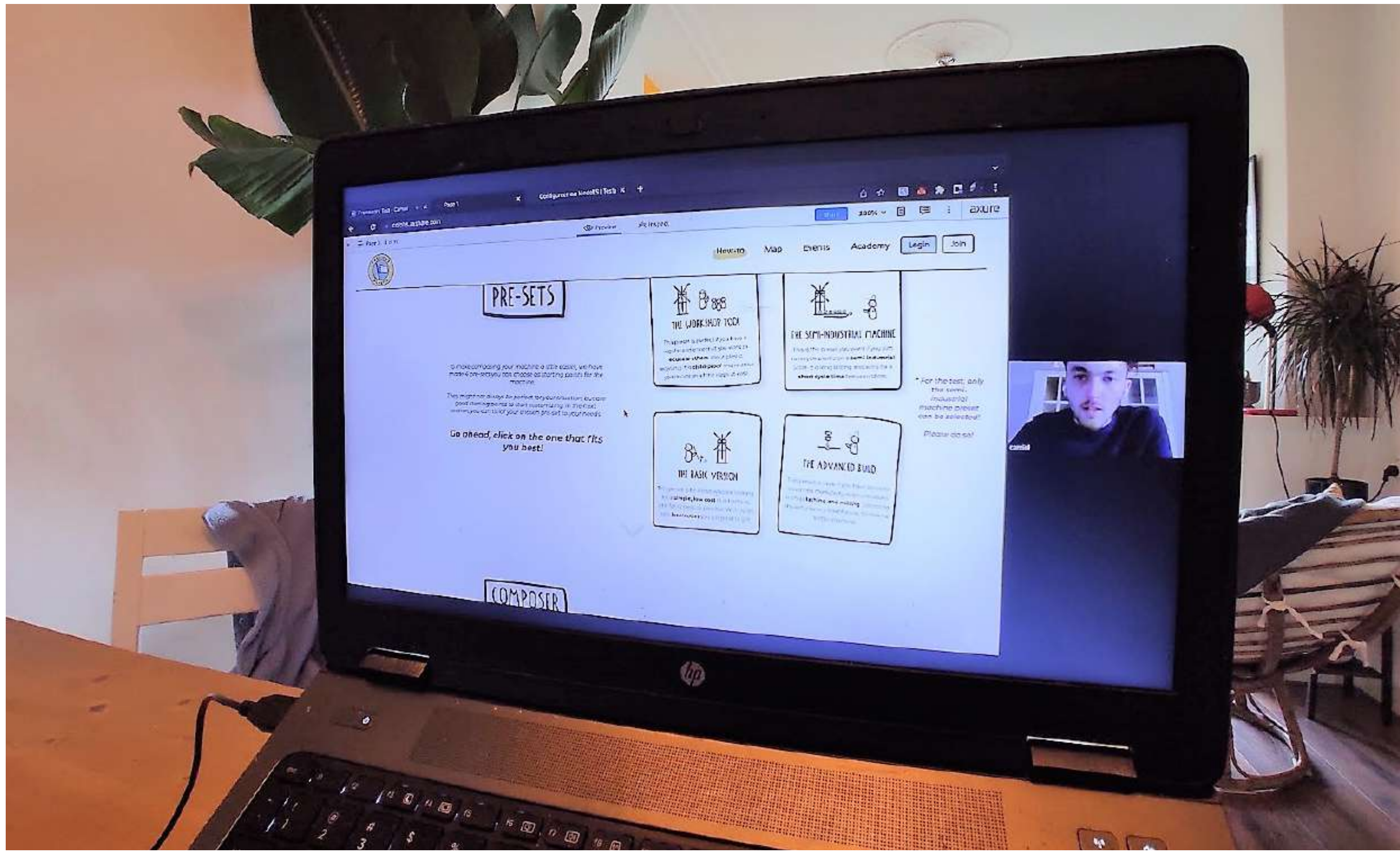
A total of 4 participants were recruited for the user test. Although this is a small test group, the qualitative nature of the user test still results in plenty of insights while also fitting in the limited time available in this project.

Participants were recruited on the Precious Plastic discord server. This was done to ensure familiarity with Precious Plastic and thus achieve realistic outcomes. The selection of the participants aimed for a diverse group of people in the factors of age, location and gender. The final group of participants showed sufficient diversity on the first two factors. Unfortunately, the diversity in gender was low due to the high proportion of men on the Precious Plastic Discord server.

The digital prototype website features the introduction, and pre-sets, composer and download & upload functionality as described in the previous sections to ensure high fidelity. However, not all sections are fully realized as this was not necessary for the evaluation of the research questions.

The test was setup online in a Zoom call to enable the participants to share their screens while interacting with the prototype (figure 59). During the session, they were sent a URL to access the prototype on their browser. They were asked to keep their microphone and camera on at all times.

Figure 59: Test setup



The test followed the following procedure:

1. Upon joining the Zoom-call, participants are welcomed and introduced to the goal and setup of the test.

2. The participants are asked to do a quick practice session on the Tesla website to get acquainted to the talk-aloud experience.

3. The participants are asked to put themselves back in the shoes of starting their machine build (sensitizing). They are instructed to gather all they need to start building on the digital prototype website and are once again asked to talk aloud while interacting.

4. The participants interact with the digital prototype. During this time, only they are able to speak.

5. Once the participants click on the download-button, the test is ended.

6. The test is concluded by the short interview.

The results of the test consisted of the participants verbal input during the talk-aloud section, observations and answers to the interview questions. The zoom-calls were recorded for later analysis once participants consented. The sessions took anywhere between 20 and 30 minutes in total. The full transcripts of the sessions can be found in appendix J.

User test Results

The sections below provide the key insights for each research subquestion.

Understanding the functionality

The functionality of the overall framework is reasonably clear and understandable. All participants spontaneously mentioned the intended functionality of the tool during the talk-aloud session.

"Ahh right.. If I scroll down I can select which things I want to build based on what my capabilities are" - Ian

- Although all participants eventually figure out the functionality, for 3 out of 4 participants this was not immediately clear. After scrolling around for a while, participants had an 'aha' moment upon seeing the composer tool.

- The introduction text and visual (figure 60) play an essential role in explaining the functionality of the tool to the participants. 2 out of 4 participants initially skipped over it, but returned a little later to read the text. These participants suggested this might have been due to the small font size, which might be an area of improvement.

  "The introduction text is quite important to understand what's happening. The image makes it very clear, I like the graphic" - Ian

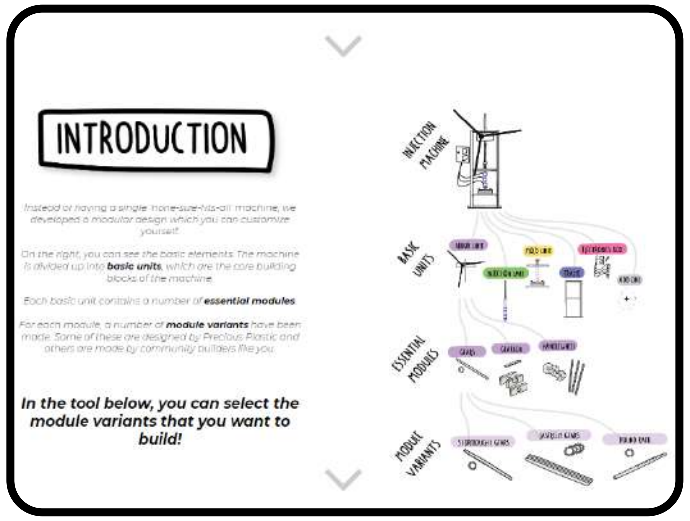


Figure 60: Snapshot of the introduction text and visual

"It is like building a character in a game: you start with a base, and then customize"

- Taylor, participant

Understanding functionality (continued)

- The presets enable participants to indicate their general preferences and are well understood.

  "It is a nice flow of information. First you get the end goal in mind, after this you can customize and go back and forth" - Andrea (figure 61)

- The composer tool enables builders to make a choice between variants upfront.

  "Building my own injection machine was like making an IKEA shelf. With this tool, you kinda create your own personal machine" - Camiel

- The 'call to action' on customizing the build should be clearer. Especially for participants who don't read the text carefully, the goal of the composer tool is not immediately clear. However, all participants eventually figured out what they could use it for.

  "If you are not paying attention, you might not know that you are able to select something" - Ian

Appreciating tailoring

The possibility to tailor and customize the design of the machine upfront is a valuable functionality.

"If I had had this with the build that I made, my life would have been much easier" - Ian

"Everyone iterates, and that's not clear on the [current Precious Plastic] site. This [tool] helps people understand that there is a lot of variants and it helps them make a good choice. Even if they don't use it, only seeing it gives them a good overview." - Taylor

- Compared to the How-To's, presenting variants upfront enriches the building process.

  "I've seen the how-to's on the [current] website, but only after I made my machine. This is a lot more inviting, as you can't really get around it" - Camiel (figure 62)

- Although the tailoring feature is appreciated, one participant mentions that it might be too overwhelming for new builders.

  "You should also have a base version that you could get without the customizer tool. That would be easier for a lot of people." - Taylor

Figure 61: Andrea figuring out the composer tool

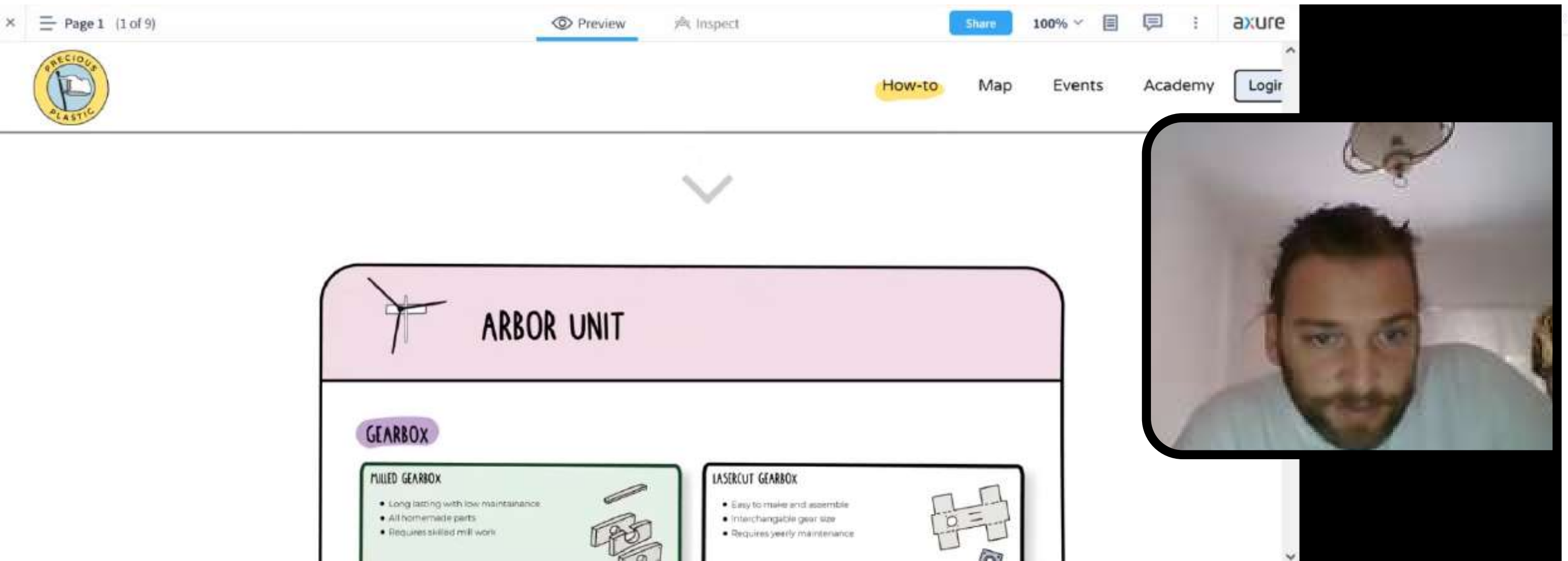
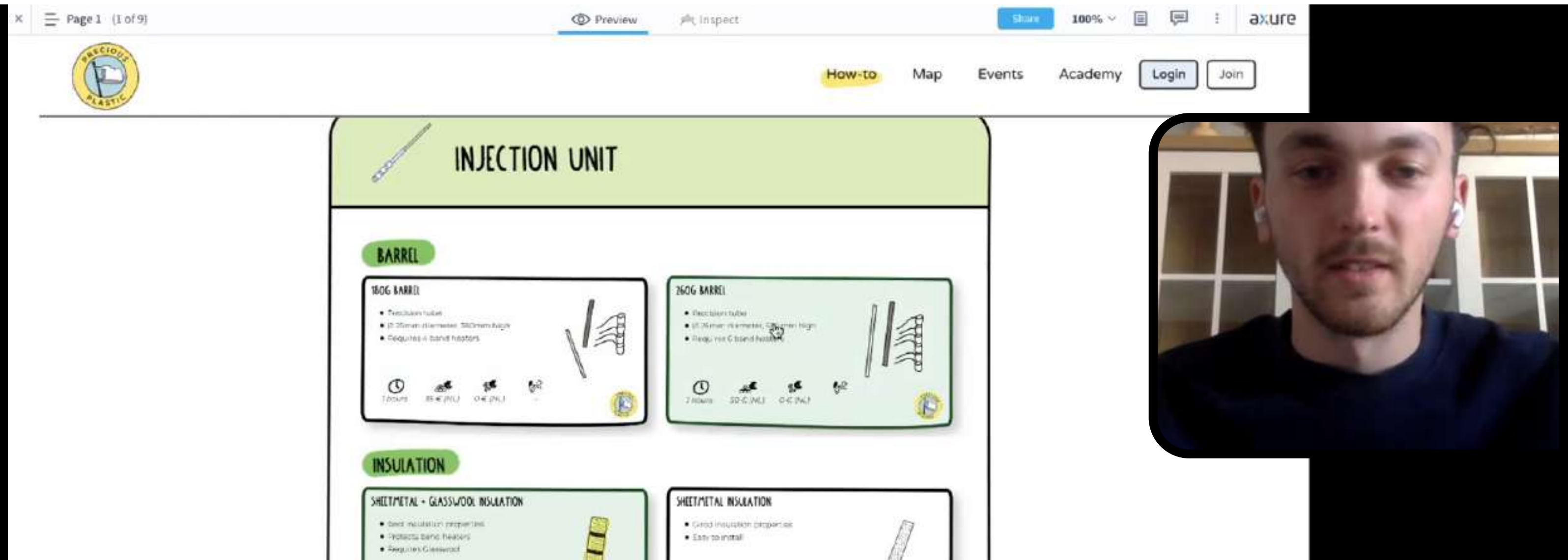


Figure 62: Camiel clicking on a module variant



Understanding impact of choice

The framework ensures builders know about the choice they make.

- Especially the choice-factor icons in the module variants give the builder a clear picture of what to expect (figure 63).

  "I see icons about money and time.. So I know the hardness of [the build]. I'm looking at hours first. Ah, this is work labour and this is materials. I deciphered from the icons. [..] I want to realize my design quickly, so I'm selecting lasercut stuff." - Andrea

- Although the developed framework enables the builder to see the impact of each variant in relation to others, there might be a lack of an overview of the resulting machine configuration.

  "It would be very nice to see the total price and [necessary] tools before I go and download". - Ian

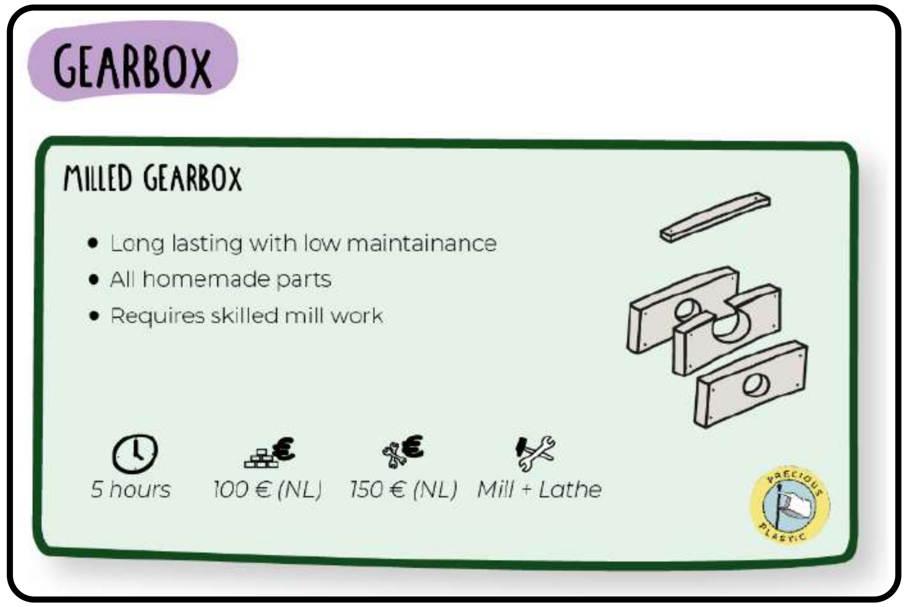


Figure 63: A module variant with choice-factor icons

Additional Insights

The user test mainly yielded insights from the evaluation of the key functionalities of the prototype. However, due to the open setup of the test, participants frequently provided insights on the current shape and appearance of the framework. Due to the early stage of the concept development, this was not a primary research objective as the functionalities described above are prioritized. However, they can be of use for future improvement of the prototype and are thus reported below.

- Due to their layout, some participants tried to click on the section headers.

  "I want to click to 'hey', it looks like a button" - Andrea

- The illustrations on the module variants are inviting, but also a bit misleading.

  "The illustrations clearly show what the module is about, it looks very nice. But it might be looking a bit too simplistic, like you don't know what you're getting into once building". - Taylor

- The icons on the module variants are small and hard to read.

- 2 of 4 participants expressed their appreciation of the existence of an upload form (figure 64). This test cannot confirm that builders will actually share their improvements more then they currently do in the How-To system. This could only be convincingly tested in a scenario where builders would actually use the Modular Design Framework for a build instead of a fictive scenario. However, the positive comments on the upload form suggest it might be a valuable addition.

  "[The upload form] is a really good idea, it makes sense to enable people to upload their new stuff. I could see myself doing it". - Taylor

Figure 64: The upload form for new variants

Discussion

Key findings

The user test aimed to investigate how the Modular Design Framework could stimulate builders into active choice-making on their machine. The following key insights were found upon analyzing the test results:

- **Users understand the purpose** and functionalities of the tool. Through the structured flow of information, users are able to adjust to the complexity of the different module variants.
- **The tool is not self-explanatory** and requires carefully reading the accompanying texts. This could be a hurdle for some builders.
- **The presets are helpful** in guiding users to their preferred machine setup. They are used in the correct way and make the tailoring process quicker for the builder.
- **Users highly appreciate the possibility of tailoring** their machine upfront. The composer tool enables builders to make a conscious choice. However, for some inexperienced builders it might be confusing and not relevant.
- **Users understand the impact of their choice**, but an overview of their customized machine could help them see the full picture.

Limitations

The small number of participants in the test limits the generalizability of the results. In all likelihood, not all builders types are reflected in the test which might give a skewed image of the results. For example, it is imaginable that certain builders might use the presets or composer tool in a different way or not at all.

Also, it is possible that the warming-up exercise on the customization tool of the Tesla website has influenced the results. As participants had already gotten used to the activity of customizing here, this might have made it easier for them to understand what they had to do in the composer tool.

“If I had had this with the build that I made, my life would have been much easier”

- Ian, participant

Conclusion

With regard to the limitations, the insights from this test still meet the purpose to evaluate the value of the Modular Design Framework. As all participants convincingly and spontaneously mentioned the functionality of the tool as a valuable addition to the building process, the results suggest at the very least that the Modular Design Framework is worthy of further development and testing.

The test results suggest the following for further development:

- **Make the tool more self-explanatory**. The structured flow of information helps the builder to understand the purpose of the tool, but relies heavily on users actually reading all the text. This is perceived as a hurdle and should be improved.
- **Show the full picture**. The test results suggest that adding an overview of the customized machine would help builders make an even better choice. This overview would show the totals of the choice-factors such as required manufacturing techniques.
- **Consider a complementary ‘fixed’ design**. The test results suggest inexperienced builders might find the tool a little confusing. Therefore, the addition of a non-customizable version should be considered.
- **Improve the layout**. Many builders commented on the, at times, confusing appearance of the tool. Being a prototype, this was expected, but future iterations should focus on creating a more intuitive tool.

5.7 Relevance and limitations

The development of the Modular Design Framework focused on delivering a support system for the design of the advanced injection machine that could enable builders to customize their injection machine based on their own needs. As the previous section validates this functionality of the Modular Design Framework, this section describes the relevance of the concept for other Precious Plastic machines and the world of Open Source Hardware in general.

One of the key limitations of the Modular Design Framework concept is the fact that it requires a design with a wide variety of feasible module variants. However, many machines designs might not lend themselves for a modular system like this. For example, the design of an extrusion machine might have less room for alternative module variants. This factor might make the further application of the concept limited.

However, the concept does have an additional relevant application outside the project scope. As chapter 3.8 concludes, the vast majority of Open Source Hardware projects are developed privately.

One of the key downsides of this way of working is the fact that the design process is often not properly publicized and documented. In many cases, only the end-result is published, leaving valuable data such as alternative design directions or concepts to be lost. Here, the Modular Design Framework could present an opportunity at an improved way of working. One of its unique selling points is the possibility for community builders to upload their own module variants. By expanding on this feature, the framework could be deployed as a decentralized platform to openly develop new innovations. Similar to how a ledger works, multiple contributors could share different versions of sub-assemblies on the platform as module variants in a structured way. This enables independent contributors to design, evaluate and share design work in a truly open way.

Ultimately, opening up the development of Open Source Hardware products would benefit their rate of innovation: Including a more diverse set of contributors enables the project to be sustained over a long time with varying contributors.

5.8 Implementation

To conclude the development in this project, this section presents the recommended next steps for Precious Plastic aiming to successfully continue the development of the concept. Upon reading this chapter of the report, it should be apparent that the Modular Design Framework is by no means a finished product. Through the Technology Readiness Levels (TRL's) developed by ESA (ESA, 2020), the current stage of the concept is estimated at TRL3: The critical functions of the concept are experimentally validated. To continue the development of the concept, the following steps are recommended.

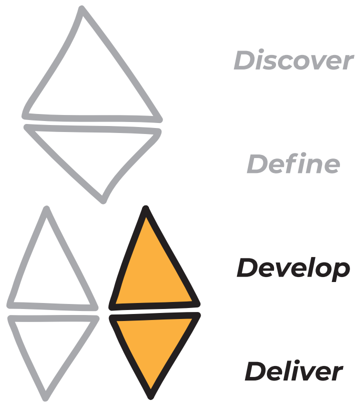
- **Internally evaluate continuation**
  In this project, no in-depth investigation was done on quantifying the required effort on implementation and maintenance of this tool. This is due to the limited scope of the project and the conceptual stage of the framework. If not, the concept should be pitched to an academic party in the world of Open Source Hardware such as Delft Open Hardware to continue the development.

- **Improve digital prototype**
  The concept validation presented in section 5.7 concludes with a number of recommended improvements on the Modular Design Framework. These should be implemented in the prototype, which should be integrated as a beta-version on the Precious Plastic website.

- **Perform real-world tests**
  Upon improvement of the digital prototype, further real-world testing of the concept is recommended. In order to successfully do this, a finished set of buildable module variants should be developed for users to test with. For these, the developed module variants for the Advanced Injection Machine as described in chapter 6.3 provide a good starting point.

6. Advanced Injection Machine

The Advanced Injection Machine is the second outcome of this design project and is the direct result of the second project goal defined in chapter 4.1.



6.1 Unique Selling Points

Figure 65 shows the final design and prototype of the advanced build.

- The machine can achieve a **pressure of 100 bar** within the barrel, which is a significant improvement compared to the 42 bar of the current injection machine. This allows the user to create injected product with more definition and smaller wall-thicknesses. This substantially broadens the scope of products that can be made with the machine and thus adds value for the recycler. Even pressures of up to 250 bars can be achieved if necessary by elongating the levers, expanding the production scope even more.

- This injection pressure can be reached with a **manual input force of only 350N**. This is another huge advantage compared to the lever injection machine, as the latter required the builders full body weight to only reach 42 bars. It not only greatly enhances the ergonomic operation of the machine, but also enables more people to use it: Within the context of vulnerable informal recyclers, this design improvement especially enables women to operate the machine which improves their position in recycling spaces.

- The usage procedure of injecting plastic is **easier and safer** compared to the current machine. Instead of needing to manually screw a hot mold to the nozzle, the mold can simply be placed on a mold table after which the nozzle self-engages. This drastically improves the machines safety while decreasing the cycle-time and human effort per injection shot.

- The advanced build meets **most criteria to be CE-certified.** This enables machine builders to sell the machine to others in compliance with European law, which stimulates growth of the Precious Plastic Universe.

- The modular design of the machine enables the builder to easily **replace or upgrade** components. For many components, this is impossible in the current injection design due to the many welded connections. Also, this has the added benefit that builders can easily resell modules to others on the Bazar ensuring a more circular system.

Figure 65: The Advanced Injection machine

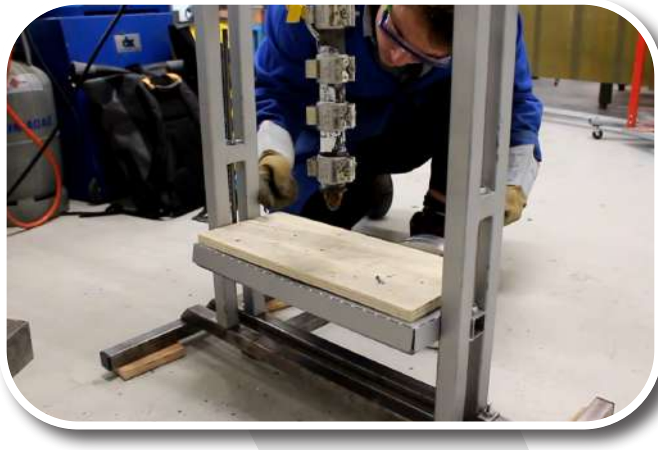
6.2 Usage Scenario

This section features a scenario of the key usage steps in succesfully using the Advanced Injection Machine.

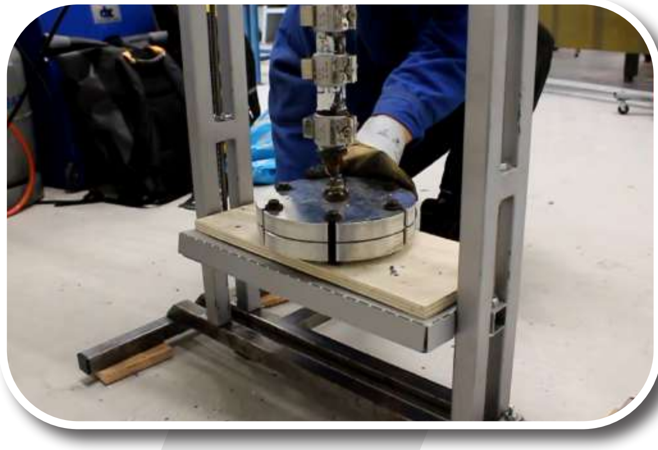
1.
The injection process starts with pouring plastic into the hopper of the the preheated machine.

2.
By applying a bit of pressure, the plastic flakes are compacted. This is done to decrease the melting time.

3.
To ensure the plastic is fully molten, the user should wait for around 10 minutes.

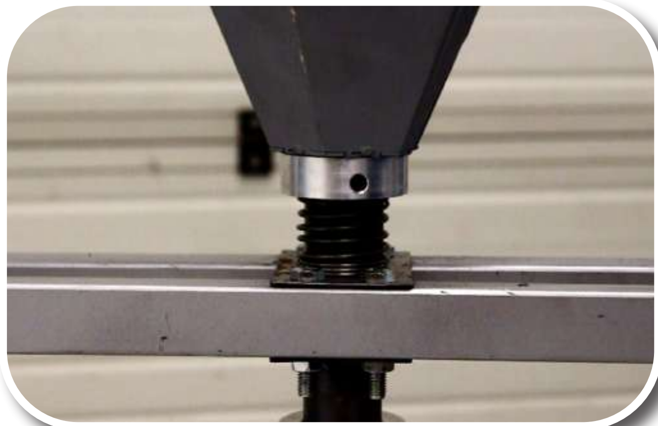


4.
By turning the bolts on either side of the mold table, it can be positioned onto the right height.



5.
The mold can be placed on the table. At this point, the nozzle should be max 2 cm above it.

6.
By applying force on the handlewheel, the user can start the injection process.

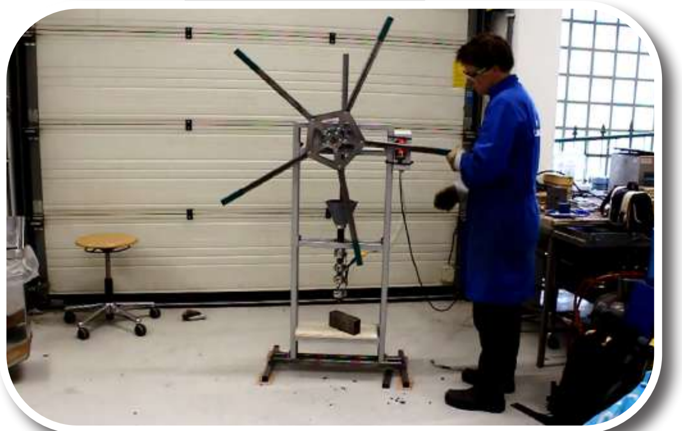


7.
Once pressure is applied, the auto-engagement spring compresses causing the barrel to lower.

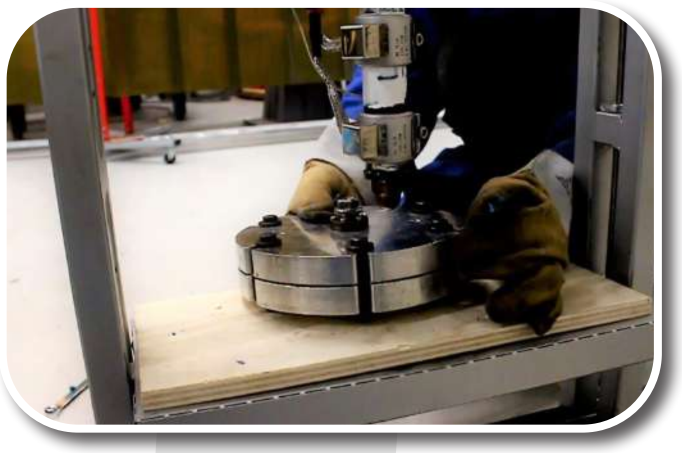
8.
As the barrel lowers, the nozzle connects with the mold opening. The injection pressure secures the seal.

9.
The user holds the pressure on the barrel for about 1.5 minutes to ensure the mold is full.

10.
By turning back the handlewheel, the pressure from the barrel is relieved and the mold deconnects.



11.
The deconnected mold can be removed. To save time, the user can already start melting more plastic.



12.
The user opens the mold to reveal the injected part, which can be carefully removed.

12.
The finished part is post-processed and checked for any defects. The user is done!

6.3 Development Overview

Introduction

This chapter describes the embodiment design of the module variants composing the advanced injection machine. To ensure this report remains readable, the following pages only present an overview of the key insights found during the development of each module. However, a detailed development overview of all modules is presented in appendix K. The reader is highly advised to read this to fully understand the design choices of the modules.

The module variants were developed in close collaboration with machine experts in the Precious Plastic Discord channel through the co-design method. In line with this method, the multiple iterations were shared online in the 3D CAD-software by GrabCad. By sharing the design online, experts could see the full details of the 3D models and comment on this. The details on the embodiment design in appendix K also include an iteration overview for each module. An example of this is presented in figure 66.

Throughout the development of all modules, the main principles of the Design for Open Development, were also kept in mind. On a practical level, these implicated the following:

- **Minimal number of different material archetypes**. For example, this means all tubes are the same which makes material sourcing as simple as possible.

- **Use of standardized parts**. To this end, only M5, M8 and M10 bolts are used.

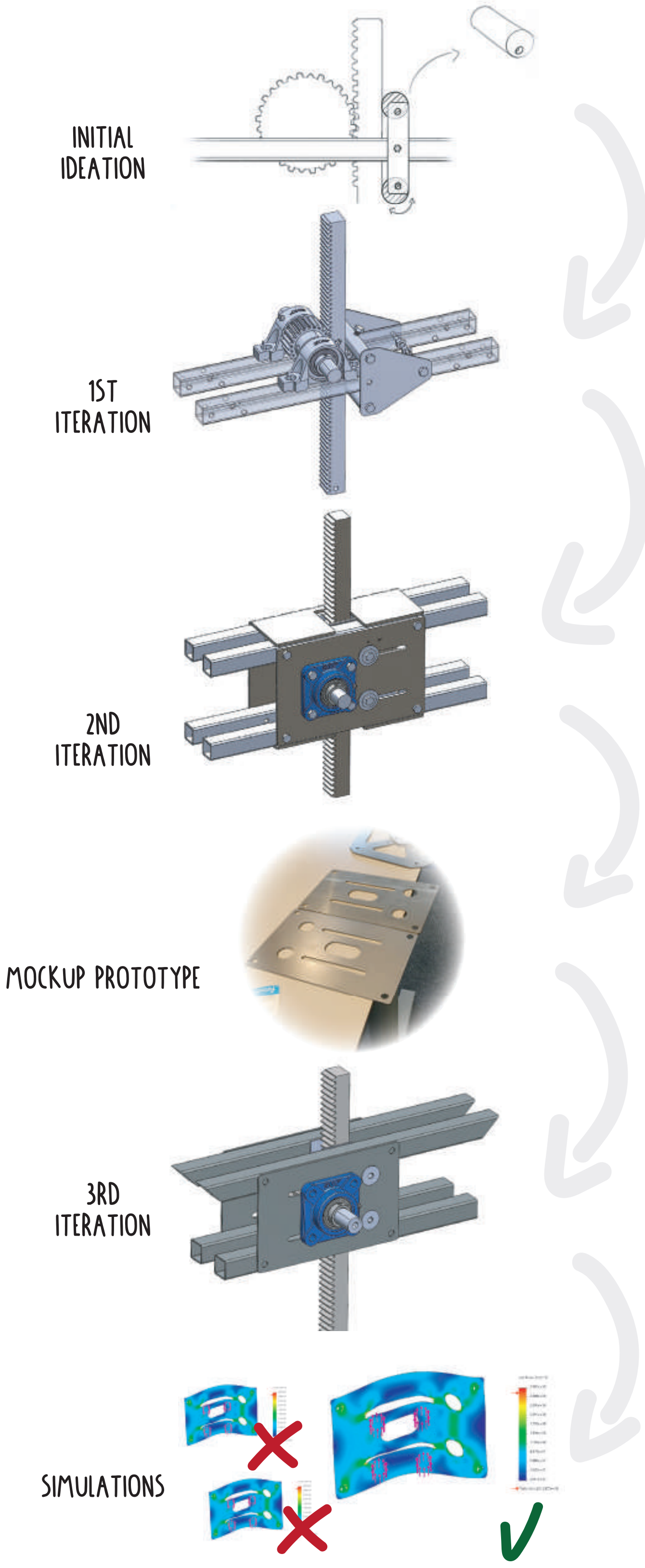
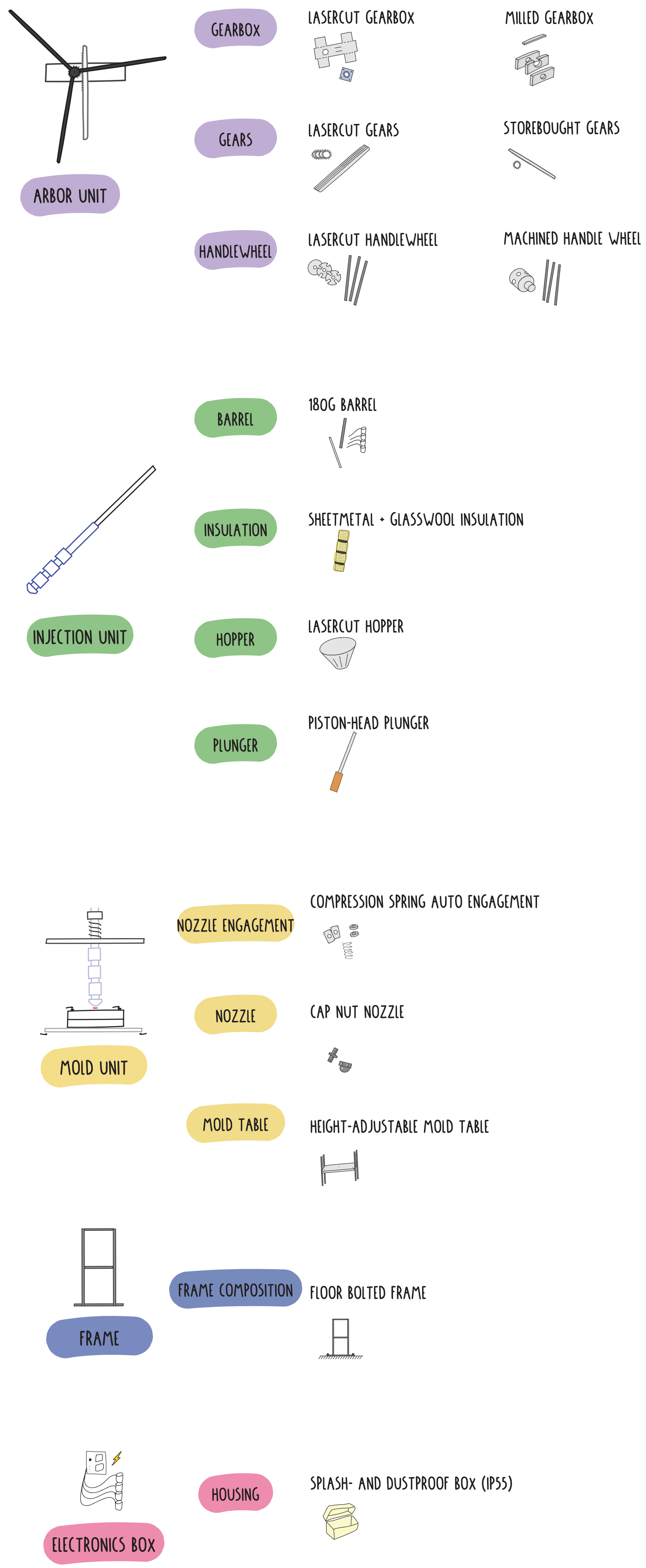


Figure 66: Example of iteration timeline



The advanced injection machine developed in this project is composed of the module variants from the 'Advanced Build' pre-set as defined in chapter 5.3. Next to these, a few module variants from other pre-sets were also developed during this project.

Figure 67 provides an overview of the developed modules.

Figure 67: Developed Modules

Ideation Overview

To capture all initial ideas, existing solutions and common upgrades, an ideation overview is made. The ideas within the overview are the result of 2 ideation tracks:

- Primarily, ideas were mentioned by machine experts in the Precious Plastic Discord Server. These should be seen as outcomes from the co-design method.
- Next to this, a creative session was organized on 08.04.2022 with design students from the IDE Faculty at TU Delft (figure 68). The session was organized following the '6-3-5' method (Rohrbach, 1968) to enable participants to draft plenty ideas.

The ideation overviews were supplemented with occasional extra ideas throughout the project.

To provide clarity, the ideas are structured per conceptual unit as defined in chapter 3.5. Figure 69 shows a snapshot of the ideation results, the full-scale posters can be found in Appendix L.

Figure 68: Ideation session in action

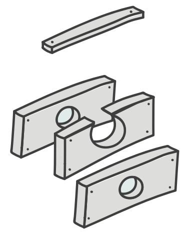
Figure 69: Ideation

Overview of Embodiment Design

Below, the key insights found in the development of the modules are described.

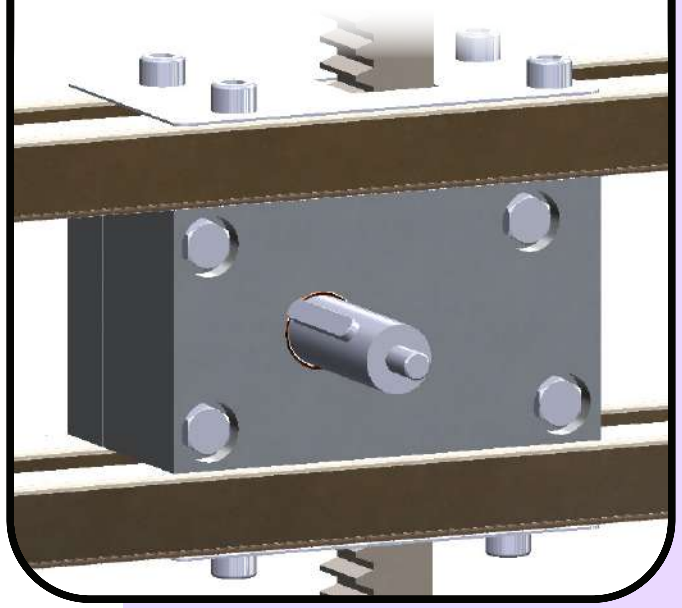
ARBOR UNIT

↳ GEARBOX



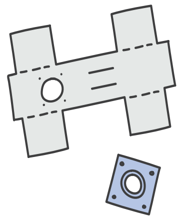
Milled Gearbox

- Features a slanted bearing block which enables the builder to perfectly mesh gear teeth to prevent long-time wear.
- Inspired by the 'Elena' Machine by Plastic-Hub and the Arbor Press by Le Recycleur Fou.
- Includes lasercut top plates to prevent the user from accidentally placing their finger in between gears.
- Primarily made from milled aluminium slabs



ARBOR UNIT

↳ GEARBOX

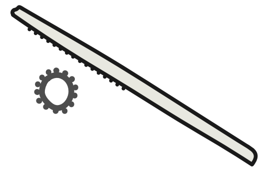


Lasercut Gearbox

- Two lasercut plates form its base.
- The rack rolls over two roller bars with sleeve bearings.
- The bearing blocks suspend the spurgear and are fixed anywhere along slots in the base plates.
- The position of the bearing blocks can be change, which allows for multiple spur gear sizes. This is a key advantage over the milled gearbox.
- The gearbox is primarily made from 3mm steel lasercut plates.

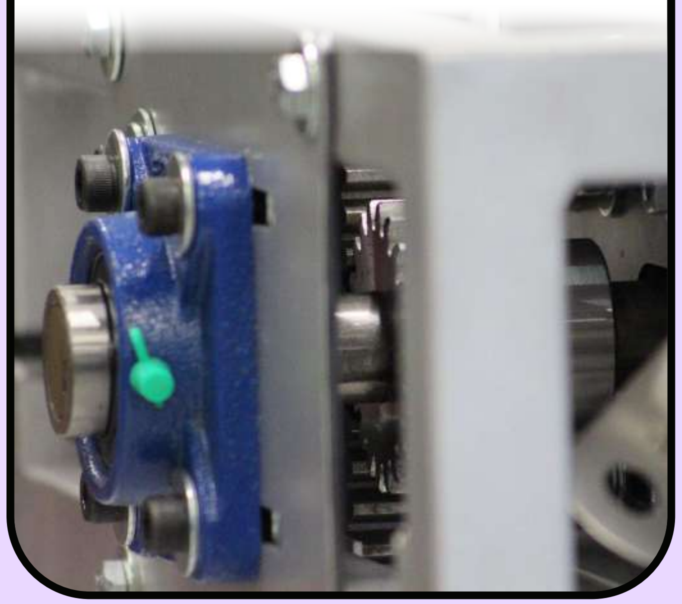
ARBOR UNIT

↳ GEARS



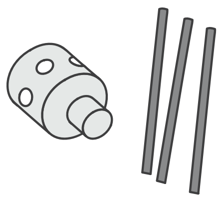
Storebought Gears

- The spur-gear for has a teeth number of 20, which gives a good balance between injection pressure and injection speed.
- The rack is 500mm long.
- The gears are of module size 3, which has the optimum strength-to-weight ratio for the forces on the machine.



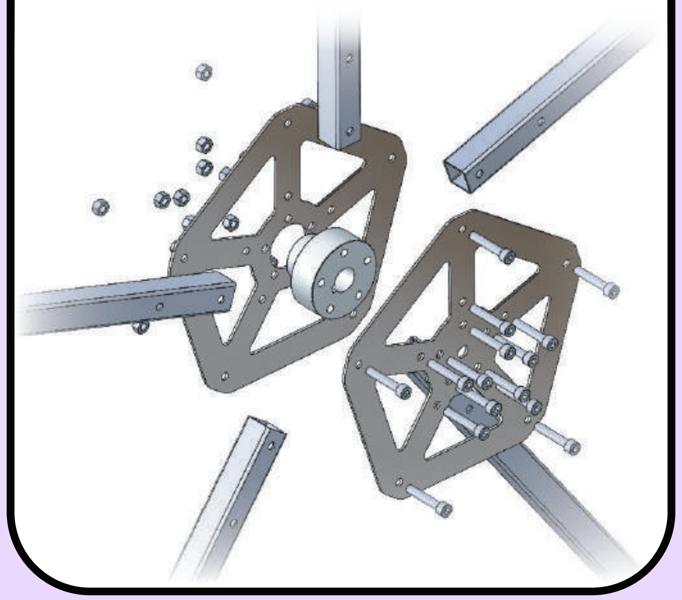
ARBOR UNIT

↳ HANDLEWHEEL



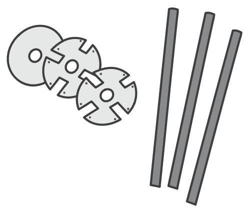
Lathed Handlewheel

- Largely inspired by the Johannplasto's injection machine and the 'Elena' Machine by Plastic-Hub.
- Features a lathed steel core which is connected to the main axis with a keyway connection
- Making the core requires a broaching tool, which makes this option only available for advanced builders.
- Main design addition is in the form of two cover plates that decrease the amount of force on the core.



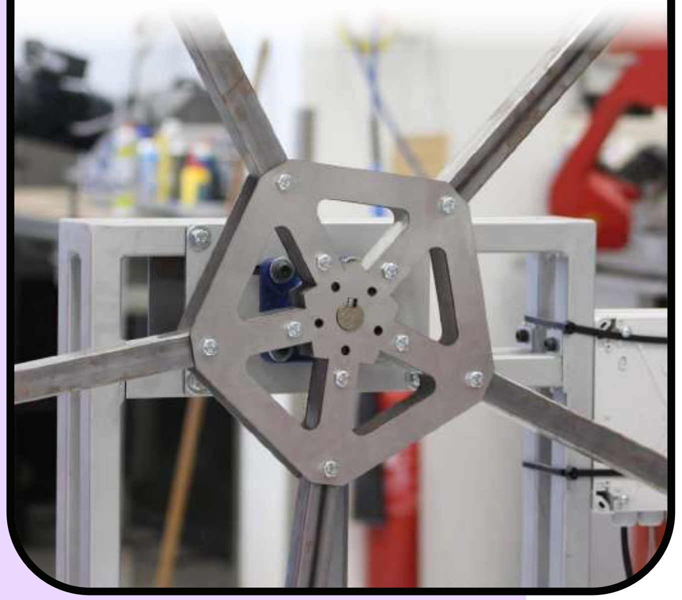
ARBOR UNIT

↳ HANDLEWHEEL



Lasercut Handlewheel

- Similar to Lathed Handlewheel, but fully made from 3mm thick metal lasercut sheets.
- Instead of a broached, lathed core, a stack of lasercut disks provides the main force transmission to the axis. As the lasercutter can cut the keyway, no broaching tool is needed. This makes variant drastically more simple to build.
- The lasercut keyway does come with an increased risk of wobble on the main axis over time.



INJECTION UNIT

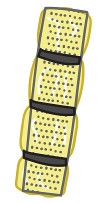
↳ BARREL

180g Barrel

- The barrel is of the same type as the one in the current injection machine.
- Its main requirement is that it should be a precision tube. These tubes are manufactured without a welding line on the inside, which ensures the plunger can run smoothly.
- The barrel is surrounded by 4 band heaters rated at 250 Watt each, generating the heat necessary.

INJECTION UNIT

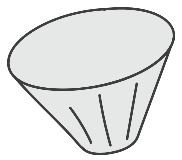
↳ INSULATION



Sheetmetal / Rockwool Insulation

- The main insulator is a 40mm thick band of rockwool, which can easily be found in larger hardware stores.
- The band of rockwool is surrounded by a thin lasercut sheetmetal housing
- The main function of this housing is to prevent the rockwool from disbanding and to keep the tiny plastic flakes away from the band heaters.
- The housing is disassemblable.

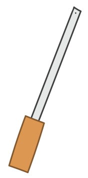
INJECTION UNIT
↳ HOPPER



Lasercut Hopper

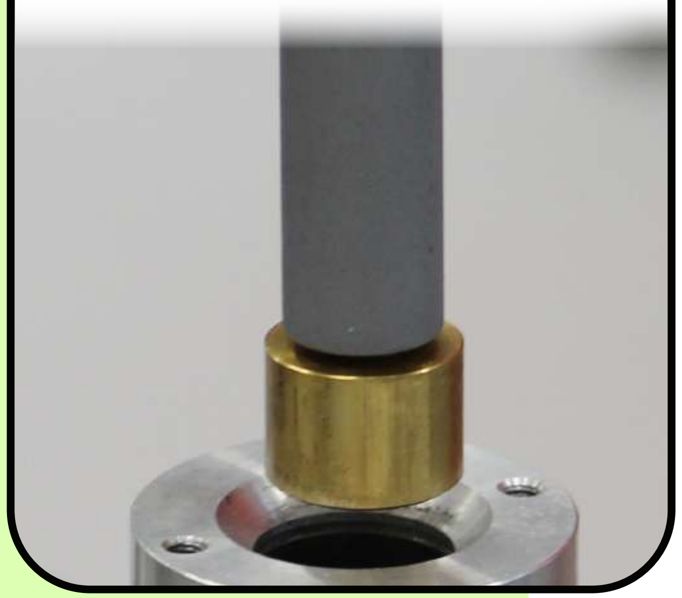
- The hopper is made from two lasercut, 1mm thick sheetmetal side-plates and one 3mm thick base plate which are welded together.
- The baseplate features two holes to connect it securely to the top of the barrel with bolts.
- The side-plates have small strips on the bottom, guiding the builder in connecting it to the base plate.

INJECTION UNIT
↳ PLUNGER

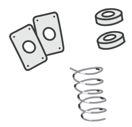


Pistonhead Plunger

- The piston-head plunger idea was proposed by builders in the Discord Community as an improvement on the solid plunger
- The piston-head is made from brass as this material has a low coefficient of friction with the steel barrel
- The plunger-head can be very easily customized to the specific barrel diameter of a builder.
- The pistonhead plunger requires access to a lathe.

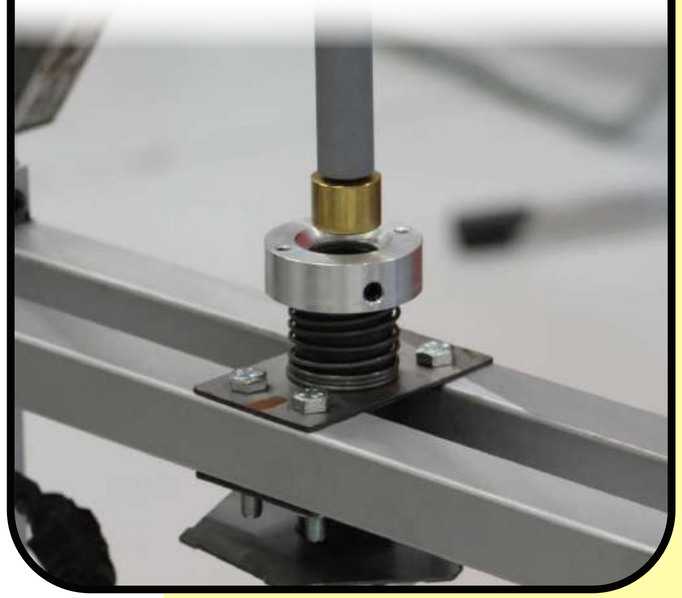


MOLD UNIT
↳ NOZZLE ENGAGEMENT

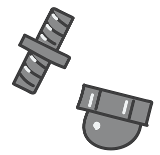


Compression Spring Nozzle Engagement

- This system is the key element in improving the user experience of connecting the mold. It automatically engages with the mold gate when injection begins.
- The key component is the spring, which holds the barrel and compresses once injection begins.
- An aluminium ring connects the barrel to the spring and guides the plunger into the barrel.
- This is an advanced feature, as it requires many lathed parts.



MOLD UNIT
↳ NOZZLE



Cap Nut Nozzle

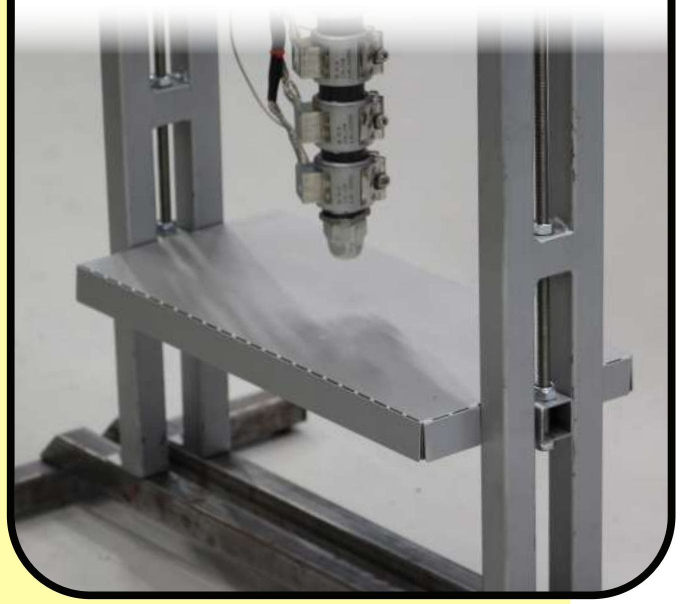
- This nozzle is made by drilling a 6mm hole in an M16 Cap Nut.
- The domed shape of the cap nut ensures a tight connection to the mold gate.
- To connect the nozzle to the barrel, a lathed connector piece is required.
- The cap nut nozzle was a suggestion made by Friedrich Kegel

MOLD UNIT

MOLD TABLE

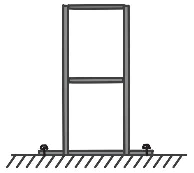
Height Adjustable Moldtable

- Its key feature is the ability to facilitate molds of different sizes.
- This is achieved by suspending the table to the frame on either side through threaded rods.
- By turning the bolts, the table can be moved up and down.
- The table should always be positioned so the mold gate is within 2cm of the nozzle.



FRAME

FRAME COMPOSITION

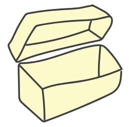


Floor Bolted Frame

- The frame is assembled from 6 separate frame parts and is mainly made from welded 30x30x2 square steel tubes
- Metal connector plates enable the builder to finely adjust the height of crossbeams in the installation process.
- The bottom section of the frame can be disconnected in case the frame needs to be shipped.

ELECTRONICS BOX

HOUSING



Water- and Dustproof Electronics Box

- The electronics box is made from an IP55-rated enclosure with 60% empty space to adhere to the EC regulations.
- The front of the box features the interaction screens of the two PID-controllers
- The PID interfaces face the user while injecting so they can keep an eye on the temperatures during injection

6.4 Solidworks Simulations

To validate the strength of structural components in the design of the Arbor press, Solidworks Simulations is used to perform Finite Element Analyses on these parts (figure 70). A finite element analysis generates a mathematical model of a CAD part and uses this to predict the part's behavior under various loads.

Load Case

To set up the analysis with the correct parameters, a load scenario is drafted to describe the most extreme use-case of the machine. In this scenario, a Dutch male of over the 95th body weight percentile would hang on the tip of an Arbor Press lever (figure 71). This would result in a weight of 104kgs (Dined, 2022) or 1,020N at a distance of 60cm from the main axis. Although this is already an extreme use case, a safety factor of 1.5 is applied to the force to ensure all parts are rigid.

Using the set of gears described in chapter 6.3, this scenario results in the following loads:

- An axial load of 24,544 N on the plunger and rack.
- A torque of 918 on the main axis and handlebars

During the development process, simulations were used to validate and iterate on parts.

Figure 71: A person holding a lever

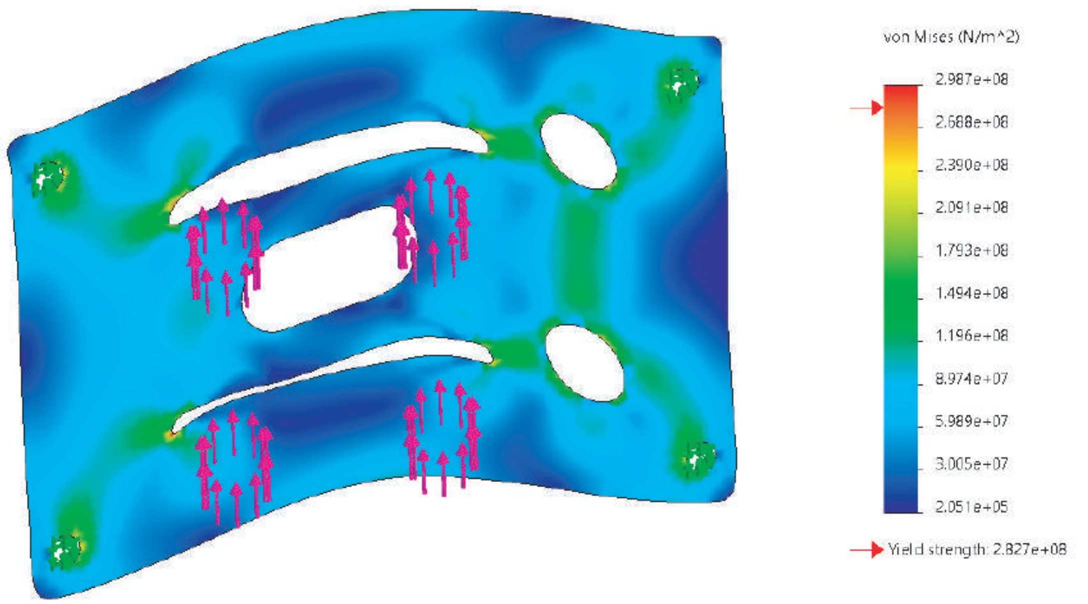


Figure 70: A Finite Element Analysis performed on the gearbox baseplate

6.5 Design Validation with Experts

Introduction and Approach

To validate the performance of the prototype, a test session was organized with experienced builders. The aim of this test was to evaluate the technical functionalities of the prototype and to find critical areas of improvement. The test was executed with Carolina Espinoza (Product Designer at the Precious Plastic Core team) and Jerry de Vos (Precious Plastic v3 team and project mentor) (figure 72).

The following research questions were drafted:

RQ: To what extent does the prototype deliver on the key envisioned functionalities?

1. ***To what extent is the prototype able to successfully inject plastic into injection molds?***

2. ***How does the prototype compare to the original injection machine?***

3. ***What are the most critical areas of improvement for the design of the machine?***

Figure 72: Caro and Jerry discussing the prototype

Methodology

To generate data on the research question, the prototype of the injection machine was tested with 3 pre-used conventional molds and 1 custom-made preformance mold.

The conventional molds included a carabiner mold, a plant-pot mold and an electrical socket mold (figures 73 to 75). According to Carolina, these molds present a representative range in filling difficulty.

The conventional molds were tested with a fixed injection temperature of 210 °C. The used material was a mix of recycled polypropylene (PP) plastic.

Figure 73 to 75: Conventional Molds

The performance mold (figure 76) was especially designed and machined for this project by Friedrich Kegel from Easymolds in Germany. Unlike the conventional molds, this mold is designed to measure the performance of an injection machine and does not yield usable products. Instead, the geometry of the mold consists of a long winding channel, which is impossible to fill all the way. After injection, the length of the injected part gives a good indication of the performance of the machine.

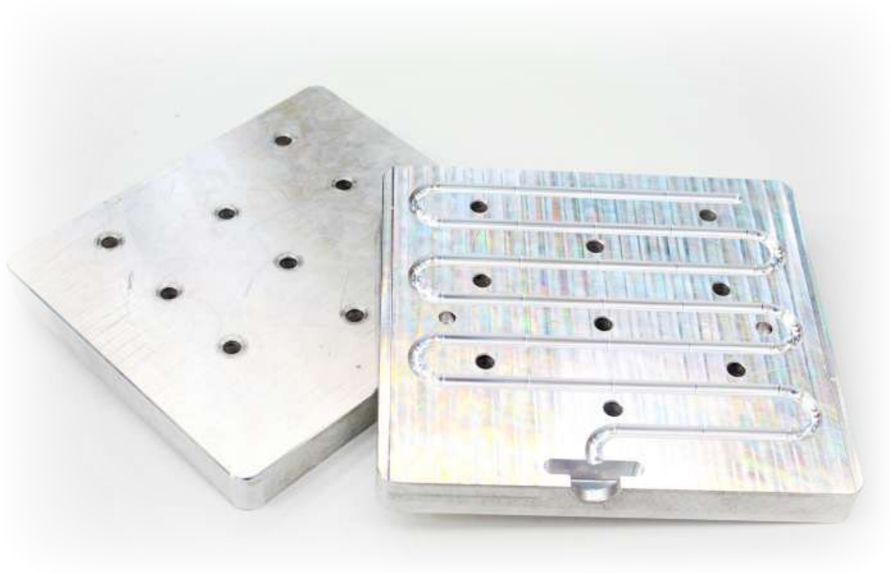
The goal of gathering data by testing the performance mold with this prototype does not lie within the scope of this project. Instead, the data will be used to compare similar injection machines on their performance in the future. The performance data gathered within this project will serve as the dataset for the Advanced Injection Machine.

The performance mold was tested with an injection temperature range of 200 to 270 °C. Different from the conventional molds, a homogenous batch of PP was used to ensure a better generalizability of results.

The testing session was executed with Carolina and Jerry, who are both experienced machine users and closely participated in the design project. As experts, they were able properly compare the prototype to the original injection machine. Due to safety concerns, no inexperienced people took part in this stage of testing.

In total, the testing session lasted for two working days. A testing procedure was not established beforehand, but made up along the way to leave room for exploration.

Figure 76: Performance Mold



Results with conventional molds

The section below discusses the results found by testing the conventional molds.

The prototype enables the user to comfortably inject existing injection molds. Figures 77 to 79 show a number of injected parts made during the testing sessions. During the testing session, Caro and Jerry mentioned the injection process was much more comfortable compared to the original injection machine.

The prototype is capable of injecting detailed features. This can be seen especially well with the injection of the electrical socket mold (figure 78). This mold has small reinforcement ridges (1mm wide, 5mm deep) which were quite hard to fill on the original injection machine according to Carolina. The prototype of the advanced injection machine filled these details with ease.

The prototype generates too much pressure for some current molds. While injecting the electrical socket mold, the pressure caused one part of the mold to deform (figure 79). By bending back the deformed part and reinforcing the mold with a steel plate, this could easily be solved after which the mold worked fine.

The springloaded auto-engagement system successfully and safely connects the nozzle to the mold gate. Besides some minor mechanical issues described in the next insight, the innovative nozzle connection enabled easy placing and removing of molds.

Figure 77: Injected Parts

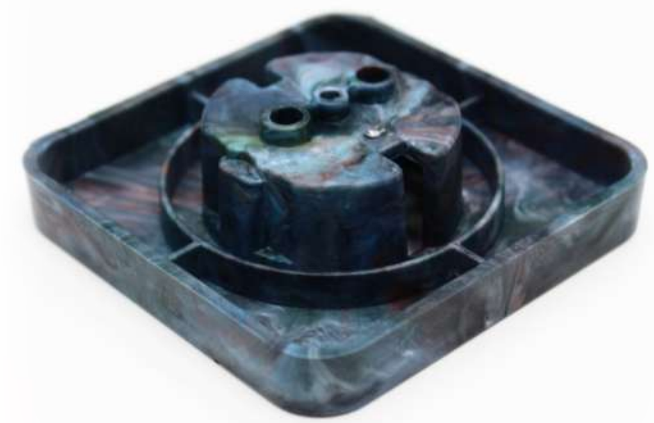
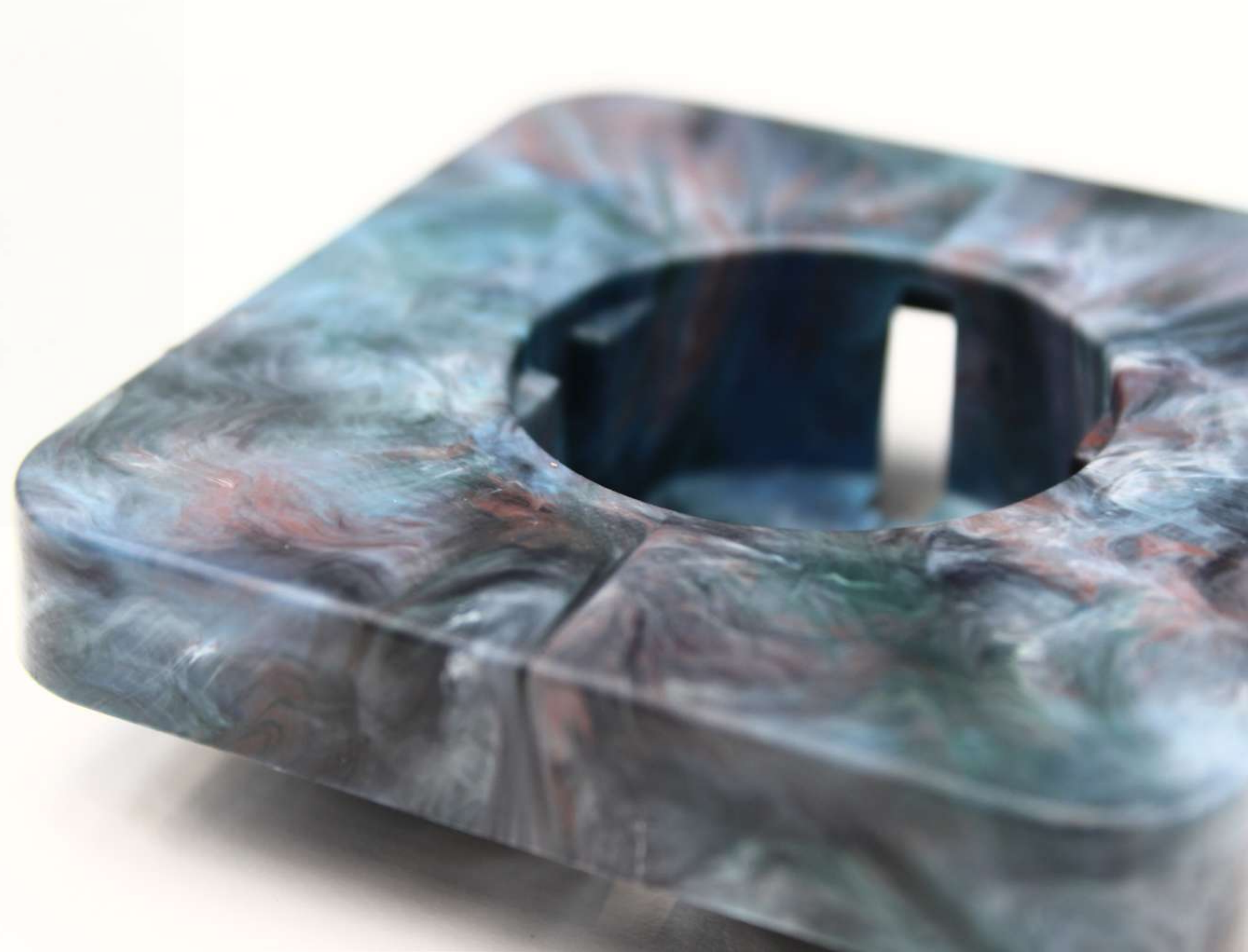


Figure 78: Socket mold with ridges

Figure 79: Part from deformed mold


Precious Plastic


Precious Plastic



The prototype has minor mechanical problems. During testing, some mechanical issues were discovered after multiple testshots.

- **The steel barrel support plate bends** while holding the barrel (figure 80). After multiple shots, this caused the barrel to slightly tilt. This is risky, as the resulting forces on the injection assembly and mold could misalign and cause the mold connection to buckle.
- **The top plate on the mold table dents** as it is not strong enough to handle the counterpressure from the molds (figure 81).
- **The barrel is able to spin** along its main axis, which could cause the cables to rip (figure 82).

Figure 80: Barrel support plates

Figure 81: Dented Mold Table

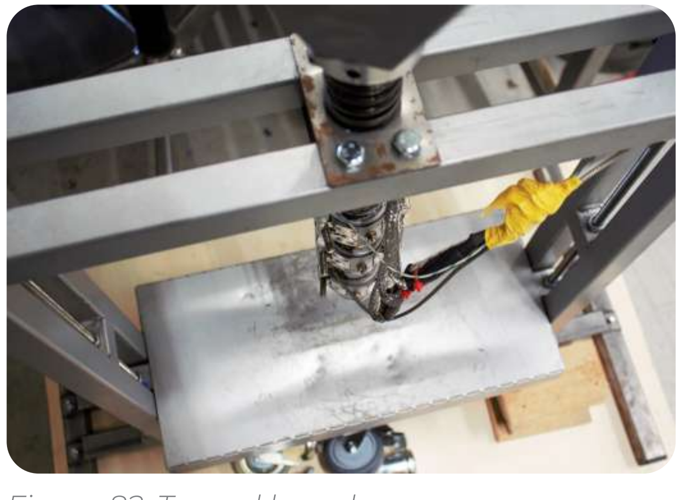


Figure 82: Turned barrel

- **The auto-engagement spring** on top of the barrel is not stiff enough (figure 83). Due to this, the barrel does not automatically deconnect from the mold after injection.
- **The bolts on roller bars** currently loosen quickly. This enables the rollerbars to turn in their holes which is undesirable.

The prototype could improve on some usage factors. The following usage problems were encountered in the testing session.

- **The nozzle oozes plastic** when compacting the plastic flakes (figure 84). During the testing session this was solved by placing metal blocks under the nozzle to prevent dripping.
- **The current height-positioning system** is not comfortable and takes too long to adjust (figure 85).

Figure 83: Auto engagement spring

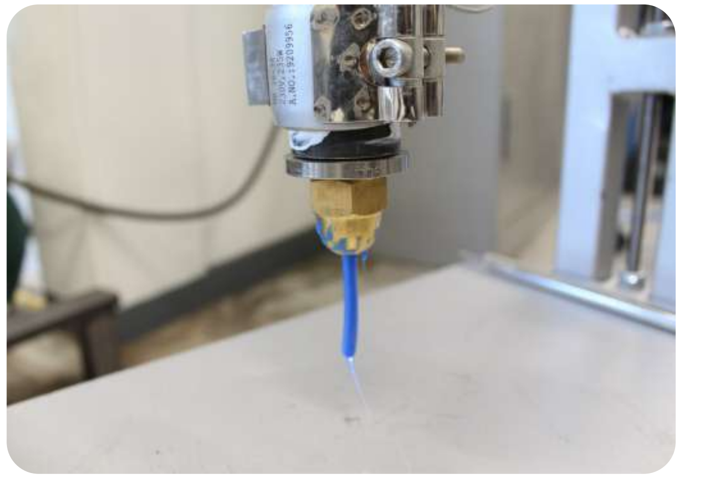


Figure 84: Plastic oozing from nozzle

Figure 85: Positioning the mold table

Some design changes could enhance Open Source sharing. During the testing days, the following suggestions were mentioned to better tailor the design for Open Source sharing.

- **The two lathed stopper rings** might be changed to storebought parts to reduce the amount of lathed parts (figure 86).
- **The threaded connection of the plunger** to the rack could be redesigned to reduce the number of lathed parts.
- **The nozzle connector** could be replaced with a storebought gas-pipe connector to reduce the number of lathed parts (figure 87).

Figure 86: Lathed stopper ring

Figure 87: Lathed nozzle connector

Results with Performance mold

In total, 8 injections of the performance mold were made during the testing session at varying temperatures (figure 88). During these tests, the input pressure was maintained at around 60 bar. By measuring the length of the resulting shots, the dataset presented in figure 89 was obtained.

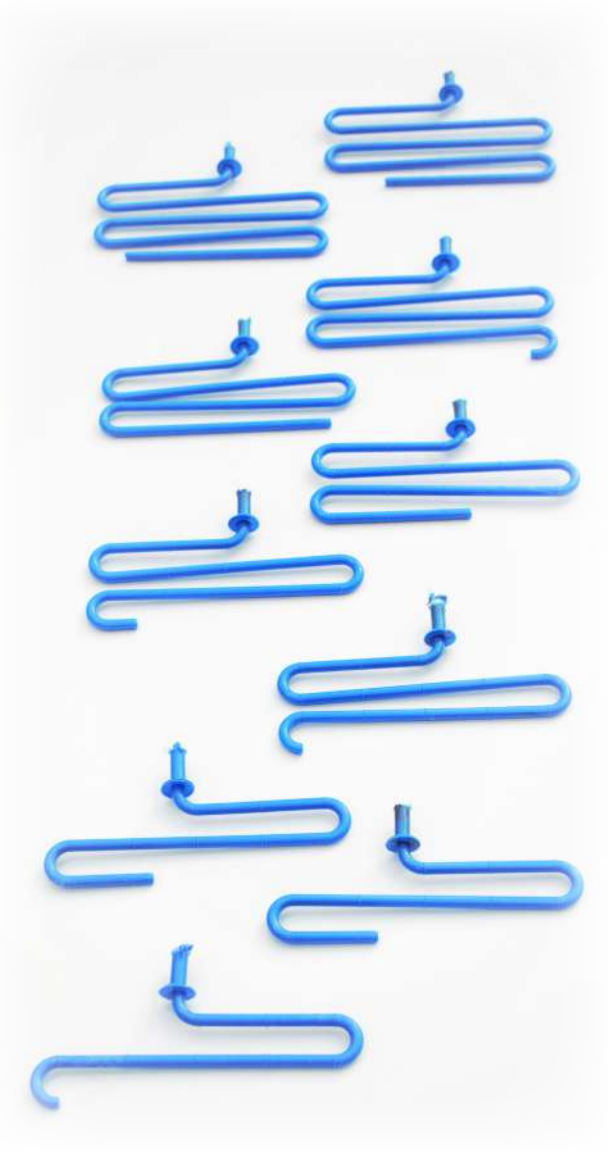


Figure 88: Test shots from session

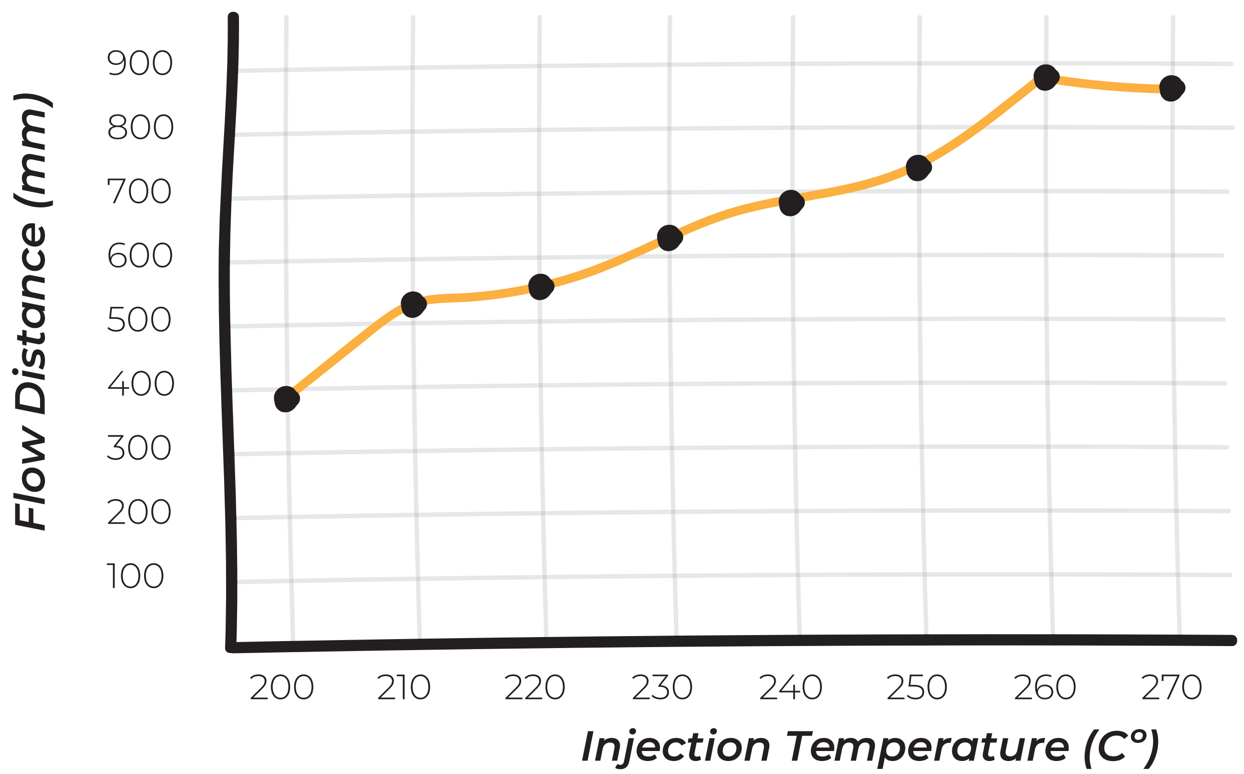


Figure 89: Performance Mold results

Conclusion

Discussion

Based on the results described in the previous section, the following can be concluded on the research questions.

The prototype is able to successfully inject conventional molds. The many successful injections made during the test session validate this basic functionality of the machine.

The prototype is more comfortable to use compared to the original injection machine. According to the experts with whom the test was executed, the prototype requires less effort to successfully inject plastic compared to the original machine.

Placing and removing molds is easier compared to the original injection machine. Although the spring loaded auto-engagement system and mold table require further refinement, the test session proved their intended functionality to enable the user to easily place and remove molds.

A number of design changes is necessary before the design can be publicized. These changes relate to the high injection pressure, minor mechanical problems, usability improvements and enhancements for open source sharing. Most notably, these include design changes to the mold table and springloaded auto-engagement. These changes are further discussed in the recommendations in chapter 6.7.

Limitations

The main limitations that apply to the test results relate to the data generated with the performance mold. Although the results from figure 89 provide a good indication of the approximate performance of the machine, they rely heavily on external factors. For instance, efforts were made to have more or less similar conditions for each of the shots regarding pressure, injection speed and timing. However, there was no way of measuring whether these conditions were actually stable over the entire testing session due to the limited time and resources in this project. Nonetheless, the results from the performance mold match the expected behavior of the machine based on simulation results found by Friedrich Kegel, suggesting that the conditions were at least somewhat stable.

Conclusion

With regard to the limitations, the test results clearly show that the prototype delivers on the envisioned technical functionalities of the design. While there are minor technical points of improvement, the overall prototype functions well and shows its worth compared to the original lever injection machine.

The test results suggest the following for further development:

- **Redesign the failing parts**. Most critically, the springloaded auto-engagement and mold table should be improved before the machine is published.
- **Execute more performance tests**. Future testing with this prototype and original version of the injection machine should generate a more thorough dataset on the performance of the machine. This would enable Precious Plastic to properly compare the advanced injection machine to others and find where improvement could be made.

6.6 Design Validation with Amateurs

Introduction and Approach

One of the key advantages of the arbor-style injection machine is the improved ergonomics of the injection process. Not only does the lower manual force input make the machine more comfortable to use, it should also allow a broader group of people to use the machine (figure 90).

While the test session executed in the previous section already shows that the advanced injection machine is much more comfortable to use, the session did not properly research whether or not the required manual input force exceed the ergonomic limit of 350N as found in the ergonomics section of chapter 3.2.

Also, the previous test session was executed with experts only. While this session provided some insights on the usability of the new design, it did not produce any guidelines for new builders on successful usage of the machine.

The following research questions were drafted:

RQ1: How much manual input force is required to successfully use the injection machine?

RQ2: What usage factors can be found in successfully using the injection machine?

Figure 90: A participant using the machine

Figure 91: Force sensor between rack and plunger

Methodology

To answer the research questions, a test session was organized in which participants used the injection machine while quantitative force measurements were taken and qualitative observations were made.

Initially, a test setup was developed in which participants were tasked to interact with a modified, static version of the prototype. However, a pilot test (appendix M) rendered inapplicable outcomes. Analysis showed that this was mainly due to the unrealistic static setup of the test, but also the concept of 'comfortable usage' seemed hard to judge for the participants. Therefore, a more realistic setup was developed in which participants interacted with the unmodified injection machine.

To collect data on the first research question, the injection machine was equipped with a force sensor. This sensor was installed between the rack and plunger of the machine to accurately measure the injection force on the melt (figure 91). A preparatory test found that the manual input force applied to the tip of the lever is transmitted to the injection force on the plunger with a 1 : 16,5 ratio. The force sensor used in the test was a 10kN load cell by Torbal, which was read by a voltage-meter. This setup allowed for the continuous registration of data over the full process.

To answer the second research question, observations were made during the injection process. Also, the degree in which the injected part was fully injected was evaluated. By jointly analyzing this data and the quantitative pressure data, relevant usage factors could be determined.

During the test, the carabiner mold used in the previous test session was used with a mix of recycled PP. This mold was selected, as experts recommended it as a representative mold, with an average filling difficulty.

The participant group was made up of inexperienced builders. To ensure their safety during the test, their only interaction with the machine was through applying force on the levers. All other necessary steps during the injection molding process were done by the research team, like placing and removing the mold. For additional safety, participants wore a protective coast, workshop shoes and long pants.

Participants were recruted at the faculty of Industrial Design Engineering at TU Delft. The selection of the participants aimed for a diverse group of people in the factors gender and length. A total of 5 participants partook in the test.

To prepare the participants, a short introduction to the project was presented. Their main task of using the injection machine to inject a mold was explained. Here, they were specifically instructed to not exceed their comfort limit. Figure 92 presents a visual overview of the testing procedure.

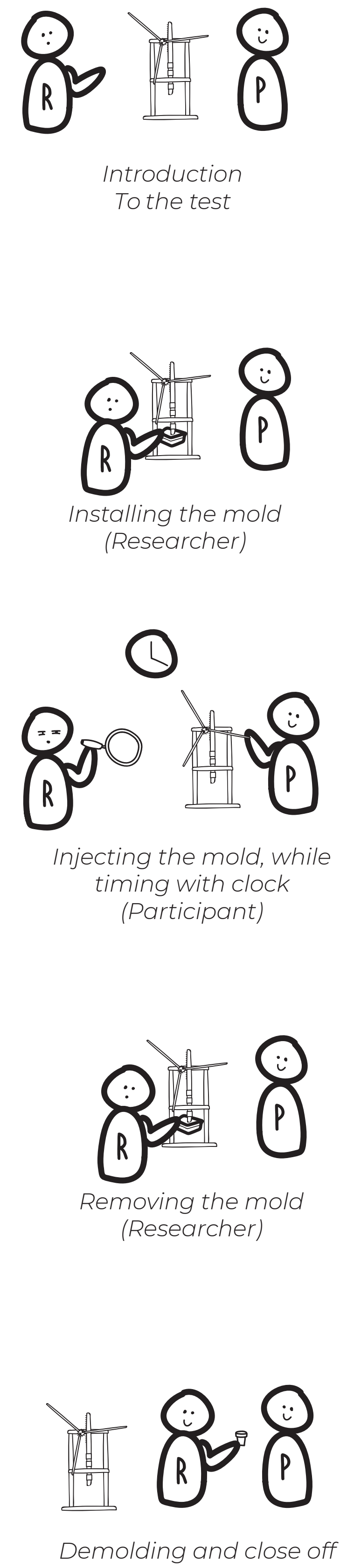


Figure 92: Testing procedure

Test Results

This section presents the data gathered during the 5 tests. Figure 93 shows an overview of the gathered data. The raw test data can be found in Appendix N.

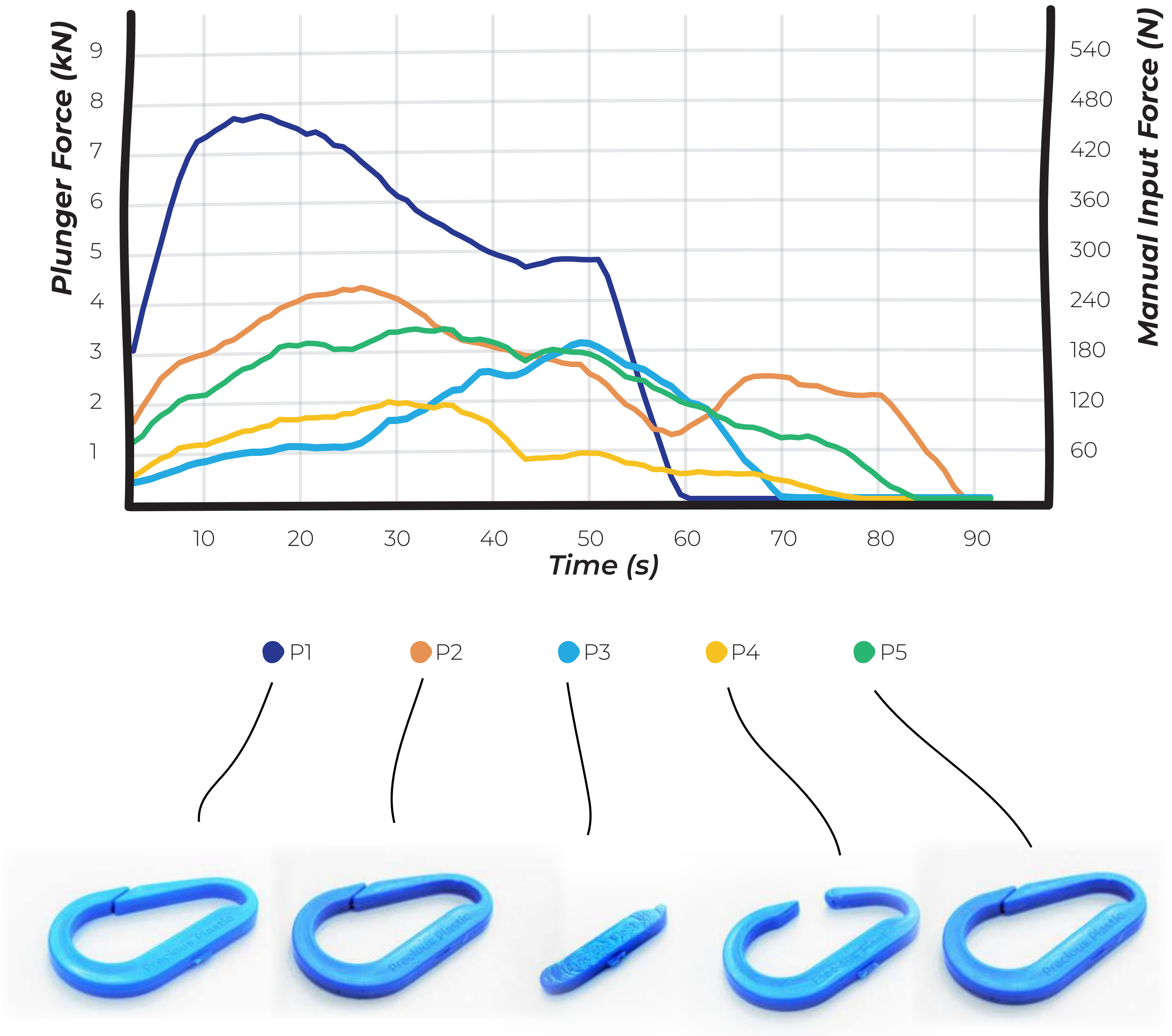


Figure 93: Test results

Participant 1
The pressure graph generated by the first participant shows the participant quickly applied a maximum manual input force of 476N generated at around t=15. At t=53, the pressure sharply drops as the participant stopped injecting.

The resulting injection shot shows a fully filled mold. On the sides, clear sinkmarks can be seen.

The following was observed:

- The participant tried to exert as much force as possible:

  "I didn't know how much pressure to apply.. so I just put as much force on it as possible" - P1

- Once the participant noticed the handlewheel had stopped turning, they relieved the pressure at once as they thought the injection process was done.

Participant 2
The pressure graph generated by the second participant shows a maximum manual input force of 261N generated at around t=27. After this peak, the pressure is maintained but slowly declines. At t=83, the pressure sharply drops as the participant stopped injecting.

The resulting injection shot shows a fully filled mold. No sinkmarks can be seen.

The following was observed:

- At around t=50, the participant mentioned expecting the injection process to be complete and thus started to relieve pressure. However, they soon remembered they needed to apply backpressure.

  "It feels ready.. [..] Oh right, you needed to keep it [under pressure]" - P2

Participant 3
The pressure graph generated by the third participant shows the participant slowly increased the pressure up to around 70N. At around t=26, they started applying more force until a maximum manual input force of 218N was generated at around t=53. After this peak, the pressure slowly declines until it reaches 0 at t=71.

The resulting injection shot shows a partially filled mold.

The following was observed:

- The participant mentioned feeling unsure in the beginning of the injection process

  "I'm not sure this is going well.. can I apply more force?" - P3

  At around t=26, they started to apply more pressure.v

Participant 4
The pressure graph generated by the fourth participant shows the participant slowly increased the pressure up to a maximum manual input force of 135N generated at around t=33. After this, the pressure sharply drops up to around 60N where it stabilized until pressure was relieved at t=80.

The resulting injection shot shows a nearly filled mold.

The following was observed:

- The participant mentioned they were a bit uncomfortable with testing the limit of the machine:

  "I wasn't sure how much [force] I could put [on the handle].. I did not want to accidentally break your machine" - P4

Participant 5
The pressure graph generated by the fifth participant shows a maximum manual input force of 221N generated at around t=33. After this peak, the pressure is maintained but slowly declines until 0 at t=85.

The resulting injection shot shows a fully filled mold. No sinkmarks can be seen.

The observations did not produce any notable insights with this participant.

Discussion

Manual Input Force

The first research question aimed to investigate how much manual input force is needed to successfully use the prototype of the injection machine. By analyzing the test results, the following arose:

Of the 5 injections, 3 were successful (P1, P2 and P5). Of these three, participant 5 applied the lowest manual input force measured at around 221N.

It should be noted that participant 3 applied an almost identical input force of 218N, but failed to produce a successful shot. However, analyzing the data in figure 93 shows that the likely reason for the failure of the shot is the relatively late application of this input force: Whereas the maximum input forces of the successful shots (P1, P2, P5, figure 94) were applied between t=15 and t=33, the maximum input force of participant 3 was applied only at t=53. The late application of force likely caused the shot to fail, as the molten plastic starts cooling down once it leaves the barrel. Once the machine user waits too long with applying sufficient pressure, the plastic solidifies and blocks more plastic from entering.

Figure 94: A participant showing his resulting shot

Successful Usage Factors

The second research question aimed to find successful usage factors. Comparing the generated pressure data of the two failed shots (P3, P4) and the successful shots (P1, P2, P5) delivers the following three insights:

- **Apply sufficient pressure**. The generated data clearly shows this is the reason for the failed shot by participant 4. Pressure was generated up, but not enough to fully reach the end of the mold cavity.
- **Apply pressure immediately**. Analysis of the generated data in figure 93 shows this is the reason for the failed shot by participant 3. Although this participant exerted a similar amount of force compared to the successful shot of P5, this pressure was only achieved almost 20 seconds later. As discussed in the previous section, this likely caused the plastic in the mold to solidify early.
- **Apply backpressure for long enough**. The generated data suggests this is the reason for the sinkmarks on the shot by participant 1. The participant relieved the pressure already after 53 seconds, at which time the plastic in the mold had likely not solidified yet. Without the backpressure, the part was therefore able to shrink in thicker places. The successful shots applied pressure until around 80 seconds at the minimum.

Limitations

The results of this test are subject to a number of limitations.

First, it should be noted that the quantitative data on the pressure graphs are heavily influenced by factors such as mold geometry, plastic type and temperature. Therefore, no single, universally applicable quantitative answers can be given to the research questions.

Next, it is also important to note that this test was executed with inexperienced participants. As with any tool, successfully using the developed injection machine will include a short learningcurve, through which the participants in the test did not go. Therefore, it should not be a surprise that 2 out of 5 participants failed to produce a successful shot.

Conclusion

With regard to the limitations of the test, the following can be concluded.

Under typical conditions, the machine can in all likelihood be successfully used without exceeding the human ergonomic limit on manual input force.
The test results show that within the tested setup, the minimally required manual input force to use the injection machine did not exceed the ergonomic limit of 350N. Three out of five participants were able to successfully inject the mold, of which 221N was the minimally required handforce for a successful shot. As this test was performed with a typical mold and the required force remains over 36% below the human ergonomic limit, the results strongly suggest that this result likely applies for most existing molds within the Precious Plastic universe. However, more research is required to give a conclusive answer.

Compared to the original injection machine, the advanced injection machine requires 70% less manual input force.
The original injection machine required over 720N to successfully inject similar molds (chapter 3.2). The 221N required to succesfully inject parts in the new prototype clearly shows the developed advantage of the advanced injection machine. However, the results show that as a side-effect, the achievable pressure is quite high. Based on the 7.8kN of maximum plunger force generated by P1, the injection pressure is calculated at 161 bars. As this research did not aim to find the maximum achievable pressure, this should be seen as an incidental finding and cannot universally determine the maximum pressure of the machine.

New users should be advised to apply pressure quickly, sufficiently and for at least 90 seconds.

The test results show that these factors are key to produce good injection shots within the tested setup. As discussed in the limitations however, the generated data can not produce conclusive and universally applicable guidelines. Nonetheless, the outcome of this test provides new machine users with some insights to shorten their learning curve (figure 95).

Figure 95: A participant learning to inject

6.7 Design Recommendations

To conclude the development of the advanced injection machine, this section describes recommended design changes based on the result of the validation tests.

As described in project goal 2, one of the objectives of this project was to deliver a complete set of technical documentation. However, the decision was made in consultation with Precious Plastic to postpone the creation of these drawing until a number of crucial refinements are validated. This ensures the machine can be released at once instead of requiring revisions later.

The CAD files have been presented to Precious Plastic and can be found on www.tinyurl.com/advancedinjectionmachine.

These recommendations presented below are divided into two categories:

- Recommendations marked with a red dot are essential to meet the requirements as defined in the LoR/W of the machine.
- Recommendations marked with a blue dot are 'nice-to-haves' and would improve on the wishes as defined in the LoR/W.

Each recommendation relating to the LoR/W concludes with the corresponding criteria in the following form: *(R/W x.x)*

Machine as a whole

- **Use locknuts instead of regular nuts everywhere in the design** (figure 96). These are a little more expensive, but ensure the machine can be safely used without bolts loosening over time. *(BW 1.3)*

Figure 96: Regular nut (L) and locknut (R)

- **Decrease the number of different sheetmetal thicknesses to a maximum of 2** (figure 97). This would require the builder to cut down on lasercut costs and ease the sourcing of materials. *(BW 3.5)*

Figure 97: A piece of lasercut sheetmetal

- **Develop a locking mechanism for the rack**. Currently, it tends to slowly drop downwards, which is impractical. *(UW 2.5)*

Arbor Unit

- **Decrease the length of levers.** Due to the aim of reducing the required manual input force to a minimum, the achievable pressure for the current machine is too high at over 160 bars (chapter 6.6). This exceeds requirement TR 1.10 by 60%. Although more research should be done on this maximum pressure (the 160 bars is currently based on only 1 participant), it is clear that requirement TR1.10 (max pressure of 100 bars) is not met. The crucial factor in this pressure is the length of the lever (figure 98). As the required manual input force found in the validation session is far below the ergonomic limit, a shorter lever might be considered. Based on the above, a proposed lever length reduction of 30% would 1) reduce the pressure achieved by P1 to the required 100 bars and 2) increase the minimum manual input force up to an acceptable 290N. However, further research and prototyping should confirm these estimations. *(TR 1.10)*

- **Try different configurations of the handlewheel**. The current number of 5 levers was chosen based on the human reaching distance and the current length of the levers. However, if the lever length would be decreased as described above, the number of required levers could also decrease. After all, shortening the levers would also decrease the distance from one tip to another, which in turn decreases the reaching distance. Figure 99 shows a number of possible configurations, including one with 30% length reduction (top version). *(UW 2.4)*

Figure 98: Participant applying force

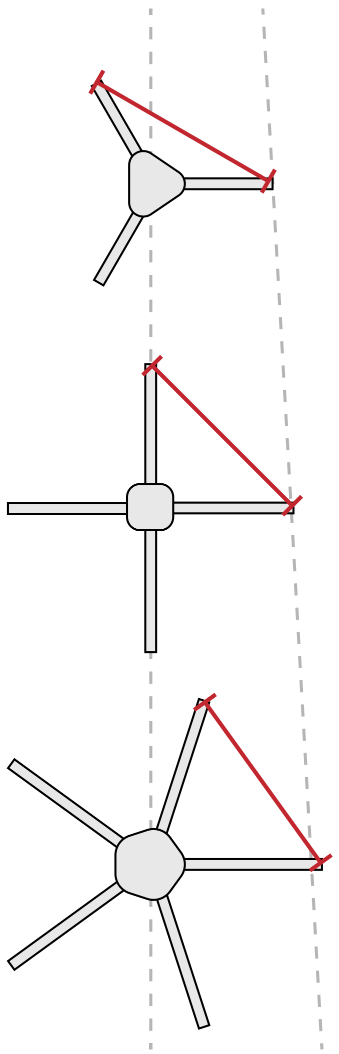


Figure 99: Other lever configurations

Injection Unit

- **The laser cut insulation cover should be redesigned for easier installation and removal**. Currently, it was observed that it is very hard to remove the cover once the installation is complete. *(BW 3.3)*

- **The head of the plungerhead piston could be made a little longer** (figure 100), which would improve its long-term durability. *(BW 3.4)*

- **The head of the plungerhead could potentially be made from steel** instead of brass. This would decrease the number of required materials. *(BW 3.5)*

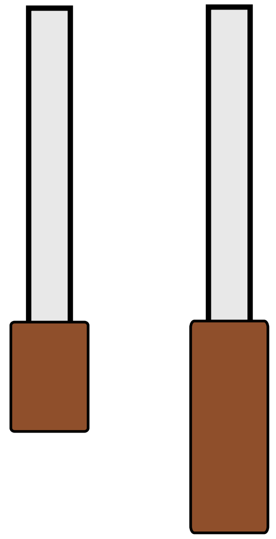


Figure 100: Longer Plungerhead

Mold Unit

- **The mold table should be easier to use**. To improve the usability of the positioning system of the mold table, a setup like presented in figure 101 could be tested. Instead of the slow and impractical threaded bar solution, this solution proposes a slotted suspension bar which could be connected to a support pin on multiple heights. This idea was developed together with Carolina and Jerry during the testing session. *(UR 3.3)*

- **To strengthen the mold table**, a thicker sheet of metal should be considered. This would ensure the table does not dent as easily as it does the current design. *(BW 3.4)*

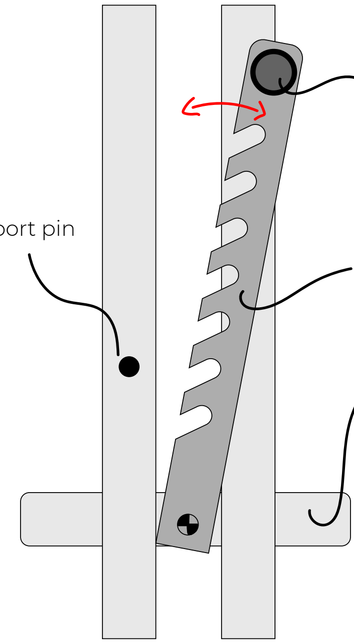


Figure 101: Mold table idea

- **The nozzle should not drip plastic during compacting**. To prevent plastic dripping from the nozzle, either of the following solutions can be tested. *(SR 2.6)*

  A) Implementing a nozzle valve, which can be opened and closed by the machine user. This option will likely be hard to machine, but would massively improve the user experience.

  B) A much simpler yet less user friendly solution can be provided in the shape of a metal plate with a mold gate welded on it. Combined with the improved mold table, this solution could securely close the mold by clamping the metal plate to the nozzle through the mold table. Figure 102 presents this idea.

- **The hopper could be made with a thicker sheet of metal** to improve its durability. *(BW 3.4)*

- **Some parts could be swapped for storebought parts** (as described in chapter 6.6). This most notably includes the stopper rings (figure 103) and nozzle connector. It is recommended to investigate these options. *(BW 3.1)*

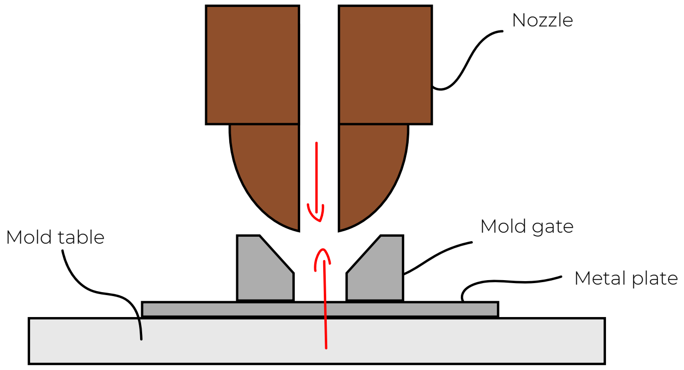


Figure 102: Other lever configurations

Figure 103: Clamping ring (would replace stopper ring)

- **Redesign the support structure of the nozzle engagement**. This could be done in multiple ways. *(TR 1.9)*

  A) Increase the thickness of the current metal plates (figure 104)

  B) Increase the vertical distance between the plates

  C) Decrease the size of the holes in the plates

  D) Investigate the integration of a support tube

- **Test a thicker spring to improve the functioning of the auto-engagement** (figure 105). A machine builder from Precious Plastic Melbourne suggests a spring with the following specifications: Wire diameter: 4mm, Free length: 50.8mm, Spring Rate: 11.140 N/mm. *(UR 3.3)*

Figure 104: Bent support plate

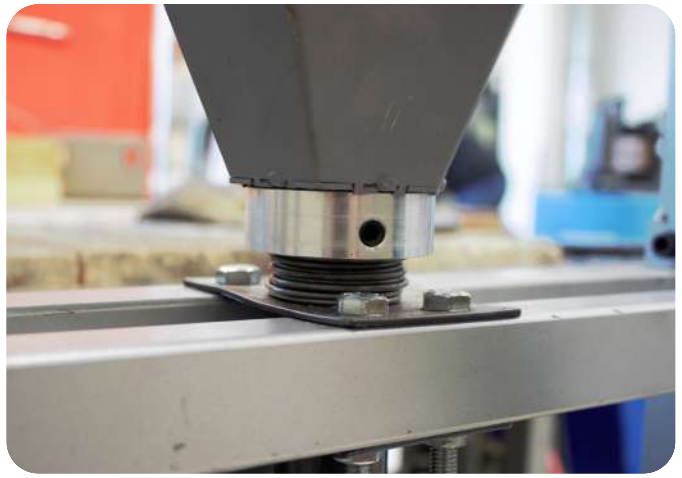
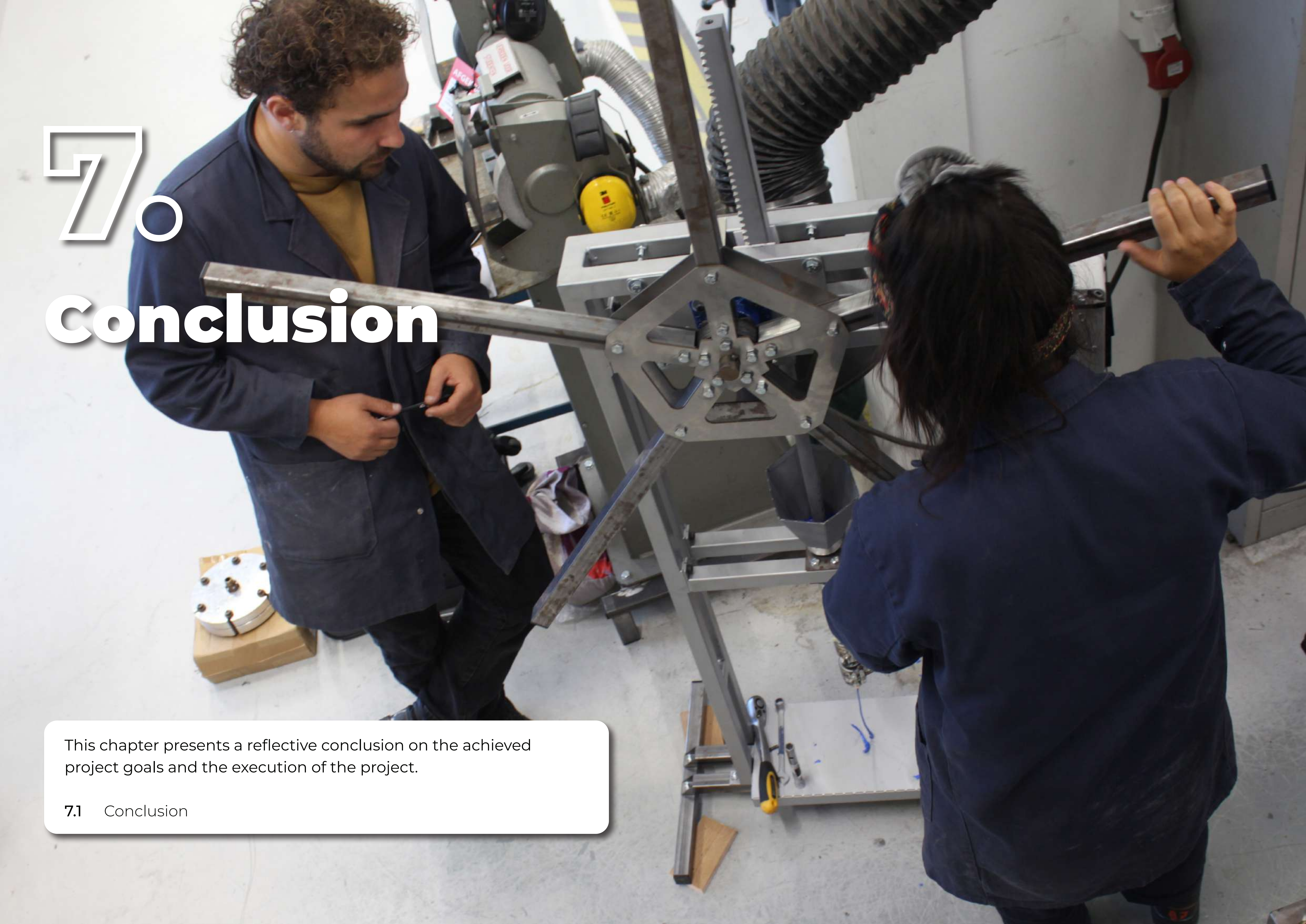


Figure 105: Compressed spring

Frame Unit

- **Increase the space below the mold table**. To facilitate a carjack (one of the described module variants), the frame beams would need to be around 10cm longer. *(TW 1.2)*



7. Conclusion

This chapter presents a reflective conclusion on the achieved project goals and the execution of the project.

7.1 Conclusion

This section of the report presents a conclusion on the achieved project goals.

Modular Design Framework

The Modular Design Framework is the result from the first project goal as defined in chapter 4.1 (figure 106). The goal aimed to transform the current monolithic design sharing system into an inviting modular framework for builders to actively compose their bespoke injection machine.

To achieve this goal, an iterative approach was taken to develop a user friendly framework. The design of the injection machine was divided into modules. For each module, multiple module variants were developed and structured in a morphological chart.
To help builders make the right choice of module variants based on their needs, skillset and budget, presets were developed based on insights on user research. Also, a digital composer tool was developed in which users could compare different module variants and tailor their choice.

The developed Modular Design Framework concept delivers on the project goals. The concept validation using a digital prototype with real users shows that users recognize its added value, appreciate the possibility of tailoring and understand the impact of their choice. The validation test also found some points of improvement, such as making the tool more self-explanatory, creating a choice overview and adding a non-customizable base version.

These findings provide incentive to further develop framework from its current conceptual stage into an embodied beta-version. The Modular Design Framework is presented to Precious Plastic and will be evaluated by them for further development. Although the concept is specifically created to support the Precious Plastic injection machine, its relevance extends into the broader world of Open Source Hardware and could find fruition here.

Figure 106: Modular Design Framework

Advanced Injection Machine

The Advanced Injection Machine is the result of the second project goal as defined in chapter 4.1 (figure 107). The goal aimed to develop, validate and document a functioning prototype of an advanced arbor injection machine.

To achieve this goal, the machine was developed in active collaboration with a group of experienced machine builders on the Precious Plastic discord server. Common solutions on machine modules were gathered and formed vital input for the design of the machine. Each iteration of the 3D CAD model was shared to gather feedback. To ensure the design was suitable for Open Source sharing, insights on the world of Open Source Hardware and building contexts were integrated into a universally buildable design. A prototype was built to validate the functionalities of the design and to evaluate the buildability.

The prototype was tested with both experts and inexperienced users. It proved that the core envisioned functionalities of the design compared to its predecessor. Primarily, the machine requires over 70% less input force and is therefore much more ergonomic in use. Next, it is able to produce a higher injection pressure resulting in more detailed shots. Also, placing and removing molds is easier and safer for the user. The tests also revealed a detailed list of improvements that could make the design more user friendly, easier to build and more tailored to Open Source sharing.

The final result of the advanced injection machine largely fulfills the second project goal. Instead of delivering finished, publication ready documentation of the machine, the project concludes with a list of recommendations on improving the design. In consultation with Precious Plastic, the decision was made to postpone the creation of documentation until the recommended design changes are successfully tested and implemented.

Figure 107: The Advanced Injection Machine

Epilogue

To conclude the report, this section provides my final reflections on the design process within this project.

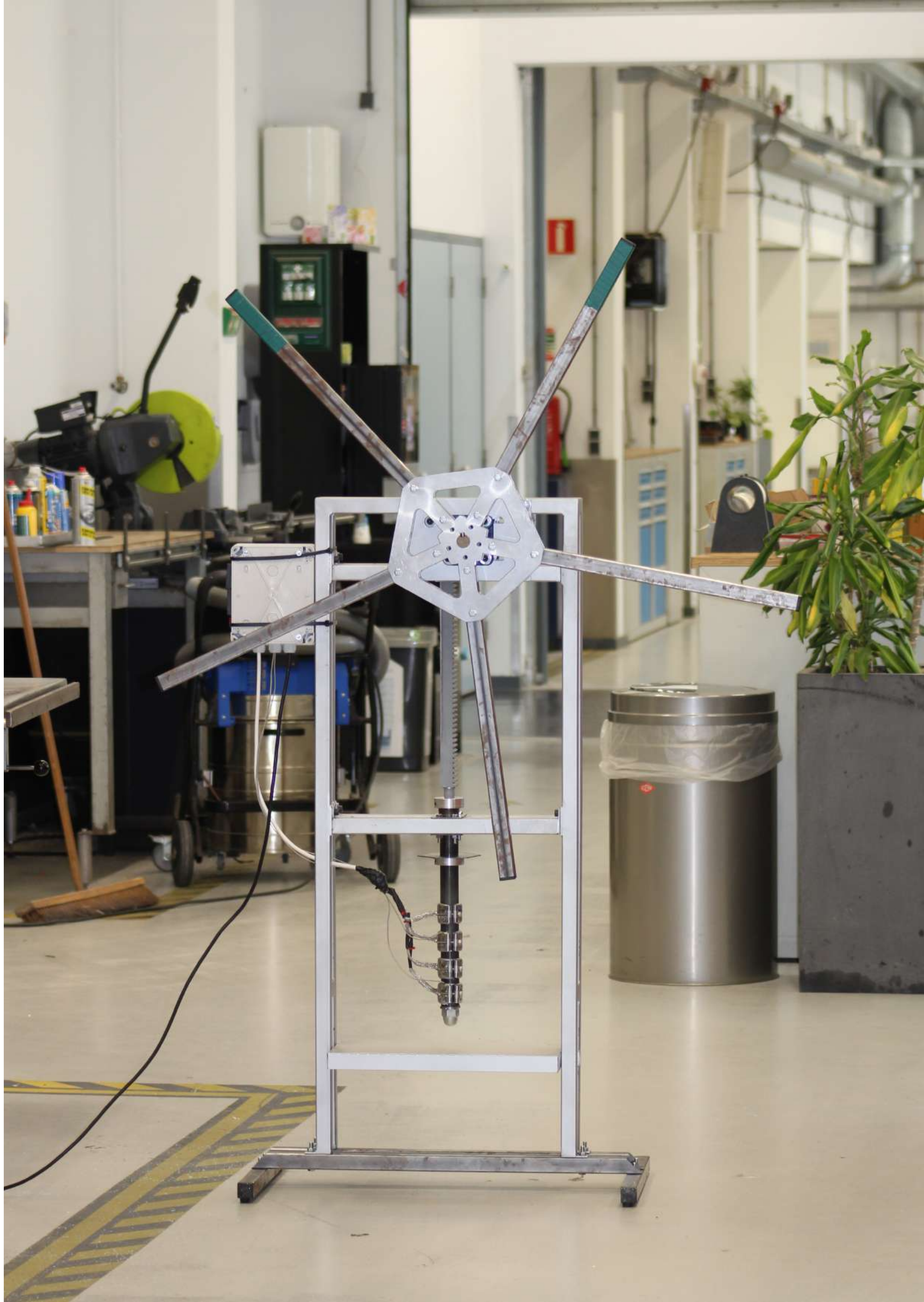
In the first place, I want to use this text to express my thanks to Precious Plastic, Carolina Espinoza and Jerry de Vos. Through their openness and help in this project, I've been able to dive into the world of informal plastic recycling. Personally, I've been amazed at the beauty of recycled plastic, skill and determination of machine builders and the impact of Precious Plastic as an organization. My connection to the Precious Plastic universe does not end after my graduation, as I'm investigating to possibility of setting up a workshop of my own. I feel proud of the results achieved in this project and hope they can prove useful to future builders. Reflecting on the design process, I've found two key learning points to take away from this project.

The first learning point has to do with setting realistic project goals. Despite the 'make a to-don't list' advice my coaches gave me, I realize in hindsight that I should have set more obtainable project goals. Although both final design outcomes are valuable design solutions, prioritizing only one of them would have benefitted the completeness of the design. For example, I feel that a more extensive and rigorous setup of the validation tests would have resulted in more convincing conclusions on both design outcomes. Also, prioritizing the design of the advanced injection machine would have likely enabled the execution of more design iterations and even a fully developed documentation.

Also looking at other projects, I notice a tendency for me to always want to solve all the problems I encounter within a project. Although this is an valuable attitude, producing complete project results will require me to narrow down a bit more in the future.

Another key learning point for me has to do with cooperating with experts. Within this project, some experts on Discord had some strong opinions on design choices I made based on their own experience. Most notably this had to do with the design of lasercut gearbox: A milled gearbox was a design which had proven its durability over time, whereas my idea for a lasercut gearbox did not. Although I stubbornly defended my choices and largely went my own way, I did find it difficult to go against these experts opinions sometimes. In the end I'm glad I did: The lasercut gearbox seems to work great and will be tested over time. Reflecting on this situation, I'll remind myself in future projects of the advantages of being a little bit stubborn sometimes.

Finally, the delivery of this thesis also marks the end of my studies at Industrial Design Engineering at TU Delft. Looking back on this project, I can see that I've learned more during my time here than I previously realized. For this I want to thank everyone I've learned from at IDE over the years. The IDE faculty will always hold a warm place in my heart.



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Appendices

Appendix O: Project Brief

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Dommisse
initials: JC given name: Joost
student number: 4442792
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): ★ IPD | DfI | SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: Honours Programme Master
specialisation / annotation: Medisign | Tech. in Sustainable Design | Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Bas Flipsen — dept. / section: SDE
** mentor: Silje Dehli — dept. / section: DOS
2nd mentor: Jerry de Vos
organisation: Delft Open Hardware
city: Delft country: Netherlands

comments (optional): Jerry will be mentoring from Delft Open Hardware, while Precious Plastic is the client. Jerry has worked with Precious Plastic for many years and can thus function as client representative. This was preferred due to time allocation.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

TU Delft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Bas Flipsen date - - signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ______ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ______ EC

List of electives obtained before the third semester without approval of the BoE

YES all 1st year master courses passed

NO missing 1st year master courses are:

name date - - signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: APPROVED NOT APPROVED

Procedure: APPROVED NOT APPROVED

comments

name date - - signature

Developing an open source Injection Machine for recycled plastic in LMIC project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 21 - 03 - 2022 09 - 09 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Plastic pollution remains one of the world's largest problems (Thompson et al., 2009). Although recycling rates continue to rise in developed countries, most plastic still ends up on landfills, in the ocean, or gets burned. This is especially visible in Low-to-Middle-income-countries (LMICs), where sufficient recycling and collection systems are often non-existent.

Precious Plastic is an organization that designs multiple machines that are able to recycle plastic into new products. The blueprints for these machines are shared open-source, enabling individuals to set up their own recycling work stations. Over 40,000 people in 400 workspaces are connected through the Precious Plastic ecosystem, in which recyclers, designers, producers and plastic collectors collaborate.

Their injection machine enables recyclers to heat and inject recycled plastic in a mold: Basically, it is a DIY injection molding machine. This original machine is low cost, easy to build, and creates a beautiful marbled aesthetic that convincingly tells the story of the value of recycled plastic. It has become a popular machine within the Precious Plastic Community, and has been built many times around the world. However, the main working principle of the design is insufficient. Among other problems, it induces an energy draining, time consuming user experience for its operator. To this end, this project aims to deliver a more user-centred design.

As the existing injection machine is shared fully open source, the design has taken on a life of its own. Many builders have implemented hacks and modifications, often improving the core functionalities and solving existing problems of the machine. While this is encouraged by Precious Plastic, they often miss out on gathering the improvements and key learnings builders implement in their machine. Due to this, valuable opportunities for development of the machine are not redeemed.

Thompson RC, Moore CJ, vom Saal FS, Swan SH. Plastics, the environment and human health: current consensus and future trends. Philos Trans R Soc Lond B Biol Sci. 2009 Jul 27.

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introduction (continued): space for images

image / figure 1: The current injection machine

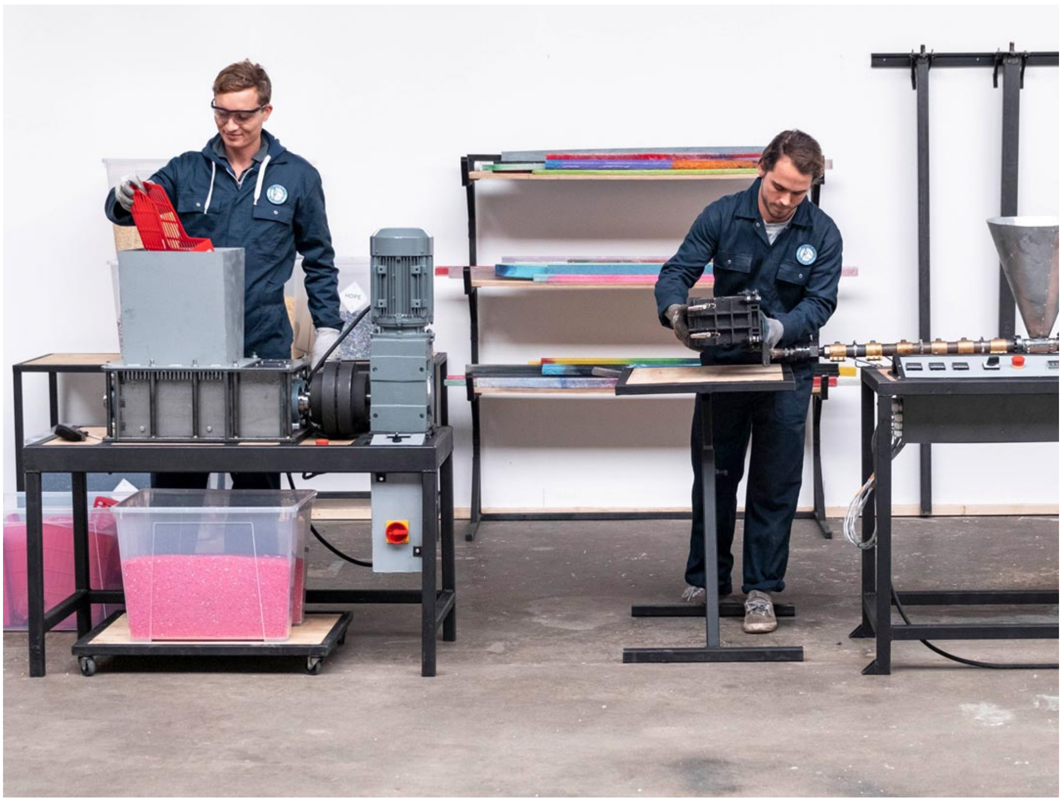


image / figure 2: A Precious Plastic workstation

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The main goal of this project is to design an open source injection machine that overcomes the operating problems encountered in the original Precious Plastic machine. Within this design, the user needs to apply a lot of force by hand for quite a long time, which is inadequate. Also, the machine is hard to clean, and connecting and removing molds is a tedious process. To substantially solve these problems, a design based on another force actuating principle is needed. One of these principles could be an Arbor-style design, which uses a rack and pinion to actuate and control the flow of plastic.

Within this project, the main challenge is to design the machine in such a way that it can be build by people in LMICs anywhere in the world. Therefore, research will be done on the resources and best design practices of machine builders and their relevant context.

Another challenge in this project will be to enable Precious Plastic to gather machine improvements and feedback from machine builders in a more substantial, routinely way. To this end, research will be done on succesfull practices in open source hardware ecosystems.

The main research questions of this project is therefore as follows:

Which aspects need to be considered when:

a) designing open source, technically advanced hardware for local recyclers in LMICs?
b) developing a feedback-stimulating building manual for open-source projects?

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Design an open-source, user-friendly injection machine for recyclers in Low-to-Middle-income-countries to locally recycle plastic waste.

The core of the assignment can be divided three main parts:

The user side of this assignment aims to research the context of LMICs and deliver a design optimized for these building settings.

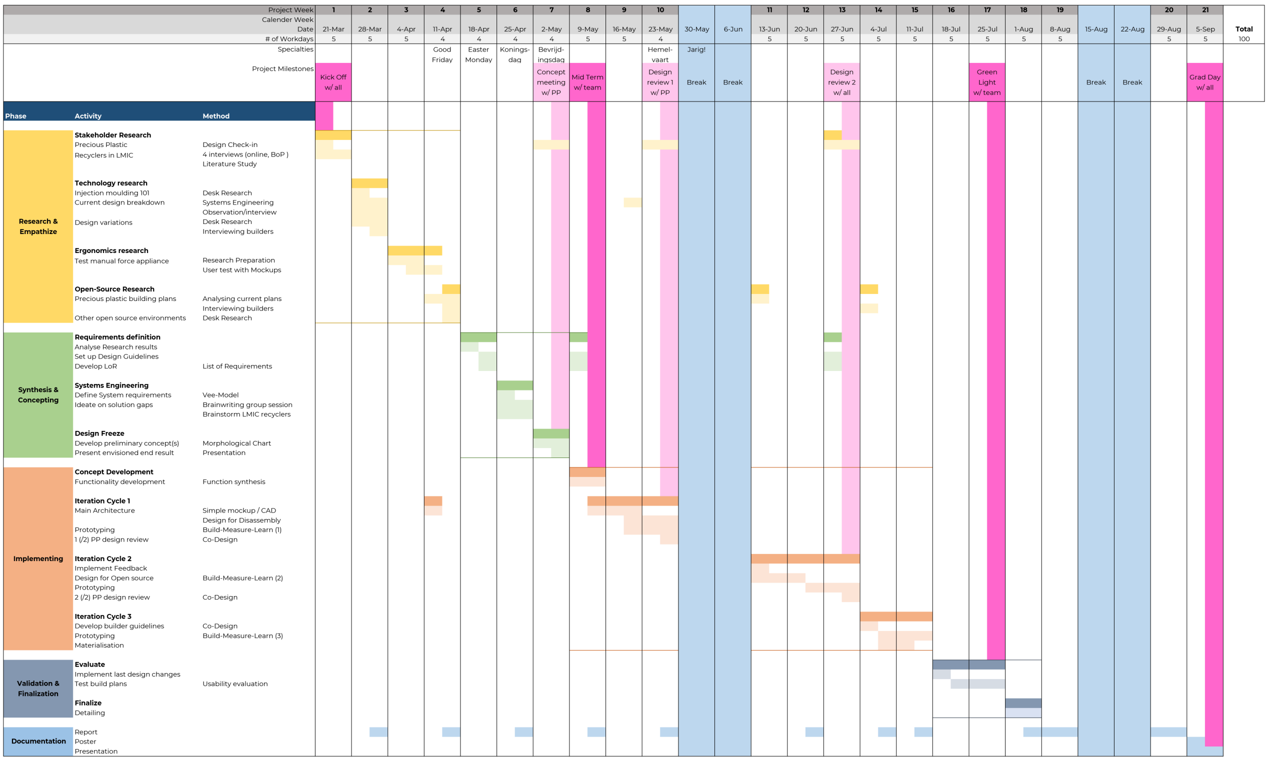
The technical side aims to deliver a validated, functioning prototype of the injection machine.

The Open Source side focuses on researching the best practices within Open Source ecosystems and delivering a building manual for the injection machine that stimulates feedback to Precious Plastic from builders on their proposed improvements.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 21 - 3 - 2022 9 - 9 - 2022 end date



The project is structured in 4 main phases and will be carried out over 21 weeks due to holidays. Also, I will take two 2-week breaks.

To develop a user-centred design, an analysis on the resources and context of machine builders in LMICs will be performed trough the Bottom of Piramid method. This will be done by doing interviews and observing people (online). During and after the embodiment phase of the project, the context-critical parts of the design will be evaluated with the target group and iterated upon.

Within the design of the Injection Machine, the Systems Engineering and Design for Disassembly methods will be followed. Also, the expertise of current machine builders will be incorporated through Co-Design. A lot of time is allocated to build, test and iterate on the prototype, which will be reviewed by Precious Plastic on multiple occasions.

To develop the building manual, existing building plans will be evaluated and best practices from other open source products will be gathered. Through a usability evaluation, these plans will be tested within an actual machine build.

Initials & Name JC Dommisse Student number 4442792

Title of Project Developing an open source Injection Machine for recycled plastic in LMIC

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

This project is an opportunity for me to gain experience with designing for Open Source and working directly with recycled plastics, which are topics I've been interested in for quite a while. Working directly on projects enabling the Circular Economy was my reason to join IPD, and as Precious Plastic offers a concrete design solution to the plastic problem, I think this project fits me very well. Also, I'm looking forward to the physical development of the Injection machine. The project will include a lot of building, prototyping and iterating, which I've missed out on in Advanced Embodiment Design due to the COVID-pandemic.

Within this project, I want to develop a number of skills. Firstly, I want to improve my choice-making abilities. Especially during my internship, I noticed that I often keep dwelling on design choices, which leaves less time for other things.

Secondly, I want to gain knowledge on the properties of recycled plastics and, in a broader sense, the current plastic pollution problem. Through courses within my education at IDE I've gained a lot of theoretical knowledge, to which this project can be a great practical addition.

Thirdly, I'm curious about working with the Systems Engineering and Design for Disassembly methods. I hope that, with these methods, will be able to work in a more structured way.

Lastly, I want to improve my communication skills within a larger team. This is bound to get tested within this project, as I'll have to involve many individual people within the Precious Plastic community.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix A: Accessibility Survey

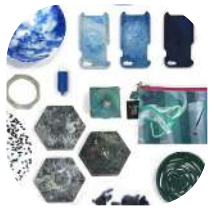
Appendix B: Usage Cases

THE SEMI-INDUSTRIAL RECYCLER

Recycling as much plastic as possible by making and selling high quality products

High Quality
They aim for high quality, finishing, durability and aesthetics

Fast
The goal is to produce quickly, so they aim for low cycle-times (around 2 - 4 minutes)



A lot of products
They make a wide range of different products

Preferences & Resources

High level of automation
They look for a high level of automation, requiring little manual labor

Thorough cleanability
Cleanability is an important factor, as this improves part quality

Quick and secure mold clamping
They often have a sophisticated clamping system, resembling that of professional injection

Advanced, near industrial injection machine
Their machines are more advanced and optimized, and therefore can be more costly (1500$+)

Advanced workplace
They build their machines with professional building machinery and are sometimes able to make their own molds. They tend to have some employees working for them and often have a local network of recyclers, machine shops and local businesses around them.

Tools and machinery
They tend to have access to a computer-numerical-Control machine (CnC), lathe and a laser cutter.

Overview

Expected cycle time per part
1 minute — 10 minute

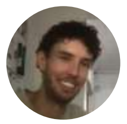
Available tools
basic — advanced

Degree of automation
manual — machinal

Based on interviews with: (thanks a lot!)

Peter-Bas Schelling

Debrah Nijdam



Mitchell Lammering

THE EDUCATOR

Practically teaching people about plastic recycling

Main goals

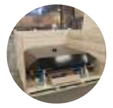
Low-Cost
They aim for a simple machine without expensive fancy parts.

Show the process
Having a long cycle-time (around 8 - 15 minutes) leaves plenty of time to explain the process

Teach about recycling
They want a machine with a clear, self-explanatory working

Preferences & Resources

Buildable with basic tools
They don't have too many advanced resources to work with, so the machine should be able to make without advanced tools



Transportable by one person
To give workshops remote, the machine should be transportable by one person

Safe for all, children included
Safety is quite a concern, as the machine will be used with unexperienced users around such as children.

Clean-cut building plans
They don't have the capacities or aim to optimize the design of the machine.

Simple workplace
They build their machine in basic workshops, in which they can do basic machining operations. They tend to work alone within either their own makerspace or at public workshop locations. This implies some parts are not manufacturable by themselves, so they divert to other locations for these.

Tools and machinery
They tend to have access to simple to medium advanced tools, like an angle grinder, standing drill and welding equipment.

Overview

Expected cycle time per part
1 minute — 10 minute

Available tools
basic — advanced

Degree of automation
manual — machinal

Based on interviews with: (thanks a lot!)

Teun Zoetemeijer

Ramdhan Abu Azzam

Suleiman Ali Mohammed

Appendix C: Building Timeline

Within the development of the machine, attention should be paid to the building process and part accessibility. As the machine will be built by individuals in their own workshop and not in a controlled factory environment, this is especially important.

Building process
As discussed in the background section in this report, the building process starts on the Precious Plastic website where builders are able to download a kit with all required blueprints and CAD models. The kit also features a building tutorial on YouTube, which provides a good picture of the building process of the current injection machine. The main steps are described below:

1)

The first component being made is the hopper, which is made from multiple metal plates. For this step, the plates are cut out using an angle grinder and the plates are welded together using a welding torch. To prevent corrosion, the hopper is coated.

2)

Next, the barrel is made from an extruded tube. It is first cut using a crosscut saw, after which an angle grinder is used again to cut out the slot for the hopper.

3)

The barrel is finished by first tapping a thread to the end of the tube, after which strips of metal that connect the barrel are welded on the tube.

4)

Next, the frame is made by first cutting metal tubes to the right length. They are then welded together and holes are cut for connections to the other parts.

5)

Once the main mechanical parts are now finished, the electronics box is made. Similar to the hopper, metal plated are cut out and welded together to create the box. The electronic components are wired together and assembled.

6)

Lastly, the sensors and heating elements are assembled on the hopper.

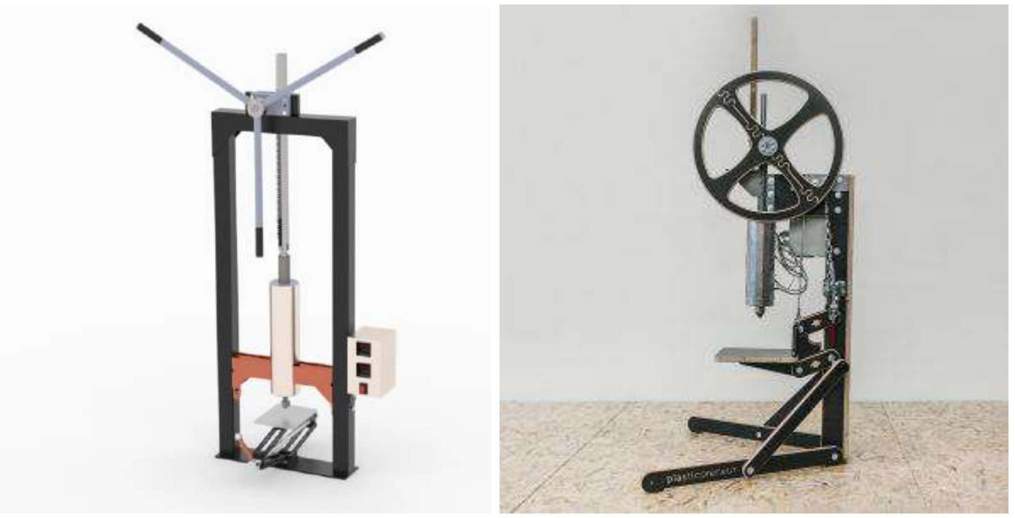
Appendix D: Overview Alternatives

Besides the injection machine made by Precious Plastic, there are many alternative designs that circulate in the builder community. These designs often improve the existing design in a number of ways. Trough discussing on the co-design channel on Discord, a clear overview of existing alternatives was made with the help of expert machine builders. They are discussed and subdivided among the main conceptual modules.

The Force Application unit
As the current lever-style force application unit is not very user-friendly, many machine builders have tried alternative designs.

Arbor mechanism based designs are one of the most popular design alternatives out there. At their core, they function through an interlocking spur-gear and rack-gear. The key improvement compared to the lever-style design is the way the minimum plunger force and distance are achieved: The gear allows both for a high transmission of force and continuous movement of the plunger. Within the lever-style design, there is always a trade-off between the force transmission and plunger movement, as increasing either will decrease the other.

The practical application of the arbor mechanism is well-tested within the communities, with even commercial machines using this principle. Examples include the PlasticPreneur machine and the 'Elena' machine by Plastic-Hub. These are shown in figures 22 to 23.



Figures 22 and 23: The Elena machine by PlasticHub and PlasticPreneur injection machine.

As mentioned, the arbor mechanism produces far more pressure compared to the lever-style design with the same input force. Initial calculations (Appendix 2) show that the pressures reached can easily be around 3 times higher using an arbor-style design. This added benefit does come at a cost, as gears are expensive machined parts.

A Carjack Mechanism was one the first alternative designs out there. The mechanism works by applying a torque to the spindle in a conventional carjack, which creates a linear movement and applies force to the plunger. The first version was made by Taller Esfèrica, a Barcelona-based recycling station. Their machine is shown in figure 24.

Similar to the Arbor mechanism, the carjack mechanism is able to generate a lot more force on the plunger compared to the lever-style design. The downside to this is that the process is quite slow, as the spindle needs to be turned many times to stretch the mechanism. According to the builders of this machine, this can lead to short-shotting.

Figure 24: The carjack machine by Taller Esferica

Electric Actuators are used by somewhat more tech-savy builders. These actuators come in different sizes with different power qualifications, which requires a bit of technical background to use. One outstanding design by Precious Plastic Melbourne uses a log-splitter to apply force, which can be seen in figure 25.

Most electrical actuator-setups result in advanced customizable injection force, speed and amount, which can be of great benefit to part quality. However, as interviewee Ramdhan describes: "It makes the process less heavy for me, but these actuators can't feel when the mold is full. So you need to really prepare and test a lot, which also cost time". Next to this, electrical actuators are quite expensive and hard to find.

Figure 25: The log-splitter design

The Injection Unit
The standard core design of the injection unit (metal barrel + band heaters) is used in almost every machine that was encountered. Instead, there are quite some smaller upgrades that circulate the community.

A nozzle tap ensures plastic will stay inside the barrel while the machine is heating up. While the plastic is melting, the viscosity of the plastic should in principle be enough to keep it from running, but nevertheless this occasionally does happen in practice. Figures 26 and 27 show some of the existing designs out there.


Figures 26 and 27: The nozzle taps made by PlasticHub and PP France

Insulation is added by many users in some shape or form, as mentioned before. This greatly reduces the amount of energy loss within the system, while also speeding up the melting process. Generally, either a simple sheet-metal cover or insulation wool is used. Figures 28 and 29 show these things.


Figures 28 and 29: The insulation wool and sheet-metal insulators

The Mold unit
In the current design of the injection machine, the mold is screwed on the nozzle at the bottom the barrel. This both holds the mold in place and connects the mold to the nozzle. The clamping force inside the mold is achieved using quick-release screws, which are assembled by the user before screwing on the mold. As this standard mold system is very time consuming, many builders have come up with alternative designs and upgrades.

A movable barrel allows the user to effortlessly connect and release the mold to the nozzle, without screwing it on. In this design, the entire barrel is suspended by a spring and is forced down a few centimeters by the plunger force until it engages with the mold gate. Figures 30 and 31 show this principle in action.


Figures 30 and 31: The movable barrel by EasyMolds

Car Jacks are also often used to clamp the mold to the nozzle. Figure 32 shows an existing design by Plastic Hub.

Figure 32: The carjack engagement

A Toggle-Joint Mechanism clamp the mold to the nozzle through a mechanism which 'snaps' in place. This is quite an abstract mechanism, which works similar to the latches on flight-cases (figures 33 and 34). The machine by PlasticPreneur provides a good example of this.

Figures 33 and 34: The toggle joint mechanism

Hydraulic Pistons are the last and by far most professional clamping method. Using an air-powered piston, the mold is clamped against the nozzle. This is the only method that does not require an internal mold clamping system such as the quick-release system, as the force generated by the piston is enough to take over the clamping function. This does allow for a very fast cycle-time, but requires an extra-strong frame and costs a lot. Figure 35 shows the design by Peter-Bas Schelling.

Figure 35: The mold table and piston by Peter-Bas Schelling

Frame

The current design has a fully welded frame, which has been altered by quite a lot of users. Below, the main variations are discussed.

A bolted frame for disassembly removes most welds in the build. This way, the frame can be (partially) disassembled for transportation or for upgrades. Figure 36 shows the design from Precious Plastic France.

Figure 36: The disassemblable machine

Wall-mounted frames are used for builders with a permanent injection location. As the frame is mounted to the wall, it is much more stable compared to the current design. Figure 37 shows the wall-mounted frame by Precious Plastic France.

Figure 37: The wall-mounted machine

Appendix E: Arbor Machine Choice

Design Choice Force Actuating Mechanism

✅ LoR-passed solutions

Arbor Mechanism

- Similar to OSR-plastic/johannplasto/plasticpreneur

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	188	Yes	Yes	80	8 (estimation)	Yes

▼ *Cost of arbor*

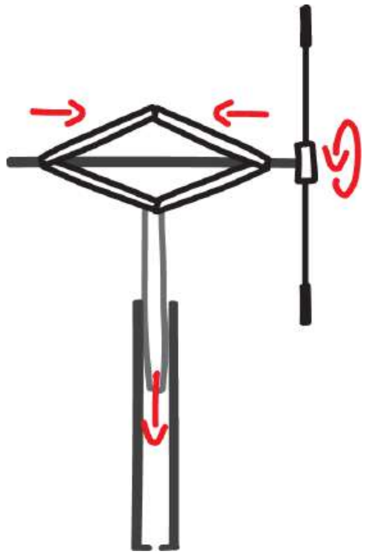
Gear: 20 €https://www.bearingboys.co.uk/Metric-EN8-Gears/SS3016B-30-Mod-x-16-Tooth-Metric-Spur-Gear-in-Steel-68469-p

Rack: 40€ https://www.bearingboys.co.uk/Metric-Steel-Racks-20-PA/SR30305-3-Mod-x-30mm-Wide-Steel-Rack-x-05m-Long-160923-p

2 bearings: 10€ (https://nl.rs-online.com/web/c/bearings-seals/rotary-bearings-housing-units/ball-bearings/)

Hub: 10€ (based on Elena)

Carjack Mechanism



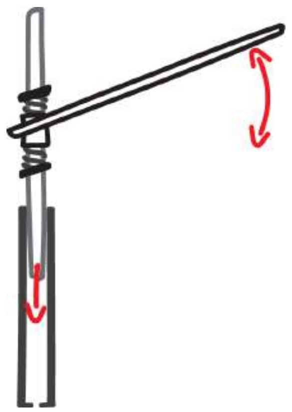
A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	100 (estimation)	Yes	Yes	30	5 (estimation)	Yes

▼ *Carjack systems*

https://www.amazon.com/CPROSP-Scissor-Capacity-Trolley-Ratchet/dp/B07M7YN1H3?th=1

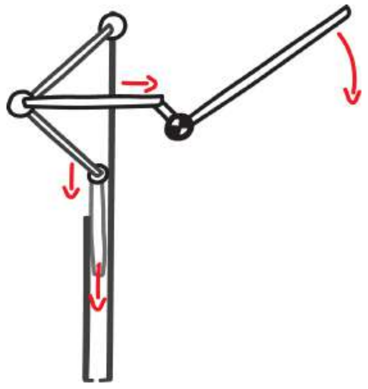
https://www.amazon.com/Torin-Steel-Scissor-Jack-Capacity/dp/B004PX8BC2

Gluegun Mechanism



A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	150 (estimation)	Yes	Yes	60	8 (estimation)	Yes

Toggle-clamp Mechanism



A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	140 (maple)	Yes	Yes	60	5 (estimation)	Yes

☑️ Choice

Wish	Weight	**Arbor mechanism**	**Carjack mechanism**	**Gluegun mechanism**	**Toggle Clamp mechanism**
0a. As accessible as possible	25	8	9	7	7
1a. Generate as much pressure as possible	20	9	6	7	6
1b. As much injection speed as possible	15	8	4	5	6
1c. As much travel distance as possible	15	9	7	8	5
0b. Cost as little as possible	15	7	8	5	6
0c. As easy to assemble as possible	15	7	8	5	5
0d. Be as durable as possible	15	8	6	4	6
1d. Use as little human force as possible	10	9	7	7	6
0e. Weigh as little as possible	5	7	8	8	6
0f. Be as small as possible	5	6	7	7	4
Total	140	1120	985	865	825

🚫 LoR-Failed solutions

Current lever press

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	Maximum human force of 350N	Minimum travel distance of 38cm	Minimum travel speed of 5cm/s	Cost a maximum of 100€	Weigh a maximum of 20 kgs	Be accessible
Yes	527 (maple)	35 (maple)	Yes	12 (BOM)	3 (BOM)	Yes

Bottle Jack

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	Maximum human force of 350N	Minimum travel distance of 38cm	Minimum travel speed of 5cm/s	Cost a maximum of 100€	Weigh a maximum of 20 kgs	Be accessible
Yes	0	18	No	25	5	Semi

▼ *Bottle Jack systems*

https://www.kippersrijssen.nl/hijsmateriaal/potkrikken/potkrik-mw-2-ton?gclid=CjwKCAjwx46TBhBhEiwArA_DjK2RvvCkSGJIxM_438Ipl-XqOf-GD4u98Ui5DFGBjGGdQag_G_EjyBoCNCcQAvD_BwE

https://www.gereedschapland.nl/product/28975/hydraulische-professionele-potkrik-3-ton-compac-cbj3?gclid=CjwKCAjwx46TBhBhEiwArA_DjP2diNyVRsOGvoWX0zbQaWdG4JWSGjamvFAo-zFwZ1OxjUh_wfJU6hoC0rYQAvD_BwE

Hydraulic Ram + Pump

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	Maximum human force of 350N	Minimum travel distance of 38cm	Minimum travel speed of 5cm/s	Cost a maximum of 100€	Weigh a maximum of 20 kgs	Be accessible
Yes	0	Yes	Yes	400 and up	20	No

▼ *Hydraulic systems*

https://www.dkmtools.nl/specs/723059854?gclid=CjwKCAjwx46TBhBhEiwArA_DjArzGFgzR_f55FxwWqDX1Ffb6zYjMdd1GTpDvgD__GiB5sbw0wGX1xoCKW4QAvD_

Hand jack

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	Maximum human force of 350N	Minimum travel distance of 38cm	Minimum travel speed of 5cm/s	Cost a maximum of 100€	Weigh a maximum of 20 kgs	Be accessible
Yes	0	Yes	No	70€	20	Semi

▼ *Hand Jack systems*

https://www.hbm-machines.com/nl/p/hbm-2-ton-122-cm-boerenkrik-handkrik-dommekracht-kelderwinch?utm_source=google&utm_medium=organic&utm_campaign=surfaces-across-google&gclid=Cj0KCQjwpcOTBhCZARIsAEAYLuWJHL5Wjdcr3Bb-omE-JVggH7nV2SNJ0yv-VNZw9Pj5APxgRzr6B7MaAhbDEALw_wcB

Linear Actuator

- Either cost, travel distance or plunger force is not sufficient
- Additionally, this solution does not allow for auto-stopping at a full mold, which will likely result in part failures.

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	0	35 and up	Yes	400 and up	1	No

▼ *Linear actuator systems*

https://www.dennisdeal.com/products/dc-12v-50-500mm-900n-stroke-tubular-motor-2-4-8-12-16-20-inch-linear-actuator-motor_1526731?gclid=Cj0KCQjwpcOTBhCZARIsAEAYLuXh1hsNeO3P_8yu2eni-siqiSz0j8FBDuONw9eNDyGinQhr-bucN9EaAgiYEALw_wcB

https://nl.aliexpress.com/item/4001013839739.html?_randl_currency=EUR&_randl_shipto=NL&src=google&aff_fcid=d300d0fda9e14845ad6687f9382d834f-1651581703670-06378-UneMJZVf&aff_fsk=UneMJZVf&aff_platform=aaf&sk=UneMJZVf&aff_trace_key=d300d0fda9e14845ad6687f9382d834f-1651581703670-06378-UneMJZVf&terminal_id=3561b83eac7b461fb9ac383a6c7016f7&afSmartRedirect=y

Spindle

A	B	C	D	E	F	G
Minimum force of 2250N on the plunger	**Maximum human force of 350N**	**Minimum travel distance of 38cm**	**Minimum travel speed of 5cm/s**	**Cost a maximum of 100€**	**Weigh a maximum of 20 kgs**	**Be accessible**
Yes	95	35 and up	No	100	3 (estimation)	No

▼ *Spindle systems*

https://horecatiger.eu/en-eu/shop/spindle-30mm-l-660mm-thread-m6-702140?gclid=Cj0KCQjwpcOTBhCZARIsAEAYLuVeBx_FPilq2YfEx9Rbb6aNdr89FAwOW-NvAqNd-2FBd4O6sSbuC5YaAsF-EALw_wcB

Wishes test:

Wishes	M1 (lever)	M2 (arbor)	M3 (jack)	M4 (krik)	M5 (toggle)
Be as scalable as possible	2	4	2	3	2
Transform human input force into as much pressure on the melt as possible	1	4	3	3	2
Be as durable as possible	3	4	4	2	3
Cost as little as possible	5	3	4		
Be able to travel as much as possible					
Weigh as little as possible					

Appendix F: LoR/W Project Goal 2

Requirements

Technical requirements

TR1.1: The machine should be able to exert a mimimum pressure of 42 bar on the plastic melt.
This is the minimum pressure needed to successfully inject conventional molds within the current Precious Plastic system as concluded in chapter 3.5.

TR1.2: The machine should have an effective barrel volume of at least 150cm3 .
This is based on the volume of the existing molds within the Precious Plastic system as concluded in chapter 3.5 and on insights from chapter 3.2.

TR1.3: The barrel tube of the machine should have a maximum radius of 15mm.
This is based on earlier experiences of other builders on increasing the diameter of the barrel as concluded in chapter 3.5.

TR1.4: The machine should induce a minimum travel distance of 38cm on the plunger.
This is the minimal distance the plunger should be able to travel to inject the required shotvolume as concluded in chapter 3.5.

TR1.5: The machine should induce a mimimum travel speed of 5cm/s on the plunger.
This is the mimimal speed to successfully inject plastic as found in chapter 3.5.

TR1.6: The machine should be able to heat the input plastic to 250C°.
This is based on the melt temperature of the most commonly used recycled plastics as concluded in chapter 3.5.

TR1.7: The machine should minimally have an area with a diameter of 380mm and a height of 170mm to place molds.
This is based on the dimensions of conventional molds as found in chapter 3.5.

TR1.8: The machine should not allow the nozzle and mold engagement to disconnect during the injection process.
This is to ensure the users safety during injection as concluded in chapter 3.5.

TR1.9: The machine should maintain structural integrity under the resulting forces subsequent to the injection process.
This is to ensure the users safety during injection as concluded in chapter 3.5.

TR1.10: The machine should not be able generate more then 100 bars during typical use.

Safety requirements

SR2.1: The machine should not tip over under the applied forces during the injection process.
This is to ensure the users safety during injection as concluded in chapter 3.5.

SR2.2: The machine should prevent the user from coming into direct contact with electrical current.
This is to ensure the users safety during injection as concluded in chapter 3.5.

SR2.3: The machine should prevent plastic flakes from direct contact with the heating elements.
This is to prevent toxic fumes as concluded in chapter 3.2

SR2.4: The machine should protect the user from Mechanical hazards such as crushing, shearing, cutting or others.
This is based on the CE requirements as described in chapter 3.7

SR2.5: The machine should protect the user from Electrical hazards such as burns and electrocution.
This is based on the CE requirements as described in chapter 3.7

SR2.6: The machine should protect the user from Thermal hazards such as burns.
This is based on the CE requirements as described in chapter 3.7

SR2.7: The machine should protect the user from Material hazards such as poisoning or explosions.
This is based on the CE requirements as described in chapter 3.7

SR2.8: The machine should protect the user from Ergonomic hazards such as fatigue or stress.
This is based on the CE requirements as described in chapter 3.7

Usage requirements

UR3.1: The machine should require a maximum human input force of 350N to reach the minimum pressure on the plastic melt.

This is the maximum ergonomic human limit in applying force for around 30 seconds as found in chapter 3.2.

UR3.2: The machine should be able to successfully inject cold molds.

This is based on the insight that mold heating currently takes a lot of time from chapter 3.2 and on insights on the advanced use case as described in chapter 3.2.

UR3.3: The machine should enable the user to place and remove any mold in under 5 seconds.

Building requirements

BR4.1: The machine design should not require welding on the barrel.

This is one of the key outcomes of the building research as is concluded in chapter 3.3

BR4.2: The machine design should not require cutting the barrel tube.

This is one of the key outcomes of the building research as is concluded in chapter 3.3

BR4.3: The machine design should not require plumbing tools during the build process.

This is one of the key outcomes of the building research as is concluded in chapter 3.3

BR4.4 The cost of the machine should not exceed 500€.

This is based on insights on the advanced use case as described in chapter 3.2.

Wishes

Technical Wishes

TW1.1: The machine would produce around 60 bars of pressure upon application of the 350N of human input force.

This value was determined as the desirable injection pressure through expert input on the co-design discord channel. Next to this, this wish is based on insights on the advanced use case as described in chapter 3.2.

TW1.2: The machine design should enable the replacements of modules as much as possible.

This is based on the research on Open Source Hardware as found in chapter 3.8

Usage Wishes

UW2.1:The machine would prevent the user to touch surfaces of over 60 C° as much as possible by design.

This is to protect the users from burning themselves as much as possible. The value of 60 degrees was determined based on literature by Lawrence and Bull (1976).

UW2.2: The machine would enable the user to engage the mold onto the machine with as little effort as possible.

This is based on user insights as described in chapter 3.2

UW2.3: The machine would enable the user to produce parts as quickly as possible.

This is based on insights on the advanced use case as described in chapter 3.2.

UW2.4: The handlewheel of the machine would enable the easy switching of hands as much as possible

UW2.5: The machine should be as easy to use as possible.

Building Wishes

BW3.1: The machine would use standardized building materials as much as possible.

This is based on one of Precious Plastic's core values to ensure worldwide replicability as concluded in chapter 2.2.

BW3.2: The machine could use advanced building techniques such as lathing and milling.

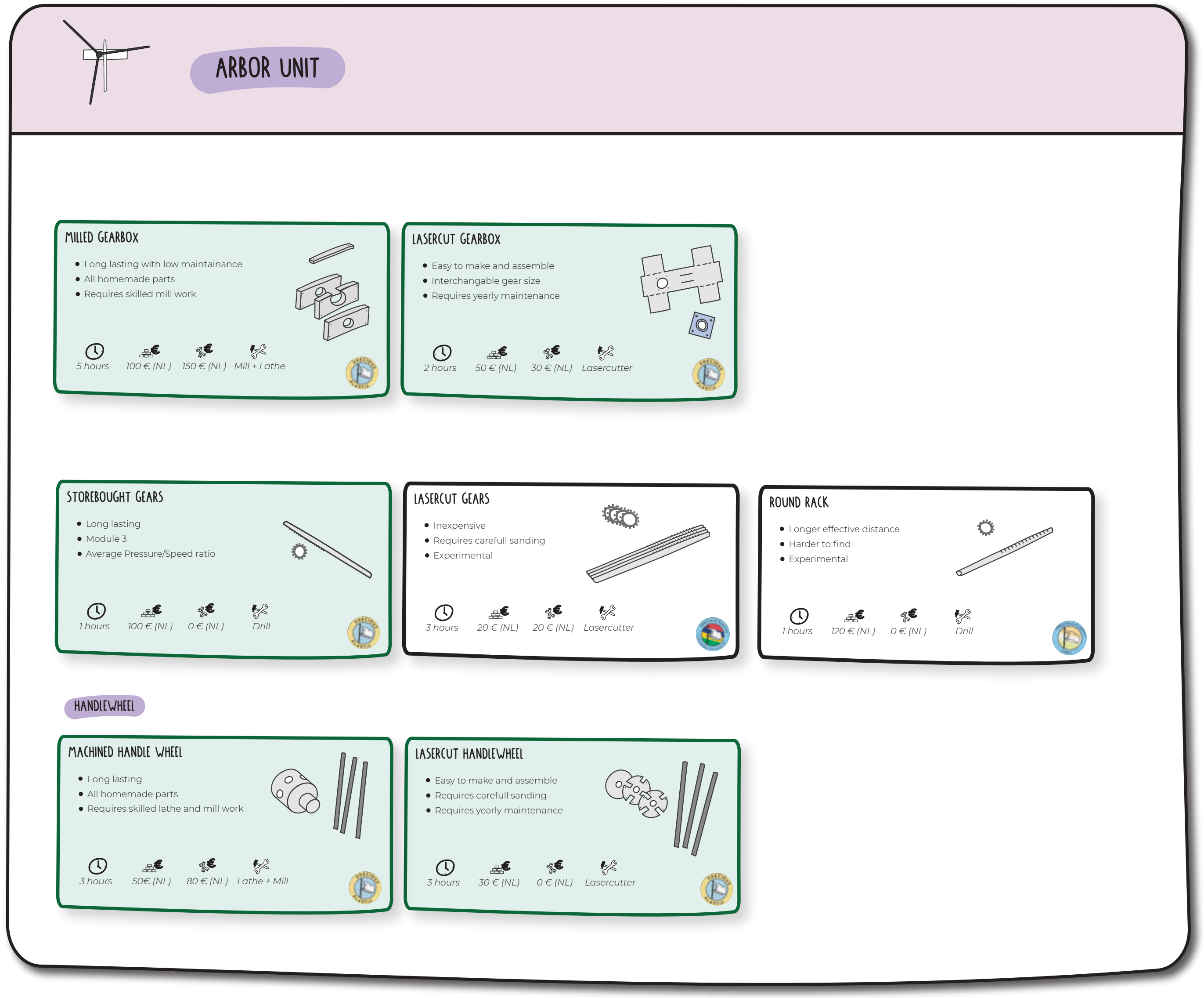
This is based on insights on the advanced use case as described in chapter 3.2.

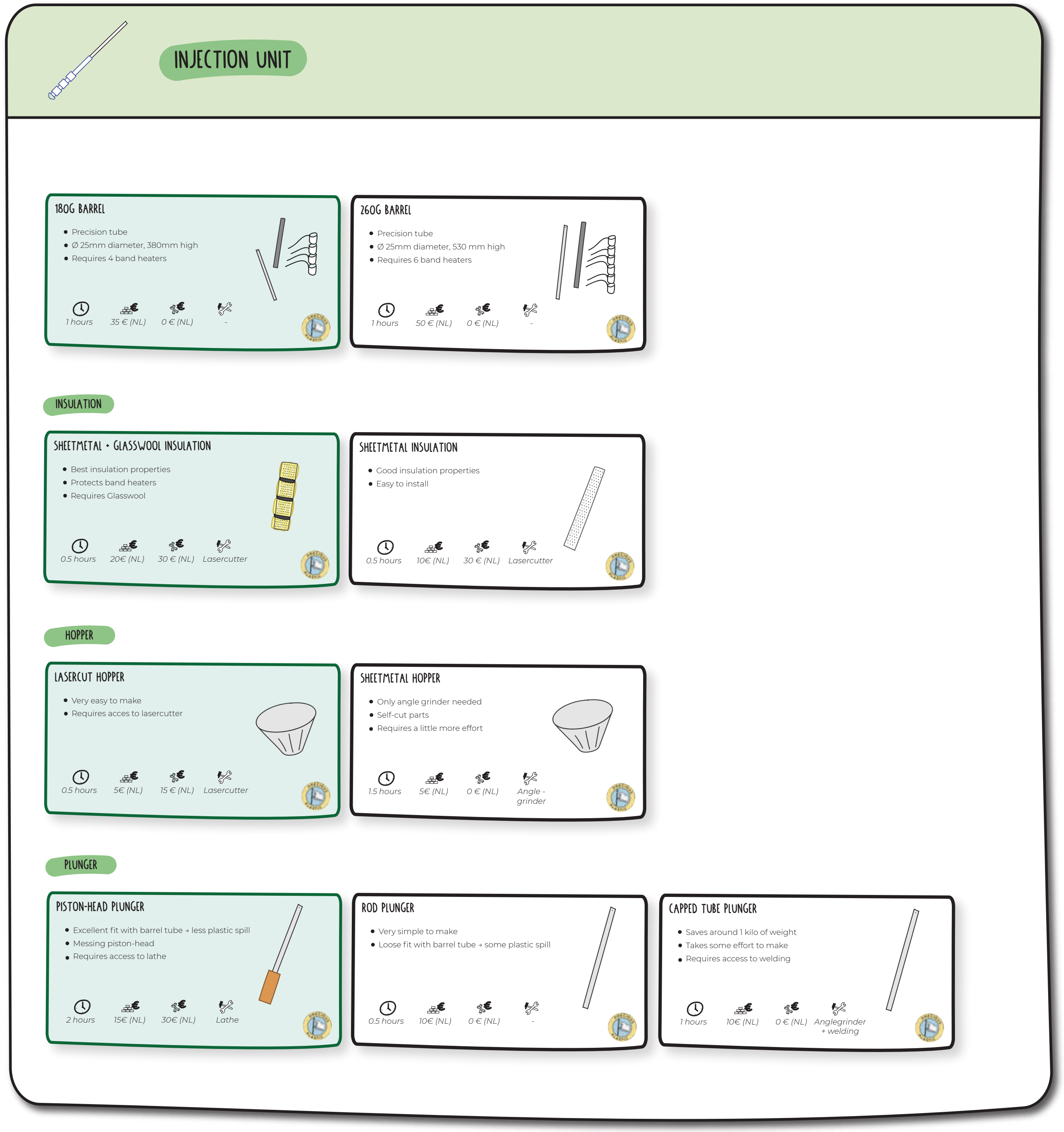
BW3.3: The machine design would require as little maintenance as possible.

BW3.4: The machine design would be as durable as possible.

BW4.5: The machine design would use as little different material types as possible.

Appendix G: Poster of Module Variants





MOLD UNIT

COMPRESSION SPRING AUTO ENGAGEMENT
- Auto-engages mold → saves time and effort during injection
- Requires Cap Nut Nozzle (see nozzle)
- Requires Compression Spring
- Requires acces to lathe

1 hours | 35 € (NL) | 40 € (NL) | Lathe + Lasercutter

PLATE SPRING AUTO ENGAGEMENT
- Auto-engages mold → saves time and effort during injection
- No need for compression spring
- Requires Cap Nut Nozzle (see nozzle)
- Requires acces to lathe

1 hours | 35 € (NL) | 50€ (NL) | Lathe + Lasercutter

SCREWED-ON BARREL
- Cycle time per injected part is higher
- Simple and cheap to make
- Requires more effort during injection process
- Cycle time per injected part is higher
- Requires more effort during injection process

0.5 hours | 5 € (NL) | 0 € (NL) | -

CAR JACK
- Easy to use
- Requires Cap Nut Nozzle (see nozzle)
- Injection process takes somewhat more time
- Requires Car Jack

1 hours | 30 € (NL) | 10 € (NL) | Lasercutter

NOZZLE

CAP NUT NOZZLE
- Best seal with mold gate
- Dependent on mold design
- Requires flexible barrel (see nozzle engagement)
- Requires access to lathe

1.5 hours | 5€ (NL) | 25 € (NL) | Lathe

CONICAL NOZZLE
- Good seal with mold gate
- Dependent on mold design
- Requires flexible barrel (see nozzle engagement)
- Requires access to lathe

1.5 hours | 5€ (NL) | 25€ (NL) | Lathe

SCREWED-ON NOZZLE
- Cheapest option
- Cycle time per injected part is higher
- Requires more effort during injection process

0.5 hours | 10€ (NL) | 0 € (NL) | -

MOLD TABLE

HEIGHT-ADJUSTABLE MOLD TABLE
- Easy to make
- Fits all molds
- Requires lasercutter

1.5 hours | 10€ (NL) | 15 € (NL) | Lasercutter

ACTIVE CLAMPING TABLE
- Decreases cycle time by a lot
- Requires advanced technical skills
- Experimental

5 hours | 150€ (NL) | 100 € (NL) | Mill + Lathe

NO MOLD TABLE
- Only with Screw-on Nozzle

0 hours | 0€ (NL) | 0 € (NL) | -

FRAME

FRAME COMPOSITION

FLOOR BOLTED FRAME
- Perfect for single-location use
- Requires solid foundation

4 hours | 50€ (NL) | 30€ (NL) | Welding

BASIC FRAME
- As easy to make as possible

4 hours | 50€ (NL) | 30€ (NL) | Welding

DISASSEMBLABLE FRAME
- Can be disassembled partially for transported
- Takes more time to make

6 hours | 50€ (NL) | 30€ (NL) | Standing drill

WALL MOUNTED FRAME
- Perfect for single-location use
- Requires solid walls

4 hours | 50 € (NL) | 30 € (NL) | Welding

ELECTRONICS BOX

HOUSING

SPLASH- AND DUSTPROOF BOX (IP55)
- IP55 rated box for long-term use
- Protects electroncis against splashwater and dust

2 hours | 30€ (NL) | 0€ (NL) | -

LASERCUT BOX
- Perfect if OEM boxes are not available
- Requires a little more time to make

3 hours | 10 € (NL) | 20 € (NL) | Lasercutter

ADD-ONS

CHILD-PROOF BARREL PROTECTION
- Covers all heated parts
- Perfect for giving workshops

1 hour | 10 € (NL) | 20 € (NL) | Lasercutter

RACK SCALE
- Shows injected grams in mould
- Simple to install

0.5 hours | 5€ (NL) | 10 € (NL) | Lasercutter

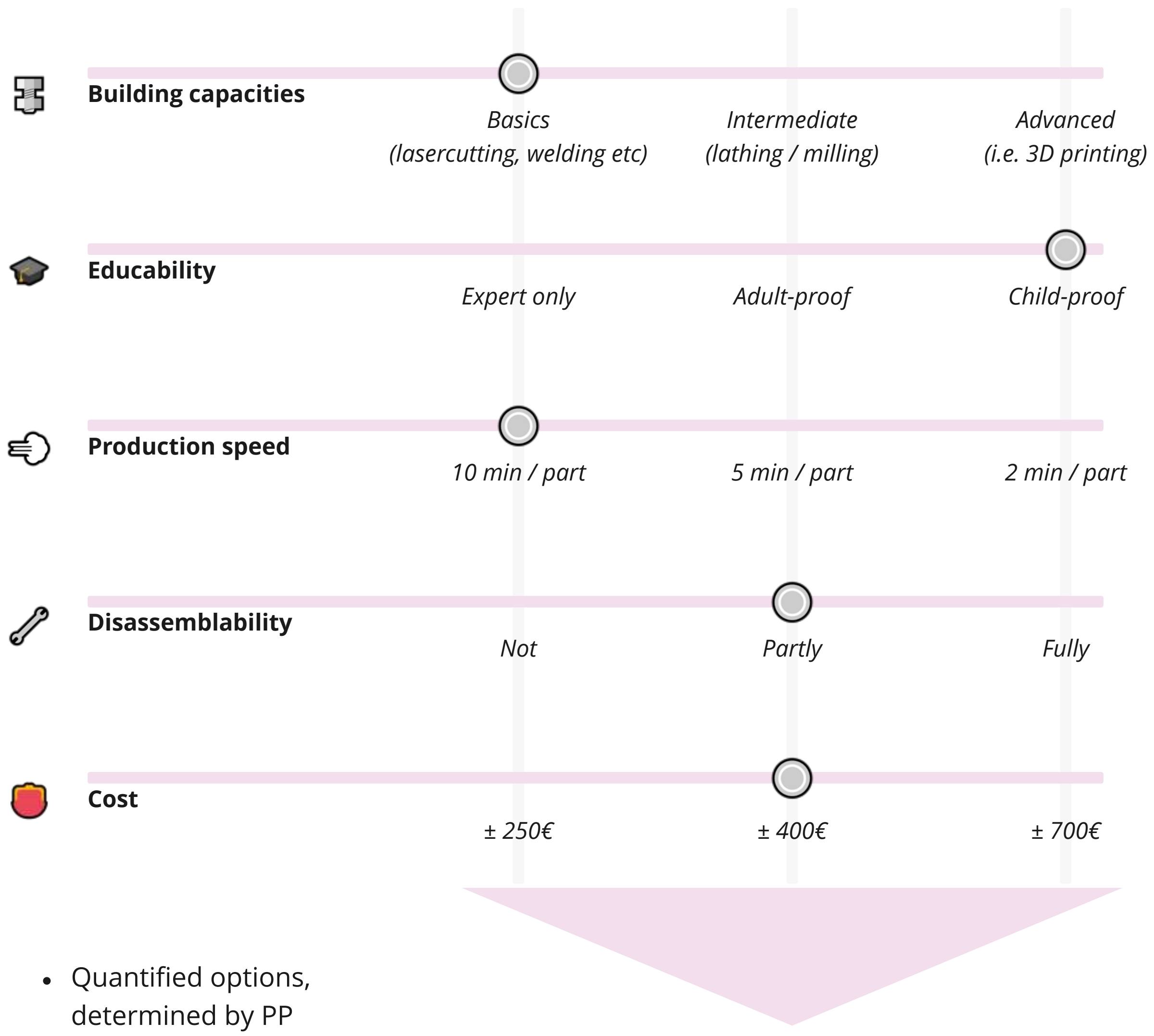
ERGONOMIC HANDLES
- Perfect for high-intensity users
- Hard to find

0.5 hours | 10 € (NL) | 0€ (NL) | -

Appendix H: Overview of Presets

Appendix I: Choice tool concepts

Choice - tool (v 1)



- Quantified options, determined by PP
- Self-adjusting scales (if user selects high production speed, cost will also change)

Taylored version

- *Basic build techniques*
- *400€*
- *10 min / part*
- *Child Proof*

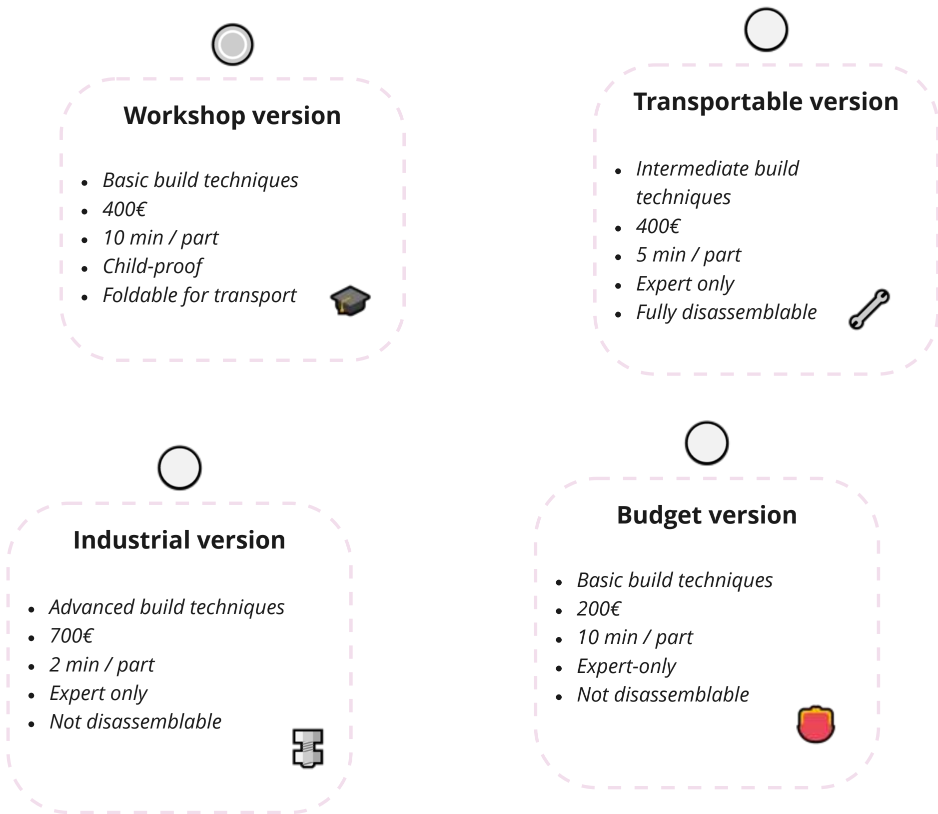
Builder doesn't need to understand the differences between options

High maintenance load for PP

Algorithm needed

Might be a bit overkill for most users

Choice - tool (v 2)



- 'Presets', defined by PP
- Based on most common/likely preferences

Easy to understand for builder

Not a lot of work to maintain

Some maintenance is needed for new versions

Less tailored choice for builder

Choice - tool (v 3)

Main aim:

Regular
- *Basic build techniques*
- *10 min / part*
- *250€*

Intermediate
- *Intermediate build techniques*
- *5 min / part*
- *400€*

Expert
- *Advanced build techniques*
- *2 min / part*
- *700€*

Design for:

- ☐ **Transportation (foldable frame)**
- ■ **Workshops (dummy-proof)**
- ☐ **Energy-efficiency (advanced isolation)**
- ☐ **XL shots (larger barrel)**

- Select 'level' on main axis, which is a mix of **aim, building techniques and cost.**
- After, select design add-ons

Easy to understand for builder

Some maintenance is needed for new versions

Also needs an algorithm

Choice - tool (v 4)

Standard machine
Single standard version

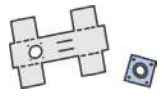
Easiest to build

Cheapest

Most accessible worldwide

Add-ons & Upgrades
Optional picks for builders

Lasercut box



CnC-ed box

- Requires access to milling
- More durable
- Smoother gear turning
- + €50 of additional cost

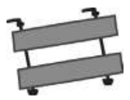
125g barrel

300g barrel

- Larger shot volume
- Shorter cycle time
- + €70 of additional cost

Note: Dimensions change in frame!

In-mould clamping



Basic clamping table

Horizontal clamping

- Shorter cycle time
- + €50 of additional cost

Note: Dimensions change in frame!

Fully automatic clamping table

- Very short cycle time
- + €250 of additional cost
- + 500W power usage

Note: Dimensions change in frame!

- One single design, user has no choice to make in advance
- Different add-ons and options are possible to upgrade the machine at wish

Least work for Precious Plastic

Builder is forced to make tailored choice, renders good data

Naturally grows, no effort needed to update system

Requires a little more engagement from the user

Appendix J: Transcripts MDF Validation

Taylor

Carefully starts working down

Text seems a bit small

Basic units → that's really clear

The introduction text is quite important to understand what's happening. The image makes it very clear, I like the graphic.

If the text would be more build next to the visual, it would be more clear.

Scrolls to pre-sets

That's cool, most people I'm building for are making workshop tools

Workshop is a vague term, some people might get confused between the meaning of the word.

Reads all the text in the presets carefully

Advanced: is there any advantage? Not clear to me.

I think its like customizing a car. I'm assuming it will give me variants on these variants after.

Oops I forgot the terms.. Could be handy to give a short legend here to explain what is what.

Labour cost icon is really small, also the euro is not very international

Gears: module 3 might not mean very much to anyone.

Shareback: ahh cool! That really makes sense. The text about it could be written more activating. It's a little unclear.

The final buttons are a bit vague..

This is a really good idea, working with the bazar also seems doable.

Everyone iterates, and that's not clear on the [current Precious Plastic] site. This helps people understand that there is a lot of variants and it helps them make a good choice. Even if they don't use it, only seeing it gives them a good overview.

I love the presets. Its like building a character in a game: you start with a base.

A nice addition would be a image that stays in your screen, and that would change once you customize the build. Having that visual would be nice

You should also have a base version that you could get without the customizer tool. That would be easier for a lot of people.

Ian Lewis

I don't remind having seen this on the original website

I'm aware of all the different parts that I might need

Skips quickly to the presets

Does not click on them

Scrolls through

Looks through everything

At the beginning: it would be cool if all of these are kind right of links, for the next time im visiting

Presets:

I like how the presets change once you click on them

I'm not sure I understand what I'm able to do

I can see that if I click the presets I can see everything changes

Ahh

If I go down I can select which things I want to build based on what my capabilities are

Where there are three options, its not very clear you can slide it across

Maybe add an arrow

In terms of language, its good to have the illustrations. I think the call to action for customization could be more specific. If people are not paying attention, you might not know that you are able to select something.

I like the interactivity in the page. The illustrations makes it relatable. It gives of the simplicity

I've just seen now, when I hover over it it says click for zip file. I thought Download and upload was a button, is a little unclear.

If I had had this with the build that I made, my life would have been much easier.

This is especially due to the flow of information. First the end goal in use, and then I can compare. It gives you the possibility to go back and forth.

Also its very nice to see the price and the tools before I go and download.

Andrea:

I want to click to hey, it looks like a button

Oh, I can go down, but I did not see the arrow.

Very beautiful image, also I can read it

It's a nice flow of things

I can see what about the machine is.. I'll start reading

I can't read the text very well..

This helps me a lot in organizing my thinking in building the machine.

When I wanted to build the machine I wanted to make modifications, now I can have an overview

There is a lot of text, but its also nice to understand

In my starting scenario I started the workshop

Oh I made the right choice, its green

It is a nice flow of information.

First you get the end goal in mind

After this you customize and go back and forth

What does composer mean? I'm not native English speaker, not sure what is means.

Ahh I can tailor

It looks like customizing

Wow.. I like this color. Its very relaxing to look at

> Scrolls down to see other units

Ah there are a lot..okay..

> starts looking at variants

Hmm.. so money and time.. So I know the hardness of it. I'm looking at hours first. Ah, this is work labour and this is materials. I deciphered from the icons.

I'm going with the lasercutter options now.. I'm already going with lasercut parts so I'll keep it standard to make my life easier.

The symbol of the tools it's a bit small, not so clear

> Checks other variants

This is very good overview, I like it

I just don't understand why there are precious plastic logos that are not the standard ones. I think its an error.

Hmm.. I want now after looking at it I'm look at the technical requirements

The milled looks at the most difficult one.

I want to realize now, so I'm looking at lasercuttable stuff.

Scrolling sideways

He does not understand that the variants are clickable..

They are green.. Ah but this is the industrial machine

Ahhhh.. I get it. Green is my selection.

Its one or the other.

Maybe make the black ones grey. I thought

I'm a little confused at the style, It's a bit not coherent

It's more an experience, well organized

I can really choose more, this is very nice

It can see the concrete value.

It comes from the real design.

The original one is much less flexible, seems not very hard to improve.

Camiel:

> Scrollt naar beneden, weer omhoog

Ik ben geen bouwkundige, om me te oriënteren is het wel heel goed om zon introtekstje te lezen

> Leest alles aandachtig door

Ik vind de tekst op pre-sets klein en moeilijk leesbaar

> Hovert lang over presets

Kan ik hierop klikken? Ah!

> Het is niet heel duidelijk dat de pre-sets klikbaar zijn

> Scrollt naar beneden en klikt op variants

> Beetje aan het kijken wat beide is

Hmm wat houdt dit in.. De Gearbox.. Juist..

Ik weet onderhand wel wat het is, maar als ik als eerste hierop kom zonder achtergrond is het misschien handig om iets meer informatie te geven.

Vind het wel heel leuk hoe het samenkomt en hoe je hier echt een keuze in kan maken

Waar ik nu zelf vooral naar kijk is de prijs, maar ook de tijd gaat belangrijk zijn voor mij

Misschien zou ik iets van overzicht daarvan willen wat mijn keuze dan voor het totaalplaatje betekend.

> Process duurt allemaal best lang, neemt echt de tijd om uit te zoeken wat er gebeurd

‘easy to assemble’ dat is wel praktisch voor mij, ik geef workshops enzo. Handig dat je heel makkelijk dingen los kan maken, ik denk dat ik dan dus deze kies.

Bij barrel: Ik denk dat wat ik hier mis is dat erbij zou kunnen staan dat je meer per shot kan produceren. Als ik dat wist zou ik betere keuze maken

> Scrollt naar downloadpage

Oh dus hier kan ik het downloaden.. oh en dit is iets van feedback.. oh nee een upload form

> Kijkt wel naar upload form maar klikt er niet op.

Hele interessante opzet! Waar ik vaak genoeg mee aankwam tijdens het bouwen van mijn injectiemachine was dat ik eigenlijk een soort standaard ikea pakket aan het bouwen was. Hiermee creeer je toch meer je eigen machine.

Voor een injecteermachine is dat heel nice!

> Final thoughts?

Heel interessant, goed dat je het samen kan stellen

Vraag me wel af hoe dat met de andere machines dan werkt. Bijvoorbeeld bij de sheetpress heb je volgens mij wel minder keuze.

Bij huidige website ben ik vooral langs de how-to’s gelopen, maar daar kon ik niet echt iets mee.

> Waarom is dat dan?

Ja dat is niet echt uitnodigend, veel koppen tekst en niet alles is echt relevant voor mij.

Appendix K: Module Development

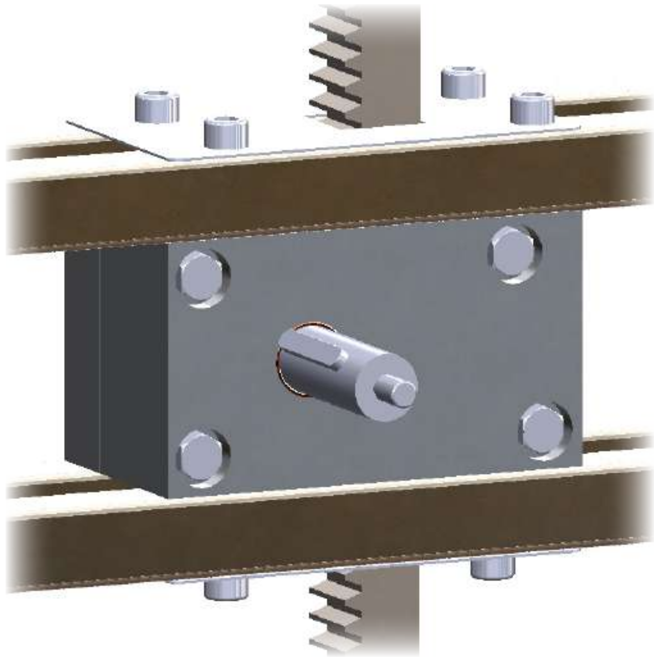
Milled Gearbox

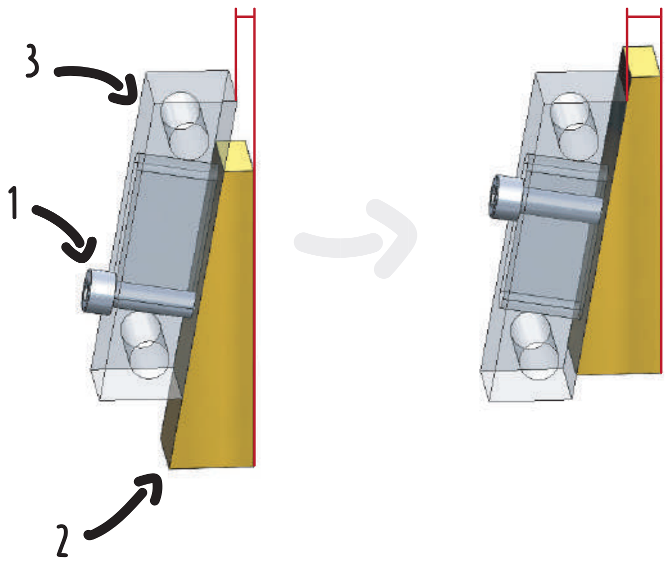
The original inspiration for the milled gearbox was found in the 'Elena' machine by Plastic-Hub and the Arbor Press by Le Recycleur Fou . It has the following key functions:

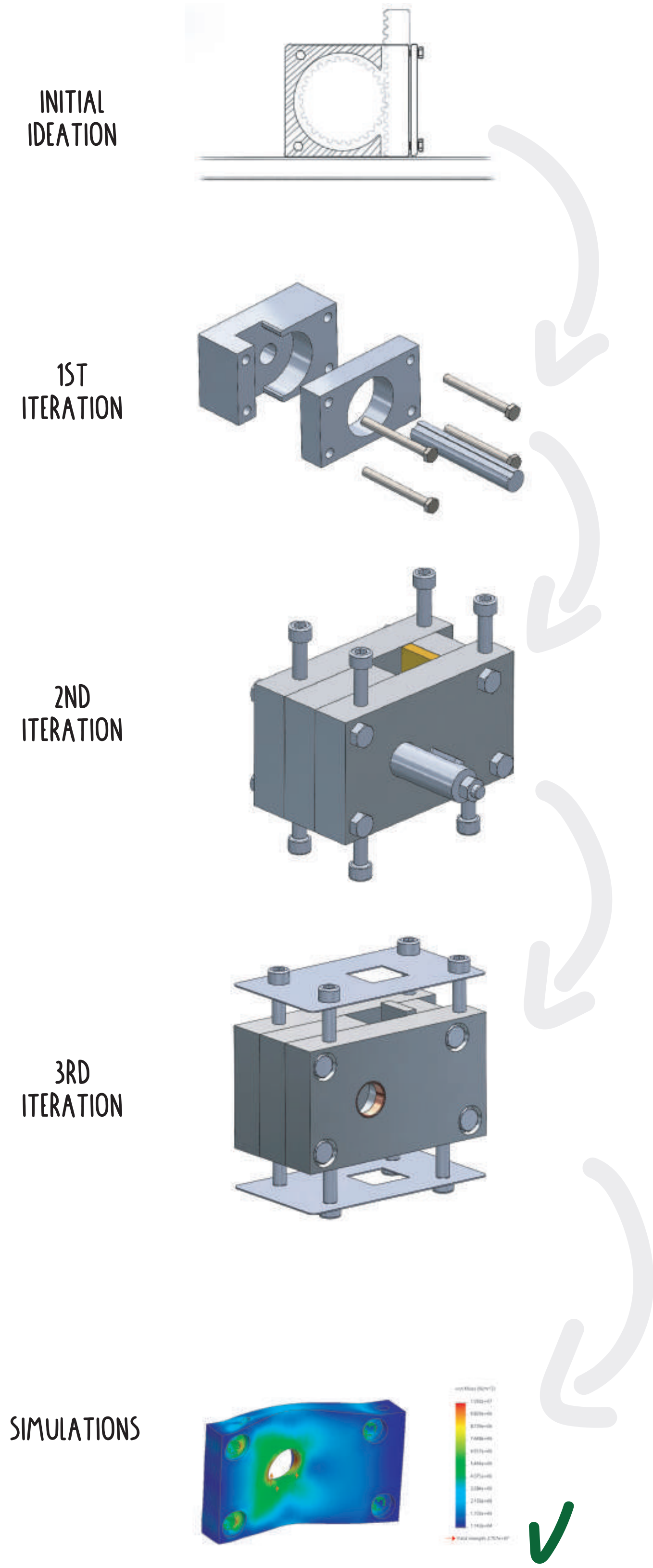
- Suspend gears
- Allow rack-and-pinion interaction
- Allow proper meshing of gears

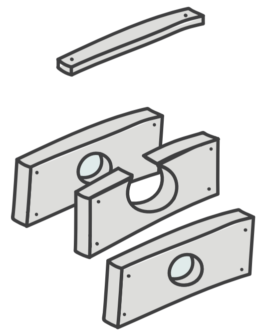
Key Features
The base of the gearbox is formed by 4 slabs of milled aluminum slabs with a width of 30mm. This composition is chosen over the simpler two-part composition from the 1st iteration as 30mm slabs are much easier to find then larger dimensions. Also, it saves unnecessary material loss during milling and it correlates nicely with the standard thickness for mod-3 racks.

The main challenge in the gearbox design is to properly mesh the rack and spur gear. This is difficult for two reasons: Firstly, they need to be meshed just right to prevent wear on the teeth. Secondly, the rack needs to slide along some kind of backplate, which will wear after time creating slack in the system. Therefore, a slanted backplate is developed in the 2nd iteration. It solves both issues: once the setscrew is loosend (1), the angled bearing block (2) can slide over the slanted backplate (3) and be positioned so the rack meshes perfectly. Once the angled bearing block has worn too much over time, the process can be repeated.



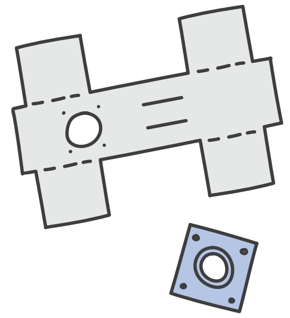






One key requirement for the slabs is their alignment relative to another. They need to be well aligned to ensure the gears run well. To ensure this alignment of the slabs, the 4 structural M10 bolts in the corners are sleeved with alignment bushings. These line up the holes in the slabs precisely and can thus achieve a perfect position tolerance between different slabs.

Above and below the gearbox, lasercut hand covers prevent the user to accidentally place their finger in between gears. These are added in the 3rd iteration and meet the CE requirements on machine safety.

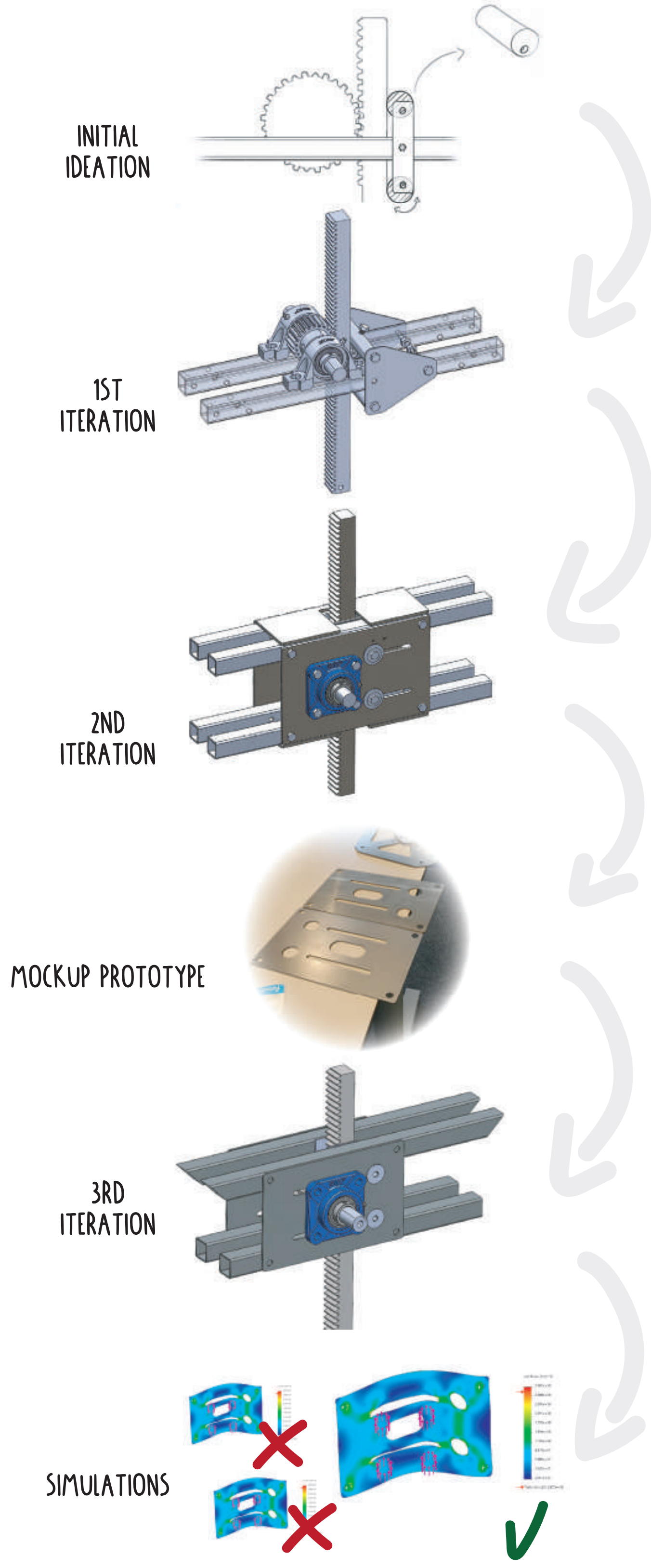


Lasercut Gearbox

The lasercut gearbox is one of the module variants that was developed without being part of the Advanced Build pre-set. It was particularly challenging to develop as all existing arbor gearboxes are designed from milling and lathing. It has the following key functions:

- Suspend gears
- Allow rack-and-pinion interaction
- Allow proper meshing of gears
- Allow multiple gear diameters

Key Features
The key feature to the lasercut gearbox is the suspension of the rack and spur gear. The rack is able to move up and down and is positioned against two roller bars with sleeve bearings. The precise meshing of the spur gear and rack is achieved through the flexible bearing block suspension of the spur gear: When loosened, the two opposite bearing blocks can slide along the slotted holes in the baseplate, allowing the user to perfectly mesh the gears. This has an added benefit of enabling multiple gear sizes, which would require a different axis position relative to the rack due to the different diameter.



The two lasercut base plates serve as the main structural components and need to withstand the extreme loads of the injection process. Similarly, they need to be as thin as possible to save lasercutting cost and spare weight. Through Finite Element Analysis, multiple thicknesses of the steel plates were evaluated and the optimal thickness was found to be 3mm. Chapter 6.4 presents an indepth overview of the simulation process.

Prototype takeaways
After building the final prototype, the following can be concluded:

- The assembly process is a little tedious, as not all parts can easily be reached.
- Lasercutting leaves small drops of hardened metal on the cutting edge of the metal plates. These need to be sanded of by the builder with an angle grinder.
- There is a little wobble in the rack, but this does not lead to issues during the injection process.
- The design functions quite well overall

Lathed Handlewheel

The initial idea of the lathed handlewheel was largely inspired by the Johannplasto's injection machine and the 'Elena' machine by Plastic-Hub. It has the following key functions:

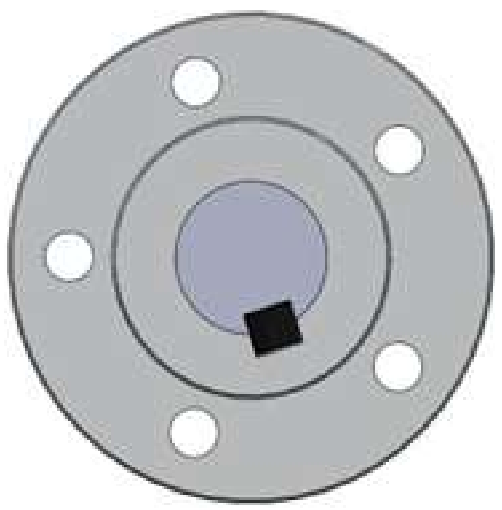
- Allow application of manual input force
- Allow transmission of manual input force
- Enable magnification of manual input force

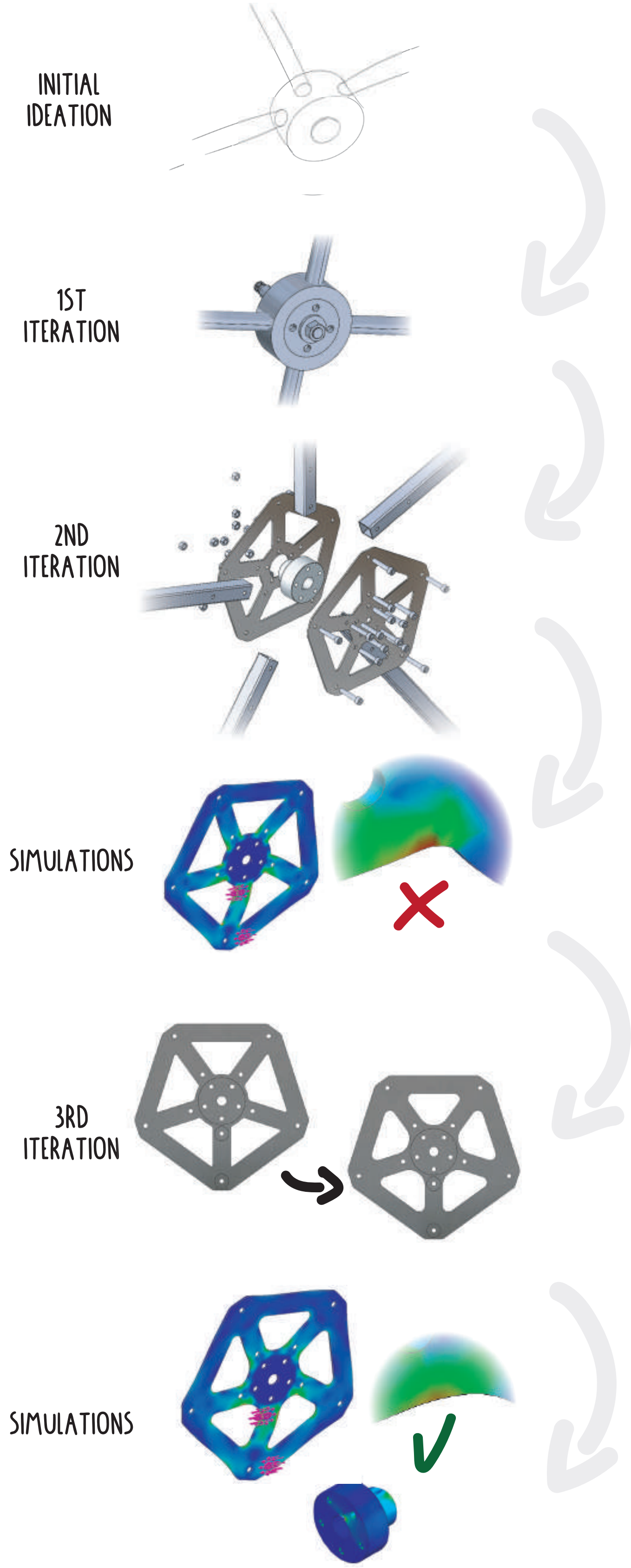
Key Features
The most crucial component of the Handlewheel is its core. This part is connected to the main axis through a keyway-connection: A small metal key fits in between the axis and the handlewheel core, which prevents the core to slide over the axis without transmitting force.

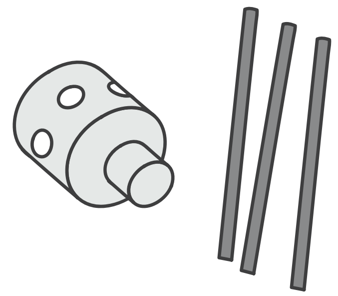
Another important structural prerequisite is a solid connection between the handlebars and the handlewheel core. Based on existing handlewheel designs, the 1st iteration saw these handlebars directly inserted in sideholes the core and tightened with a set screw. However, many users on the discord community channel reported this to be one of the main flaws in existing handlewheel designs: Often, the connection would apparently loosen over time leading to irreversible part failure.

To counter this, a lasercut sideplate is developed. This sideplate connects to the core and the handlebars through bolt connections and distributes forces on the connections over a larger area, ensuring a more durable connection. The sideplate is made from a metal sheet with a 3mm thickness as other lasercut parts.

After developing the 2nd iteration, a finite element analysis was performed on the sideplate. This found that most stresses accumulated on the corners of the spoke-features within the sideplate, which would eventually lead to part failure. To counter this, the angles were given a large fillet which distributed the stress more evenly over the part.





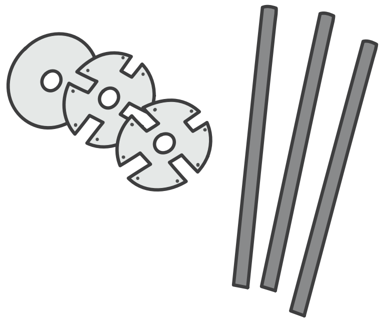


The handlebars themselves are made from 30x30x2mm square metal tubes, which are the same as the frame. This makes material sourcing for the build easier, as the builder will already need these tubes for the frame. A downside of the square tubes is the less ergonomic grip for the user in comparison to a round tube. However, these tubes could easily be replaced for more ergonomic round tubes in another module variant without loosing performance.

Requirements
The following requirements were found in development of the Lathed Handlewheel:

Prototype takeaways
After building the final prototype, the following can be concluded:

- The keyway in the handlewheel core needs to be broached with a special broaching tool. Although this is a fairly common operation, not all workshops might have this tool. This is a consideration for the builder that should be noted in the module variants description.



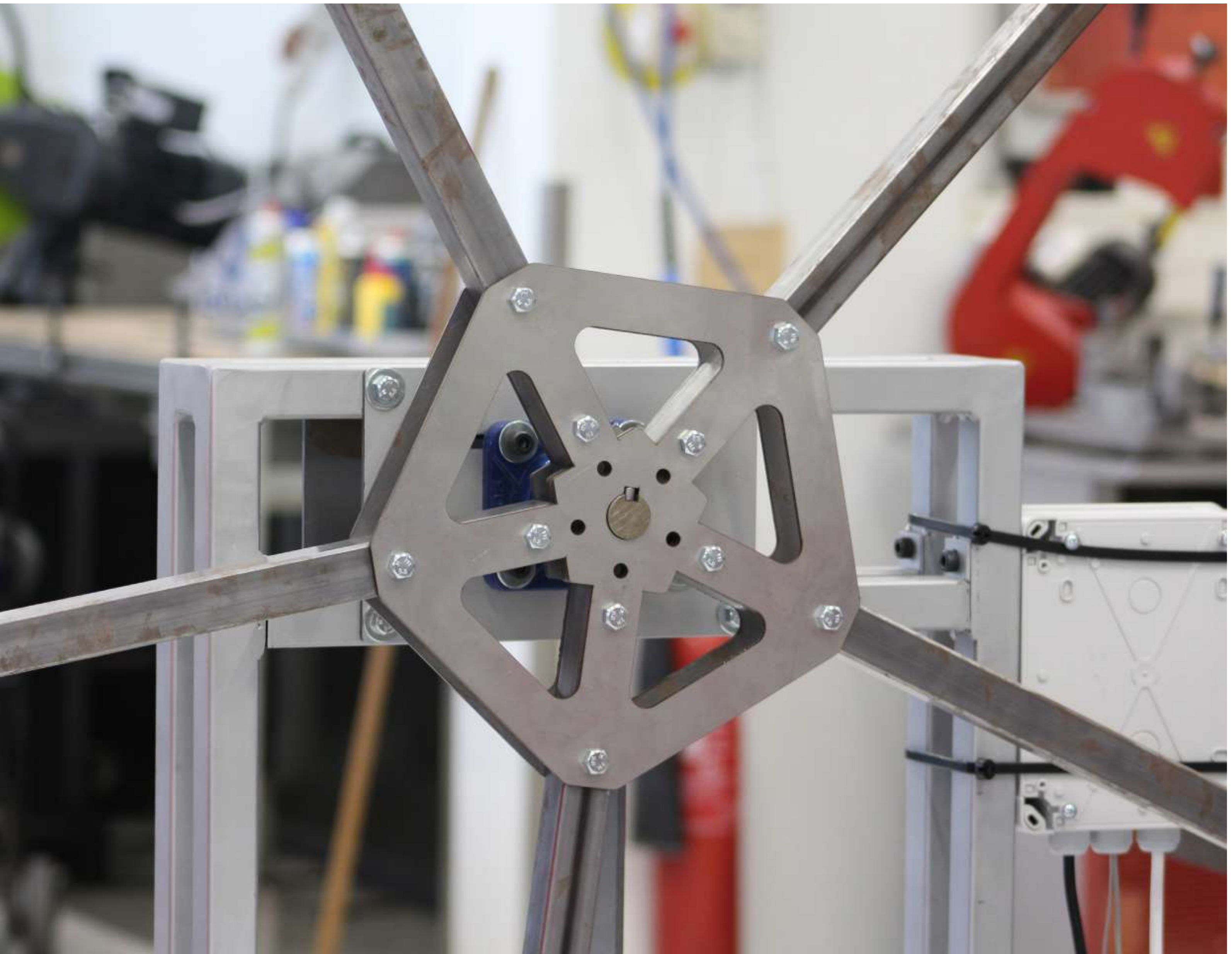
Lasercut Handlewheel

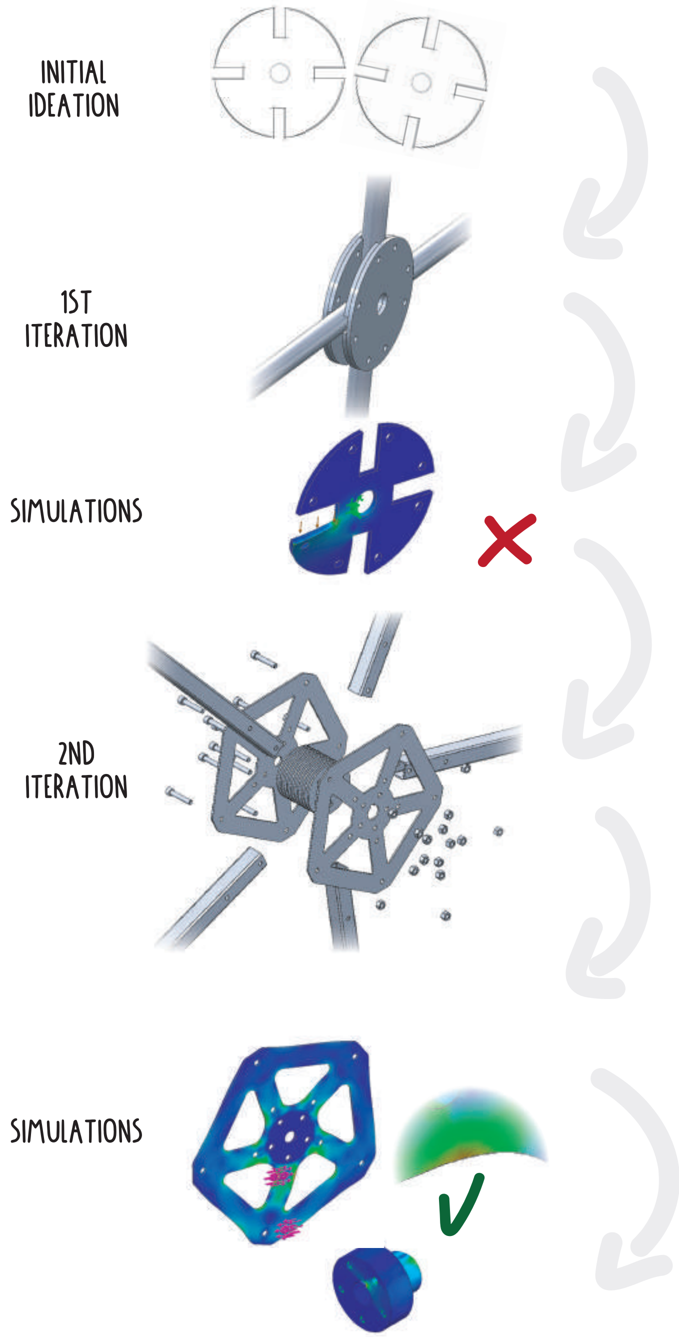
Similar to the lasercut gearbox, this module variant is not part of the Advanced Build pre-set. It has same functionality as the lathed handlewheel described in the previous section:

- Allow application of manual input force
- Allow transmission of manual input force
- Enable magnification of manual input force

Key Features

The lasercut handlewheel is identical to the lathed handlewheel with one key difference: In this version, the core is made from a stack of 10 lasercut plates instead of a single lathed part. This makes this part drastically mode simple to build, as it removes the keyway broaching operation. Instead, the keyway is simply lasercut in the core plates, requiring no substantial post-processing.



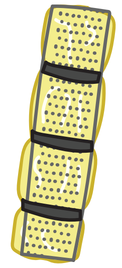


Prototype takeaways

After building the final prototype, the following can be concluded:

- A small wobble exists on the connection to the main axis. This is due to the low achievable tolerance in lasercut parts and is hard to overcome. Generally, steel lasercutters are able to achieve tolerances of up to 0.05mm (Jablons, 2021). Although this might seem insignificant, it can increase over time until failure of the part. Although this is merely speculation at this point, this should be investigated in long-term testing.

- Besides the slight wobble, the design functions perfectly overall



Rockwool Insulation

The Rockwool insulation module largely builds on earlier work done by other machine designers in the Precious Plastic community. The module has the following key functions:

- Decrease energy usage
- Keep plastic away from band heaters
- Shield band heaters from human contact

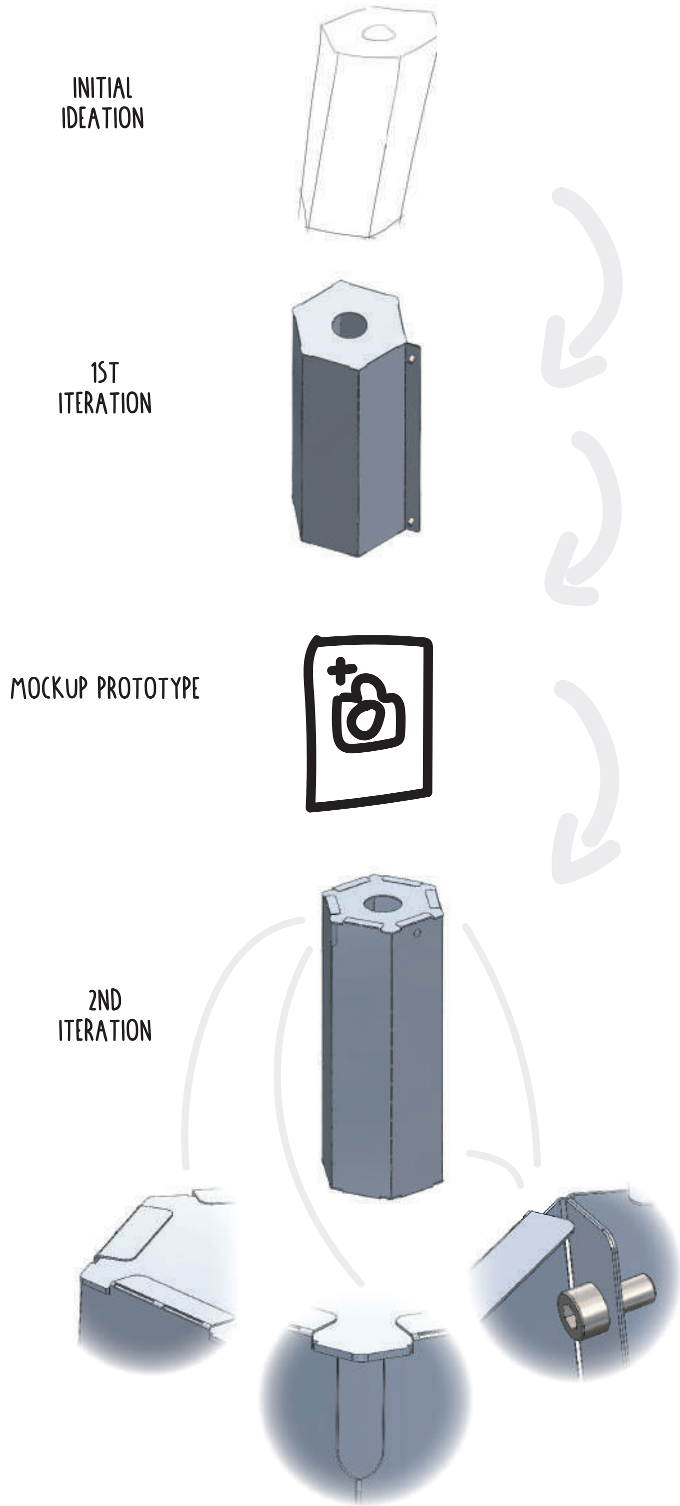
Key Features
The main insulator is a 40mm thick band of rockwool fitted within the sheetmetal housing. Rockwool is an excellent insulator and can easily be found in larger hardware stores.

The main alternative to rockwool is glasswool. Although this is also a widely used insulator, Rockwool has a number of advantages over glasswool. First of all, it has around 40% better insulation properties: Glasswool has an R-value of around 2.2 – 2.7 (KW^−1*m2), while rockwool ranges between 3.0 - 3.3 (K*W−1*m2) (Hebei Ever-shine, 2022).

Next to this, glasswool sheds small glass fibers which tend to irritate the skin and respiratory system. The only significant downside of rockwool is the 10% increase in cost over glasswool (Insulation Super Store, 2022).

The band of rockwool is around 40mm thick. Although this is an important dimension affecting the insulation performance, no thorough thermal simulation has been done on this part due to the limited available time in this project. Instead, this value is estimated based on the existing designs of other builders.

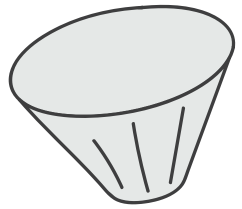
The band of rockwool is surrounded by a thin sheetmetal housing. The main function of this housing is to prevent the rockwool from disbanding and to keep the tiny plastic flakes out. The sideplate is made from 1mm thick sheetmetal to enable easy bending. The sideplate can be folded over 6 indicated folding lines to create the final shape. On top of one of its corners, a small gap is left to fit the wiring of the band heaters.



The top- and bottom plates are somewhat thicker at 3mm to strengthen the assembly. They feature small, bendable strips which fit in corresponding slots on the endplates. The strips can be folded over the top- and bottom plates to join the assembly together. In earlier iterations, joining the three plates together would be done by spotwelding. However, this would lead to the component being un-disassemblable which it unacceptable.

Prototype takeaways
After building the final prototype, the following can be concluded:

- The foldable top- and bottom strips work as intended, although they could break after repeated folding. This feature should be improved in a future version.
- The wiring gap works as intended within the prototype but could only be tested with the band heaters used in this prototype. Other bandheaters could use a different, less flexible wire type which might not fit through the hole.



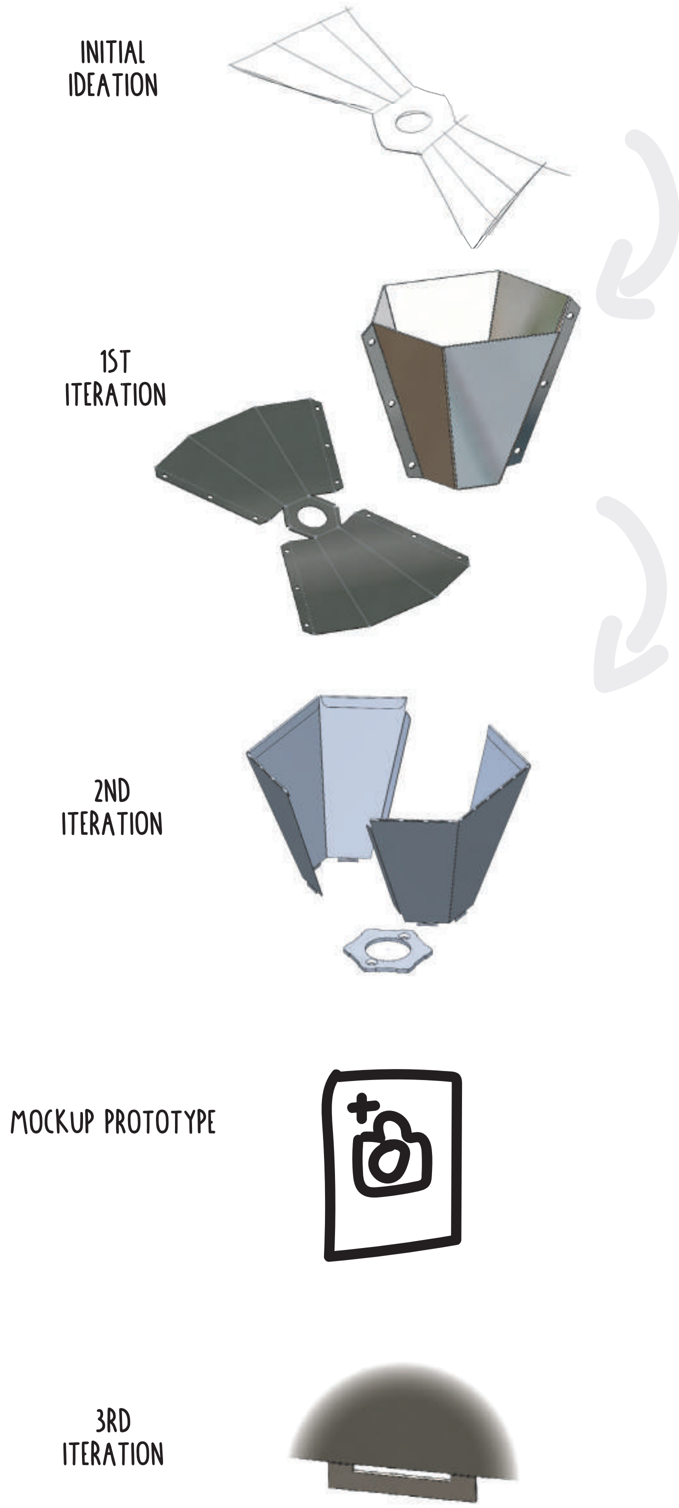
Lasercut Hopper

The initial idea of a foldable, lasercut hopper was derived from the kick-off ideation session. It has the following key functions:

- Collect plastic flakes
- Guide plastic flakes into barrel

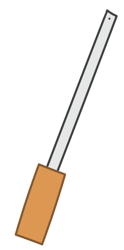
Key Features
The lasercut hopper is made from two identical lasercut, 1mm thick sheetmetal side-plates and one 3mm thick base plate. Similar to the rockwool insulation module, the side-plates have small strips on the bottom connecting the parts to the base plate. On top, the sideplates feature larger foldable strips that completely fold. These serve to add strength to the assembly. The baseplate features two holes to connect it securely to the top of the barrel with countersunk M5 bolts.

In the 1st iteration, the hopper was made by folding one single piece of sheetmetal. Although this was an elegant option, it proved impractical. First of all, cutting the hopper from one single sheet results in a lot of residual material. Secondly, assembling the hopper by folding only inevitably creates tiny holes for the plastic to fall through. Therefore, the hopper is split up in three parts and assembling is done by welding the folded parts on the baseplate.



Prototype takeaways
After building the final prototype, the following can be concluded:

- Welding the hopper is quite tricky, as the sheetmetal parts are quite thin.
- The bendable flaps at the top might not be necessary.



Pistonhead Plunger

The piston-head plunger idea was proposed by builders in the Discord Community as an improvement on the solid plunger. It has the following key functions:

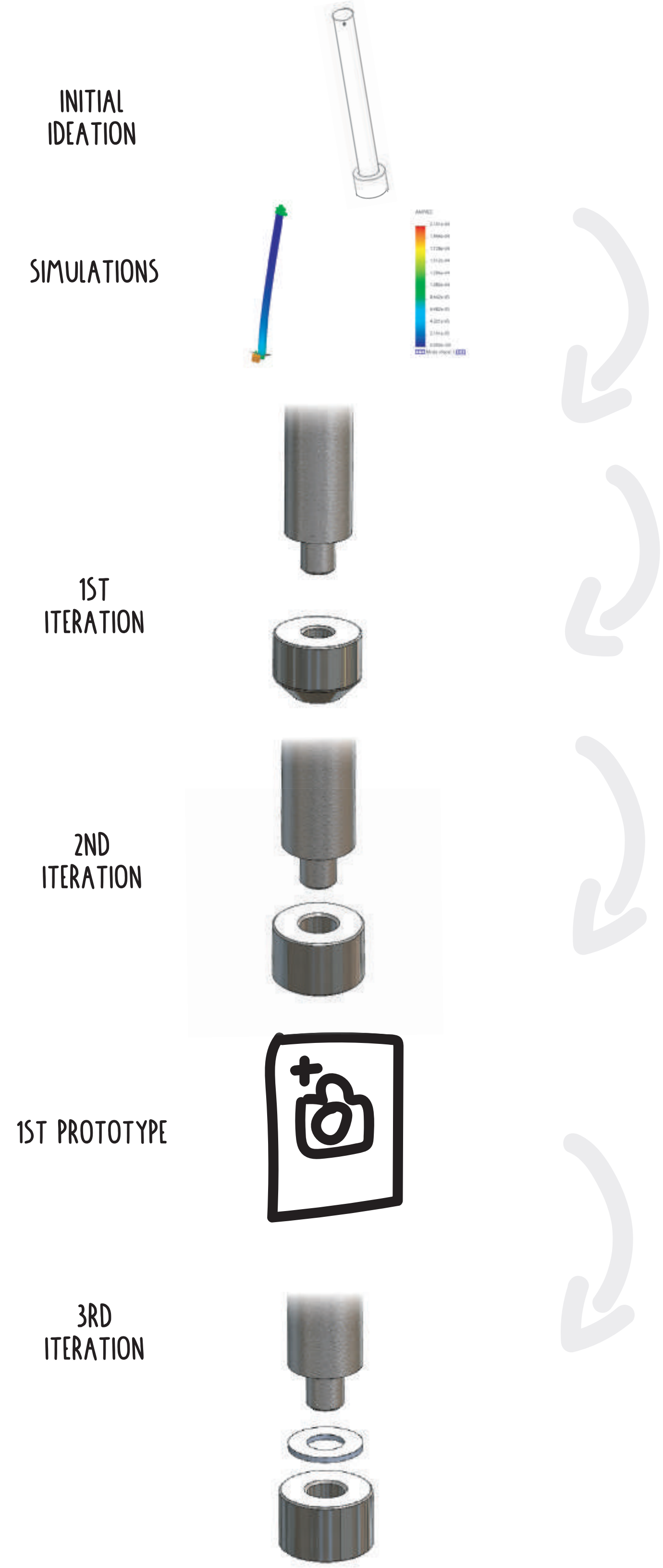
- Transmit magnified human force on plastic melt
- Compress plastic flakes to ensure proper melting

Key Features

The plunger shaft is the key structural component for the piston-head plunger as it delivers force to the piston-head. Compared to the conventional solid plunger, it has a number of advantages. Firstly, it has a smaller diameter and therefore lower mass. This not only helps saving weight, but also decreases the energy usage of the machine as less heath leaks away through the plunger. Next to this, the separate plunger-head can be very easily customized to the specific barrel diameter of a builder.

To find the minimal diameter of the plunger shaft, a finite element analysis was done to find the bucking diameter. This analysis concluded that a diameter of 14 mm was minimally necessary to prevent buckling. The final plunger diameter of 15mm is chosen as this is a standard rod diameter and therefore easy to find.

The piston-head is made from brass as this material has a low coefficient of friction with the steel barrel. It is made on a lathe and finished by tapping a hole in the center. Alternatively, it could be made from stainless steel in case brass is hard to find.



Prototype takeaways

After building the final prototype, the following can be concluded:

- One unexpected discovery in manufacturing the piston-head plunger is on the alignment of parts. The initial prototype showed that forming a perfectly co-linear connection between the piston-head, plunger and rack was very hard to do. Time and time again, parts would misalign slightly no matter the precision. A solution was found in inserting a small ring in between thread connections. This ensured the faces any two parts would be pulled straight, which made aligning the parts much more failsafe.

MOLD UNIT

NOZZLE ENGAGEMENT

Compression Spring Nozzle Engagement

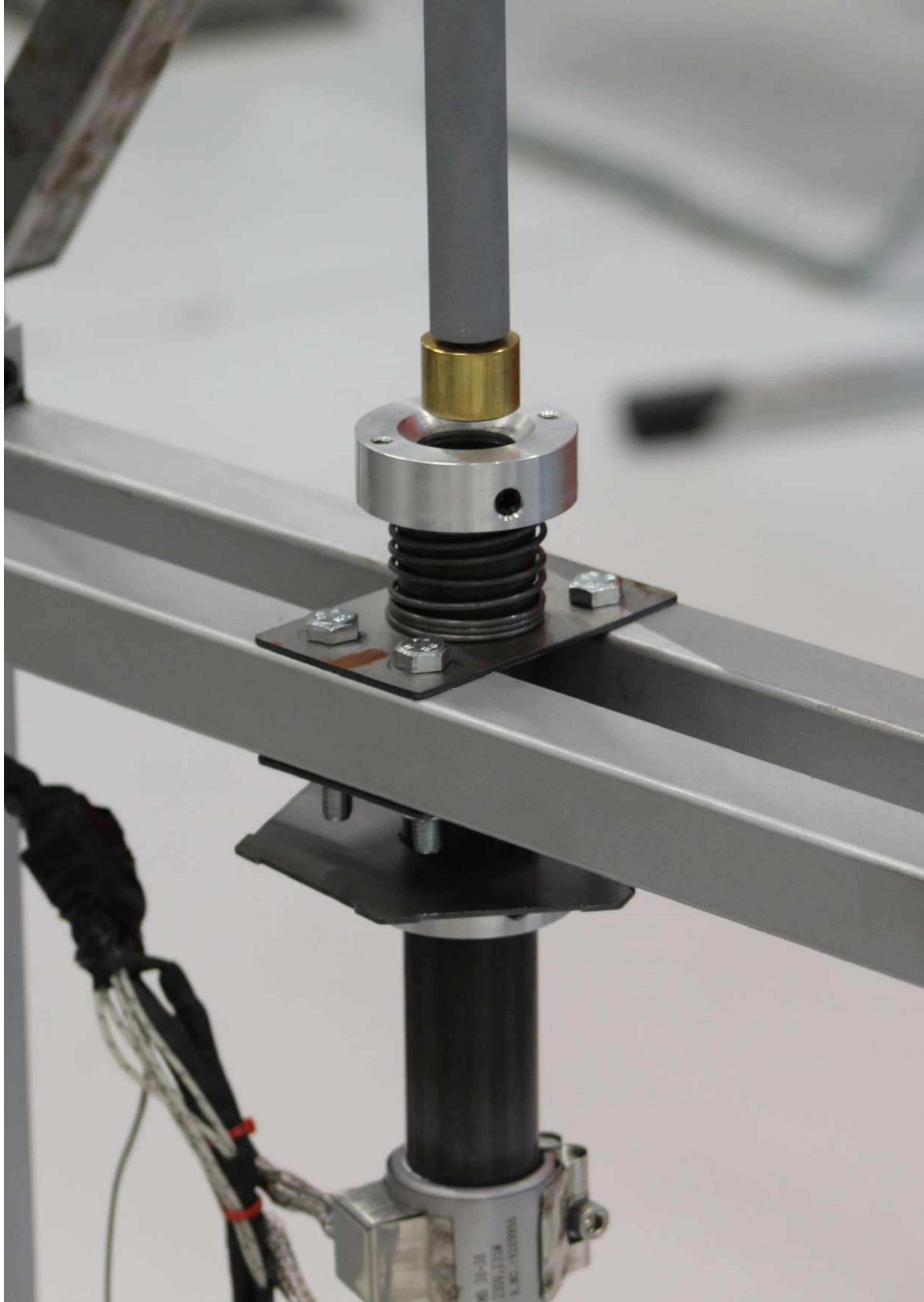
The initial idea for a flexible nozzle engagement was inspired by existing desktop injection machines. The nozzle engagement has the following key functions:

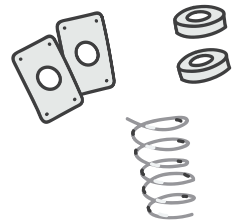
- Allow the nozzle to connect to the mold
- Allow the mold to be inserted and removed
- Connect the barrel to the frame
- Enable the barrel to move up and down
- Restrict sideways barrel movement
- Guide plunger into barrel
- Connect the hopper to the barrel

Key Features

The nozzle engagement system mainly improves the user experience of connecting the mold to the nozzle. Instead of screwing the mold directly to the barrel, the mold can be simply placed the mold table after which the nozzle automatically engages when injection begins. This process unfolds in three steps:

1. Before the injection process, the compression spring only holds the barrel in its up position. At this moment the spring is slightly compressed, but only by the weight of the barrel assembly.
2. Once the users begins the injection process, the plunger travels down through the barrel. As soon as the plunger hits the molten plastic, some pressure is exerted on the plastic. This initial pressure is unable to escape the barrel cavity due to the high viscosity of the plastic and starts transmitting the plunger force onto the barrel.
3. This causes the barrel to move downwards, which further compresses the spring. Once the nozzle meets the mold gate, the barrel can no longer move downwards. As all components but the plunger are now static, the pressure starts increasing and the injection process begins.
4. Once the injection process is finished and all pressure is relieved, the plunger and barrel start traveling upwards again which releases the mold .



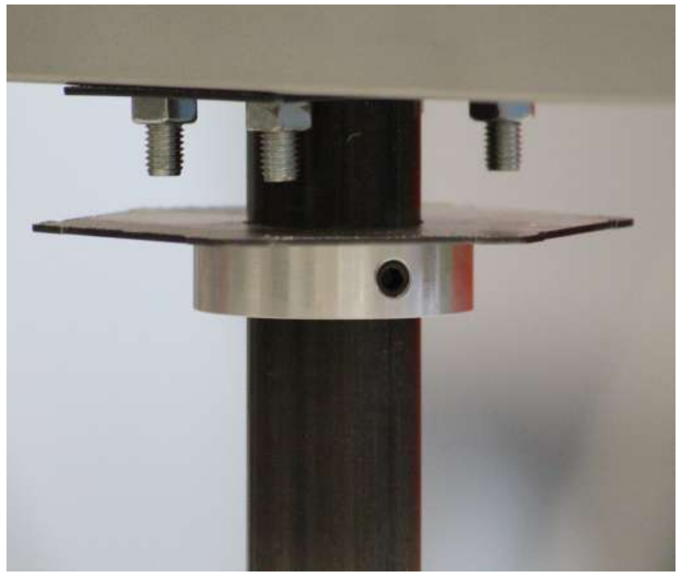


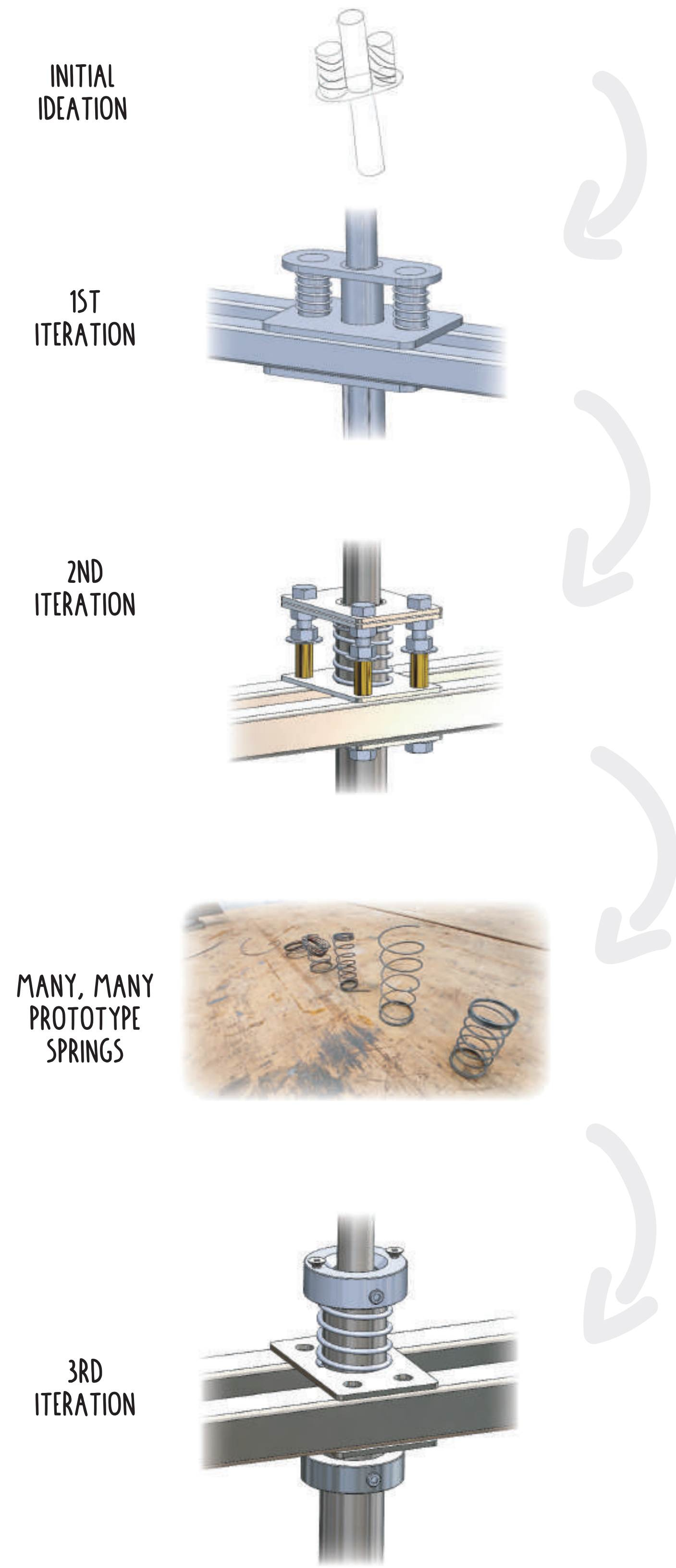
The key component within this process is the compression spring. Contrary to gut feeling, this spring needs to be quite flexible: Although it should be able to carry the weight of the barrel, it also needs to allow the barrel to move downward with ease. Multiple springs were made in prototyping to find the optimal design of the spring.

The compression spring can either be bought in a hardware store or made on a lathe. Another crucial part in the engagement assembly is the top limiter ring, which is an aluminum part made on a lathe. The top ring executes three functions. Firstly, it acts as the top limiter for the compression spring, enabling it to suspend the barrel. Secondly, it has a chamfered edge on the plunger hole, which securely guides the piston-head of the plunger into the barrel. Lastly, it provides a mounting place for the hopper .

A similar part is the bottom limiter ring. Primarily, it prevents the barrel from moving up with the plunger once the injection process is finished. This is expected to happen due to the viscosity of the plastic. Also, it provides an attachment point for the insulation housing onto the barrel.

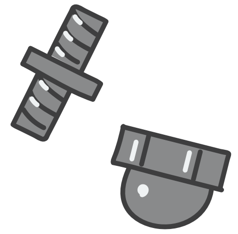
Lastly, there are the two support plates. Mainly, they ensure the barrel is unable to move or pitch sideways by guiding the barrel through their center hole. Also, they form a stationary point for the compression spring to push against.





Prototype takeaways
After building the final prototype, the following can be concluded:

- Making the spring on a lathe is doable but requires working carefully, as the spring can easily snap and hit the builders fingers.
- The two support plates need to be very precisely aligned, otherwise they lock the barrel and prevent it to move. Removing one of the plates seemed to overcome this issue without creating too much slack in the barrel.



Cap Nut Nozzle

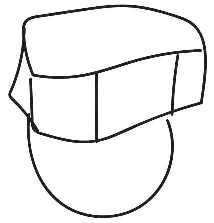
The Cap Nut Nozzle was a suggestion made by Friedrich Kegel, the owner of mold-maker Easymolds. It ensures a tight connection to the mold gate and is very easy to make. It has the following key functions:

- Enable the flow of plastic from the barrel into the mold

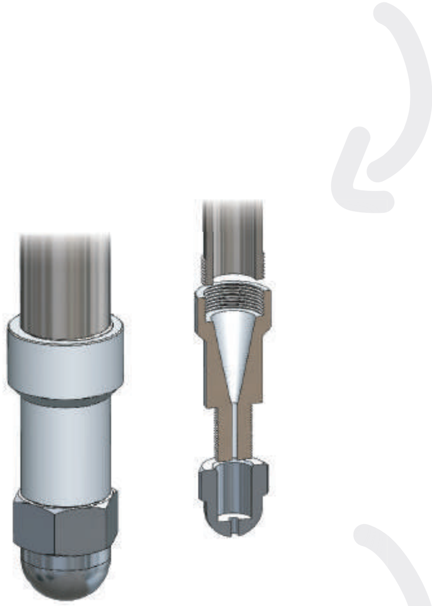
Key Features
This module contains only two parts. The main component is the M20 Domed Cap Nut, which can be found in conventional hardware stores. The domed cap nut provides an excellent seal to the mold gate as it concentrates all pressure along a single contact line. This nozzle style is widely used in industrial injection nozzles, as it provides an optimal seal while minimally denting the mold. The nozzle is made by drilling a hole in the nozzle center on either a lathe or a vice.

The second part of this assembly is a connector piece, facilitating the connection of the nozzle onto the barrel. It is somewhat complex to make, as it requires milling, lathing and threading. However, this part does not require professional plumbing tools to create the thread and thus improves the current building experience.

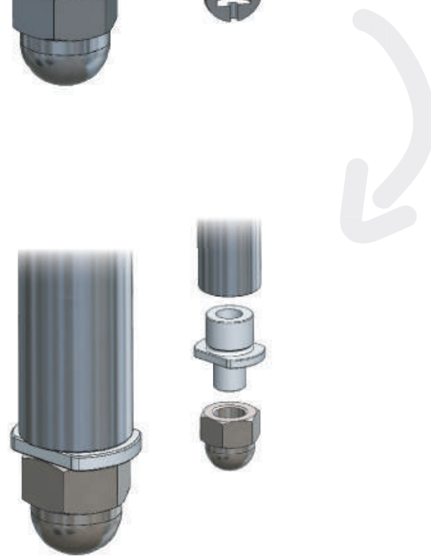
INITIAL IDEATION



1ST ITERATION



2ND ITERATION



Prototype takeaways
After building the final prototype, the following can be concluded:

- Threading the connector piece should be done with care, as the threads can easily break.
- The domed cap nut leaves a small bit of plastic at the mold gate that is difficult to remove. To counter this, multiple nozzle designs will be tested in the final stage of the project. The results of this will be shared in the final report.

MOLD UNIT

MOLD TABLE

Height Adjustable Mold Table

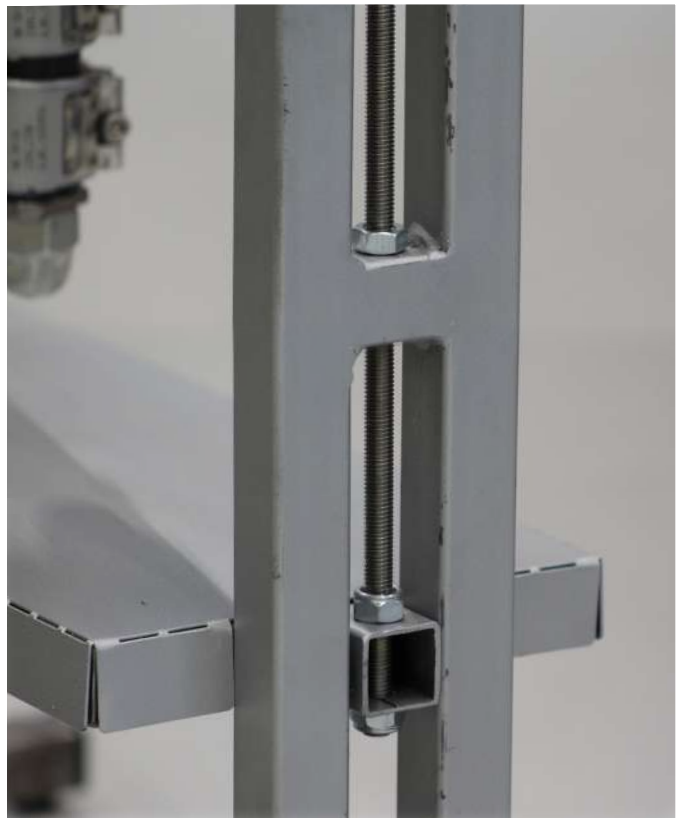
The Height Adjustable Mold Table is the final part of the mold unit. It has the following key functions:

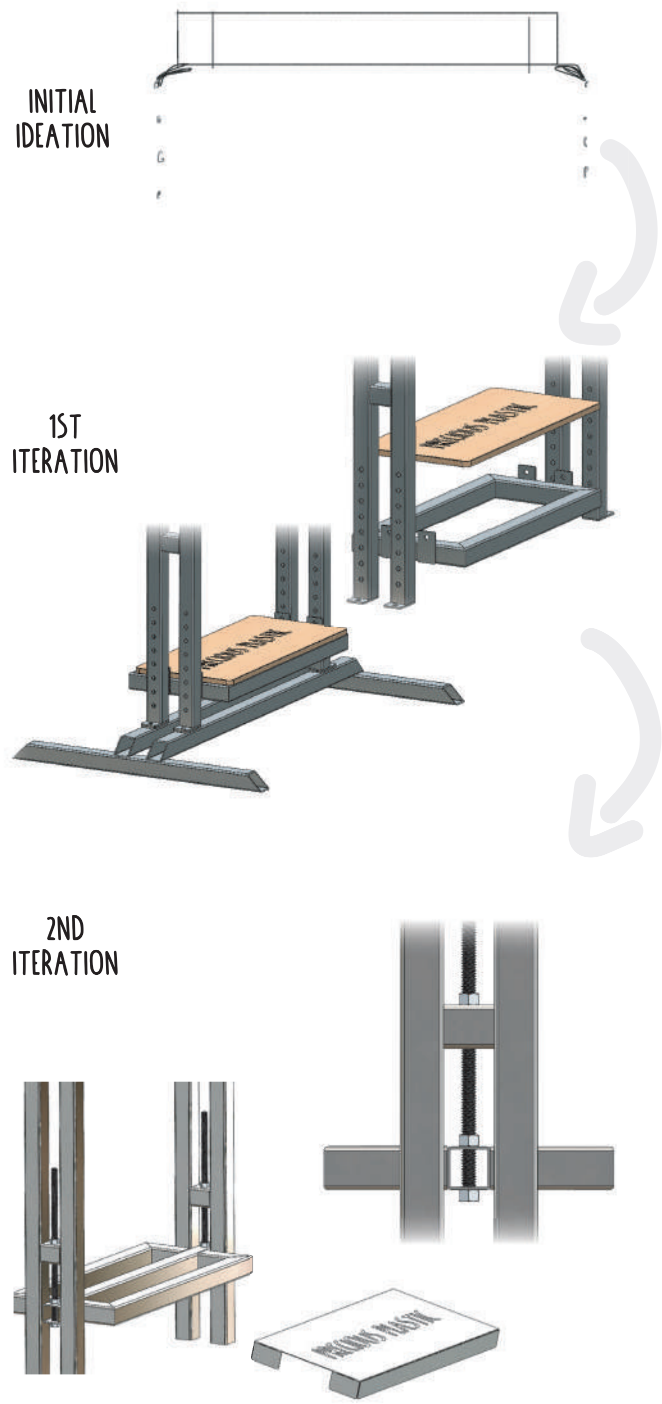
- Support the mold during injection
- Enable the nozzle to be clamped against the mold

Key Features

One of the key features of the mold table is the ability to facilitate molds of different sizes. This is achieved by suspending the table to the frame on either side through threaded rods. By adjusting the position of the bolts on the rods, the mold table can be lowered or lifted depending on the mold thickness.

The frame of the mold table is made from the same square tubes as the frame. These are welded together to form a firm assembly. Either side of the mold table has a small protrusion which sticks out between the main frame beams. This guides the mold table and prevents sideways motion.





The mold table is capped by a laser cut sheet metal cover of 1mm thick. This cover provides a flat plane for the builder to place their mold on and prevents smaller molds from falling through the table's structural beams. Sheetmetal was chosen over the wooden cover from the 1st iteration due to its longer durability.

Prototype takeaways

After building the final prototype, the following can be concluded:

- Assembling the mold table within the frame is a little tricky, but doable.

FRAME

↳ FRAME COMPOSITION

Floor Bolted Frame

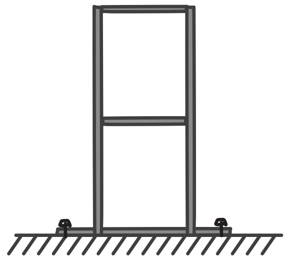
The floor bolted frame has the following key functions:

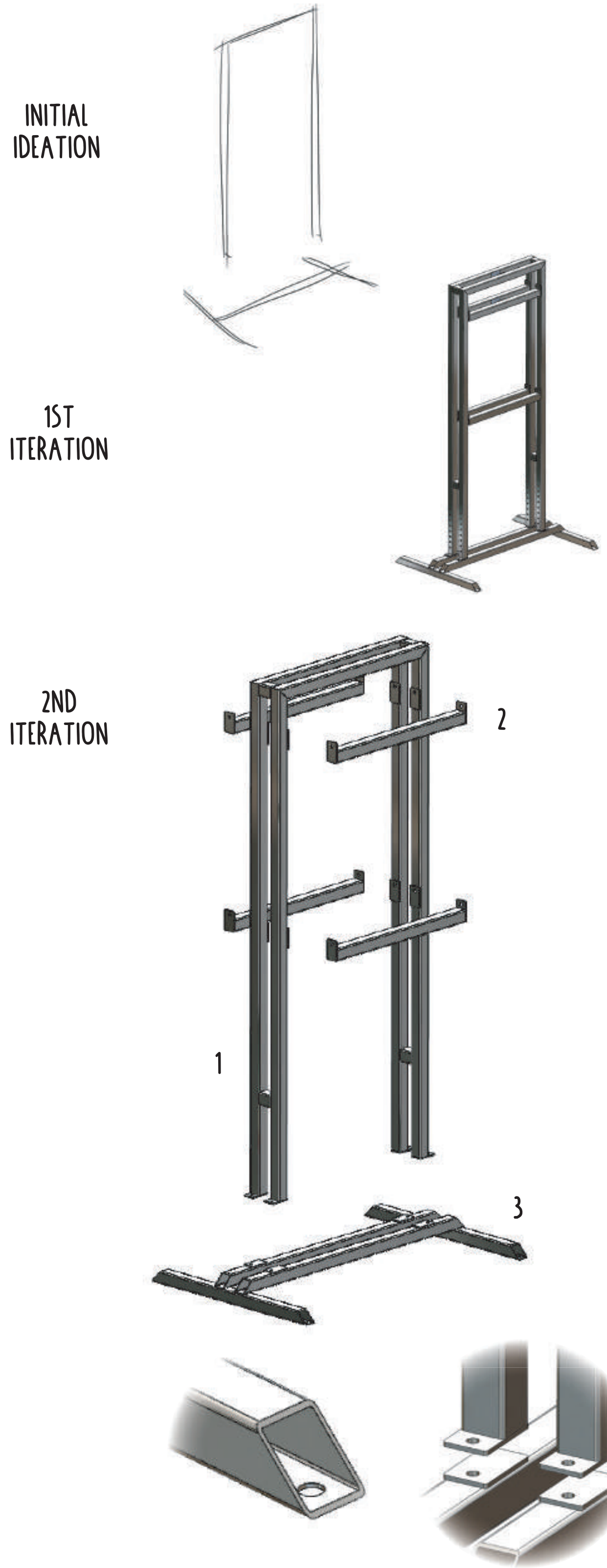
- Provide structural support to all other modules

Key Features
The frame is assembled from 6 separate frame parts and is mainly made from welded 30x30x2 square steel tubes. The main part (1) provides the basis for the suspension of the gearbox, nozzle engagement and electronics box. It is around 120cm high, which is the optimum height for ergonomic use of the handle wheel axis as found in chapter 3.2.

Within this part, 4 identical crossbeams (2) are bolted on to the frame through connector plates. These plates enable the builder to finely adjust the height of the crossbeams in the installation process relative to the main frame. If the crossbeams were to be welded to the frame directly, this would not be possible.

The floor base (3) is attached to the main frame using the same plates. As the floor base is the only perpendicular part to an otherwise thin flat frame, enabling this part to be temporarily disconnected allows for space-efficient transport.



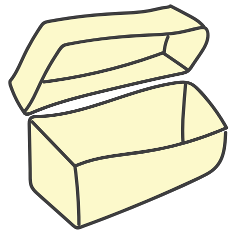


Prototype takeaways
After building the final prototype, the following can be concluded:

- Welding the frame can be tricky for a new welder as welded parts tend to creep. The builder should be aware of this when starting the build.

ELECTRONICS BOX

HOUSING



Splash- And Dustproof Box

The Splash- and Dustproof electronics box is a direct outcome of researching the CE requirements. It has the following key functions:

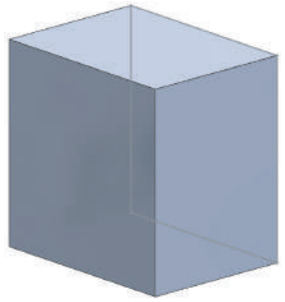
- Suspend all electronic components (except band heaters)
- Protect electronic components from dust ingress
- Protect electronic components from low pressure water jets

Key Features

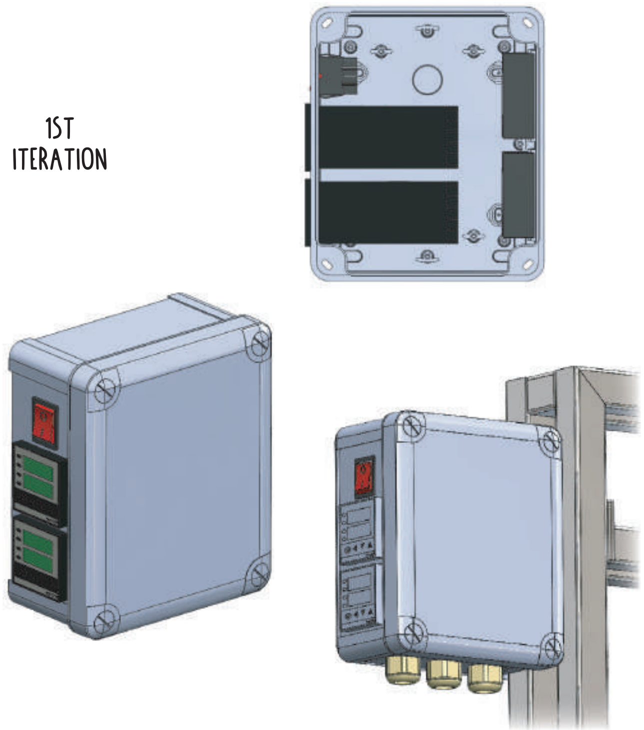
The main component in the electronics box is the IP55-rated enclosure. This part is one of few that cannot be made from scratch, as adhering to the EC standards it requires official approval. For this reason, there is no standardized box for this module variant: the builder should do some research on finding a suitable enclosure as the best available product heavily depends on the local supply. Under ‘requirements’, the main demands are listed for the builder to guide in their search.

INITIAL IDEATION

MOCKUP



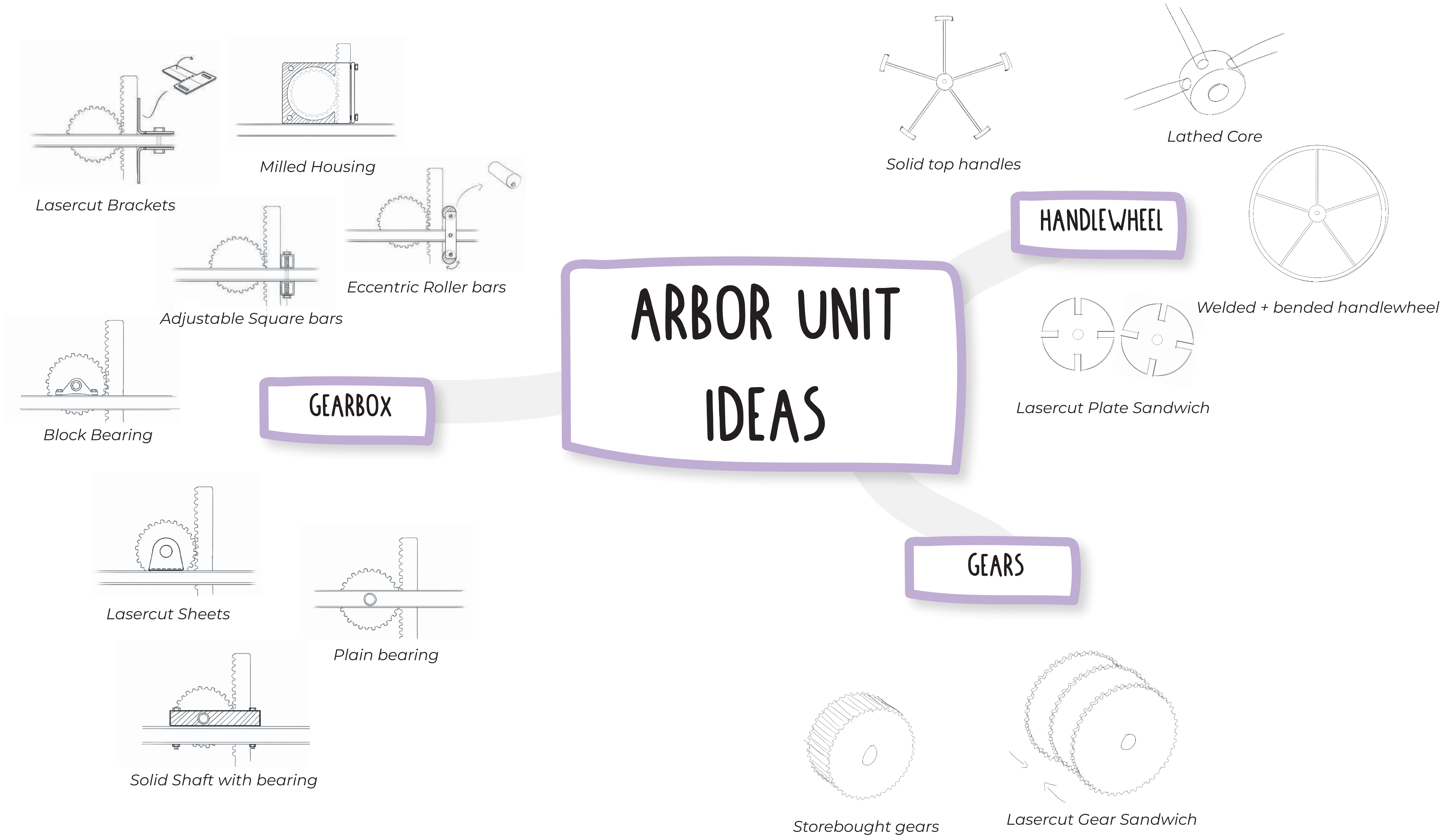
1ST ITERATION

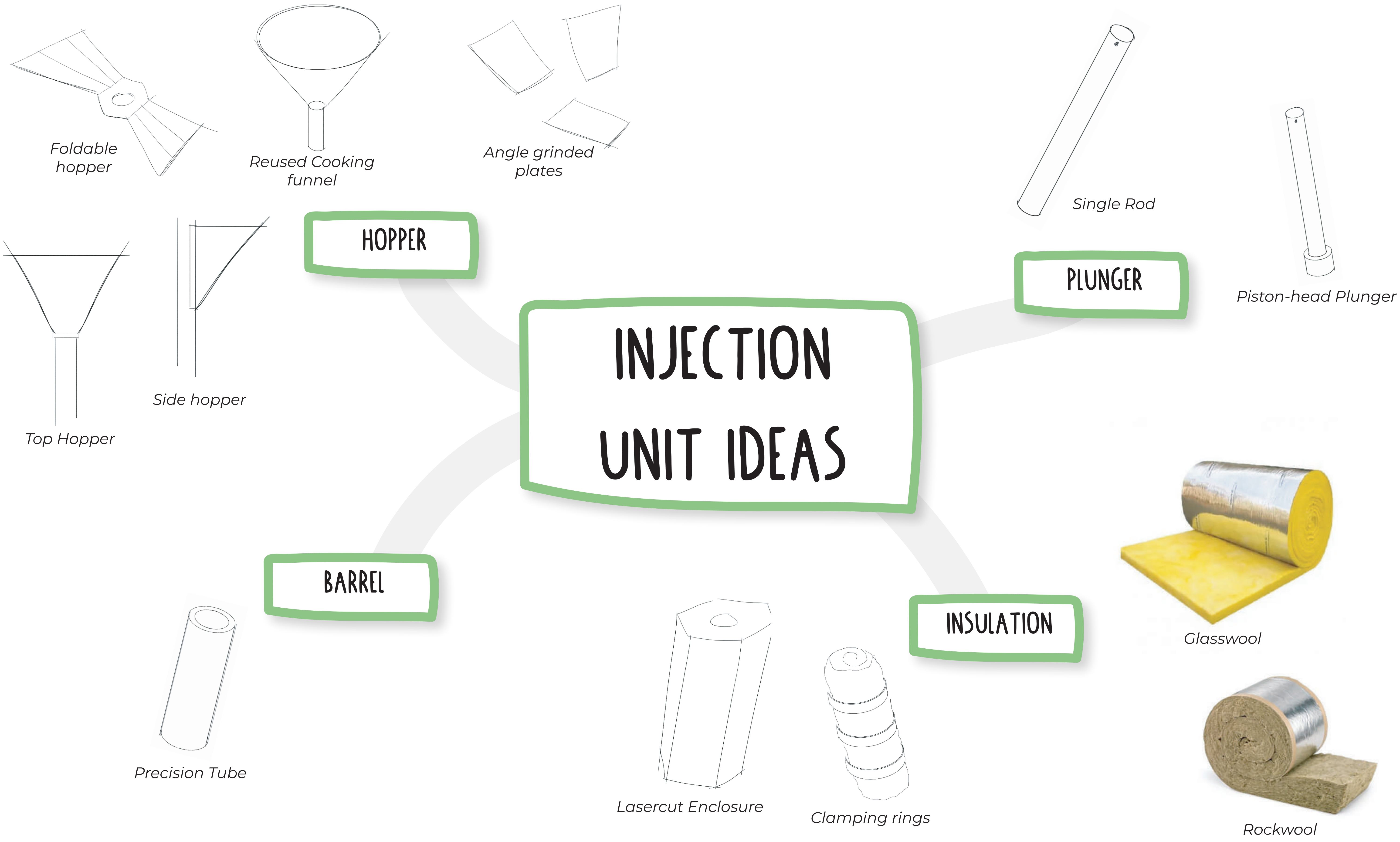


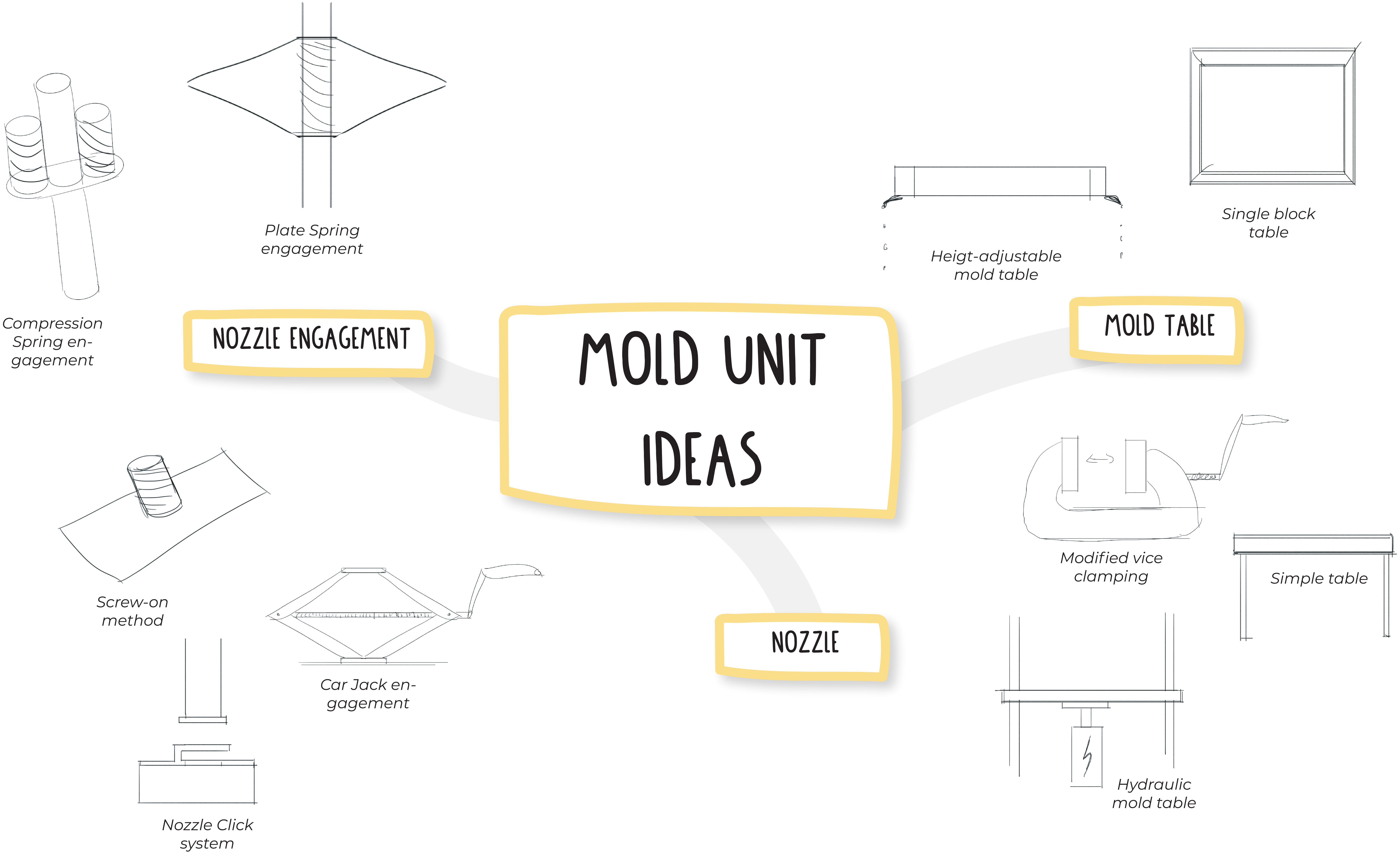
The box selected for this prototype was chosen as it is the smallest available IP55 enclosure while still meeting the 60%-empty requirement. It is suspended on the frame by a universal connector plate. This thin sheetmetal plate can be very easily customized to support the selected enclosure and can made with either a laser cutter or by hand.

The front of the box features the interaction screens of the two PID-controllers. The top PID controls the three upper band heaters, while the bottom PID does so for the bottom one. This is done so the bottom band heater can be set to a slightly higher temperature to prevent clots froming.
The PID interfaces face the user while injecting so they can keep an eye on the temperatures during injection.

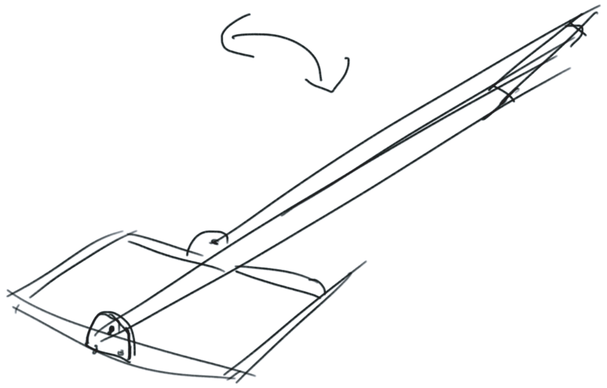
Appendix L: Ideation Posters



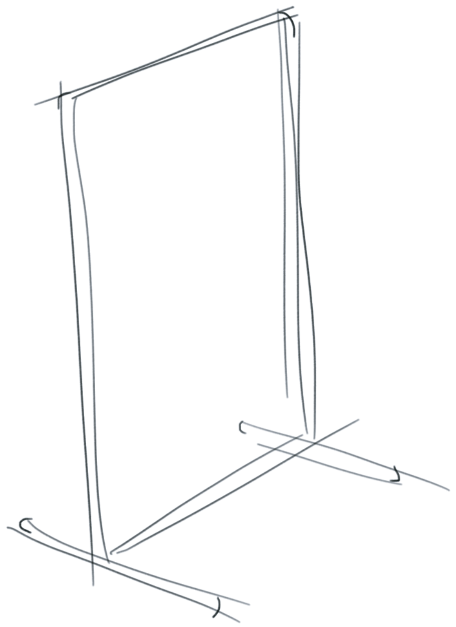

INJECTION UNIT IDEAS
HOPPER
Foldable hopper
Reused Cooking funnel
Angle grinded plates
Top Hopper
Side hopper
PLUNGER
Single Rod
Piston-head Plunger
BARREL
Precision Tube
INSULATION
Lasercut Enclosure
Clamping rings
Glasswool
Rockwool


MOLD UNIT IDEAS
NOZZLE ENGAGEMENT
Compression Spring en-gagement
Plate Spring engagement
Screw-on method
Car Jack en-gagement
Nozzle Click system
MOLD TABLE
Heigt-adjustable mold table
Single block table
Modified vice clamping
Simple table
Hydraulic mold table
NOZZLE

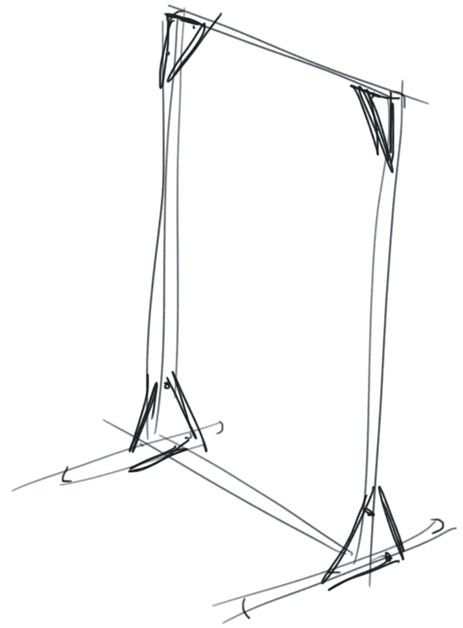
FRAME IDEAS



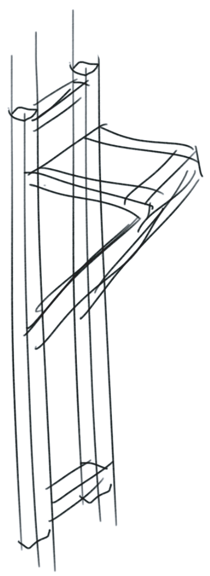
Foldable frame



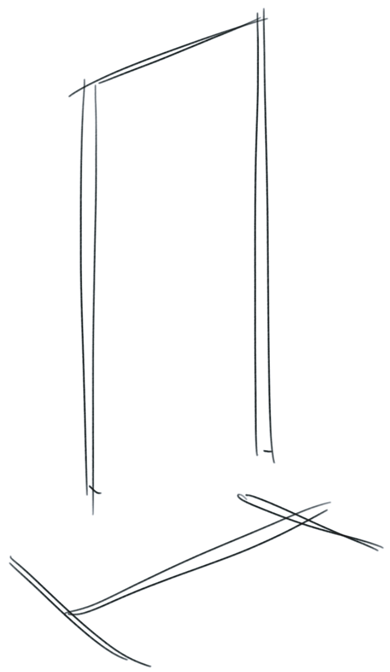
Simple welded frame



Fully disas-semblable frame

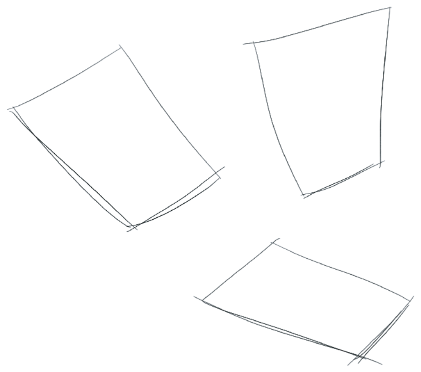


Wall mounted frame

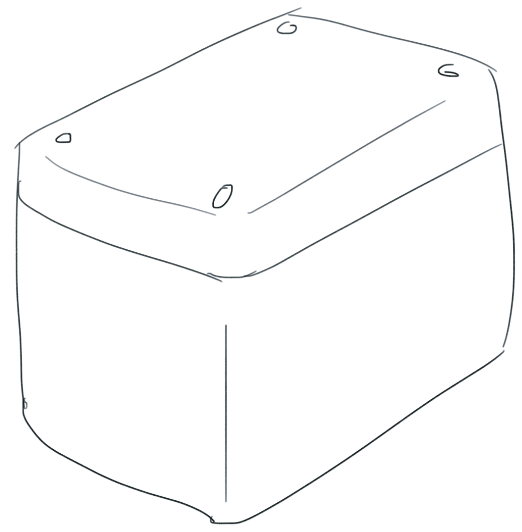


Partly disas-semblable

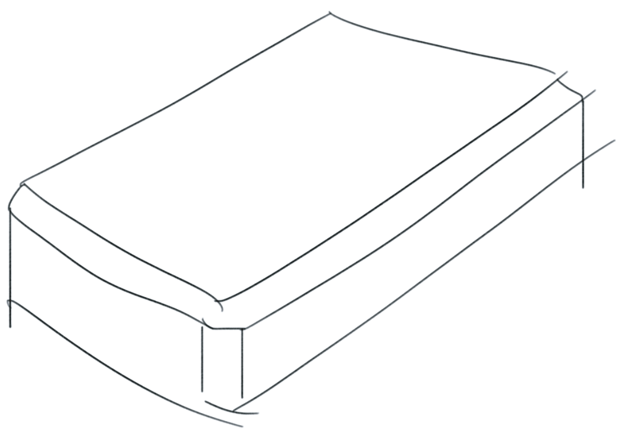
ELECTRONICS BOX



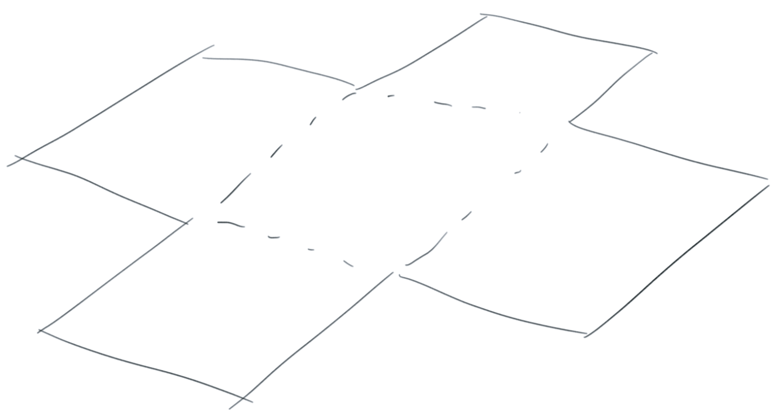
Welded plates



Storebought
sealed box



Repurpoused
old box



Lasercut
folded box

Appendix M: Pilot Test Validation with Amateurs

Basic info:			
	P1	P2	P3
Name	Joost	Paulien	Marinka
Age	25	24	23
Sex	M	V	V

0 deg

			Comfort Scale		
F plunger (KN)	F hand (N)	Bar	P1	P2	P3
0.3	18	6		1	1
0.6	36	12		2	3
0.9	54	18		3	5
1.2	72	24		5	
1.5	90	30			
1.8	108	36			
2.1	126	42			
2.4	144	48			
2.7	162	54			
3	180	60			
3.3	198	66			
3.6	216	72			
3.9	234	78			
4.2	252	84			
4.5	270	90			
4.8	288	96			

10 deg

			Comfort Scale		
F plunger (KN)	F hand (N)	Bar	P1	P2	P3
0.3	18	6		1	1
0.5	30	10		2	2
0.7	42	14		2	3
0.9	54	18		3	4
1.1	66	22		4	5
1.3	78	26			
1.5	90	30			
1.7	102	34			
1.9	114	38			
2.1	126	42			
2.3	138	46			
2.5	150	50			
2.7	162	54			
2.9	174	58			
3.1	186	62			
3.3	198	66			

10 deg

			Comfort Scale		
F plunger (KN)	F hand (N)	Bar	P1	P2	P3
0.3	18	6		1	1
0.5	30	10		1	2
0.7	42	14		2	5
0.9	54	18			
1.1	66	22			
1.3	78	26		5	
1.5	90	30			
1.7	102	34			
1.9	114	38			
2.1	126	42			
2.3	138	46			
2.5	150	50			
2.7	162	54			
2.9	174	58			
3.1	186	62			
3.3	198	66			

20 deg

			Comfort Scale		
F plunger (KN)	F hand (N)	Bar	P1	P2	P3
0.3	18	6			
0.6	36	12			
0.9	54	18			
1.2	72	24			
1.5	90	30			
1.8	108	36			
2.1	126	42			
2.4	144	48			
2.7	162	54			
3	180	60			
3.3	198	66			
3.6	216	72			
3.9	234	78			
4.2	252	84			
4.5	270	90			
4.8	288	96			

Appendix N: Force Measurement Data

	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
0:01	0.18	0.31	0.12	0.11	0.58	10.8	18.7	7.3	6.5	34.7
0:02	1.11	0.48	0.14	0.06	0.25	66.6	28.9	8.2	3.5	14.9
0:03	1.95	0.86	0.16	0.15	0.66	117.0	51.5	9.8	9.0	39.4
0:04	2.12	1.53	0.29	0.36	1.12	127.2	92.0	17.1	21.4	66.9
0:05	2.53	1.65	0.38	0.28	1.13	151.8	99.1	22.8	16.8	67.9
0:06	3.61	2.25	0.41	0.73	1.60	216.6	134.9	24.5	43.7	96.0
0:07	5.03	2.50	0.45	0.86	1.92	301.8	149.8	26.9	51.6	115.2
0:08	7.18	2.67	0.50	1.02	1.82	430.8	159.9	30.2	60.9	109.2
0:09	6.58	2.82	0.45	1.01	1.60	394.8	169.3	26.9	60.5	96.0
0:10	6.58	2.64	0.52	1.12	2.23	394.8	158.3	31.0	67.4	133.9
0:11	7.27	3.19	0.69	1.06	1.96	436.2	191.1	41.6	63.4	117.5
0:12	7.59	2.80	0.78	0.87	2.03	455.4	167.7	46.5	52.1	121.8
0:13	7.30	2.94	0.92	1.42	2.56	438.0	176.3	55.5	84.9	153.8
0:14	7.17	2.80	0.99	1.03	2.23	430.2	167.7	59.6	62.0	134.0
0:15	7.65	3.02	0.91	1.03	2.08	459.0	181.0	54.7	61.6	125.1
0:16	7.93	3.06	0.71	1.07	2.00	475.8	183.3	42.4	64.4	120.0
0:17	7.63	3.50	0.90	1.58	2.65	457.8	209.8	53.9	95.1	159.0
0:18	7.44	3.74	0.94	1.58	3.17	446.4	224.6	56.3	94.6	190.5
0:19	7.41	3.63	0.97	1.64	3.15	444.6	217.6	57.9	98.2	188.9
0:20	7.30	3.87	1.01	1.45	2.98	438.0	232.4	60.4	86.9	178.6
0:21	7.68	3.99	1.10	1.55	2.99	460.8	239.5	66.1	92.8	179.2
0:22	7.55	3.98	1.01	1.58	3.21	453.0	238.7	60.4	95.0	192.9
0:23	7.32	3.59	1.07	1.29	2.81	439.2	215.3	64.5	77.7	168.4
0:24	7.22	4.20	1.16	2.00	3.44	433.2	251.9	69.4	119.9	206.5
0:25	7.13	4.12	1.22	1.57	2.98	427.8	247.3	73.4	94.4	178.6
0:26	6.91	4.30	0.94	1.56	3.09	414.6	258.2	56.3	93.7	185.4
0:27	7.44	4.36	0.92	1.98	3.56	446.4	261.3	55.5	118.8	213.6
0:28	7.63	4.12	0.86	1.41	2.93	457.8	247.3	51.4	84.3	176.0
0:29	6.94	4.08	1.18	1.70	2.78	416.4	244.9	71.0	102.0	166.7
0:30	6.17	4.26	1.06	1.55	2.48	370.2	255.8	63.6	92.8	148.8
0:31	7.09	4.15	0.99	1.83	2.87	425.4	248.8	59.6	109.6	172.4
0:32	6.17	4.06	1.44	2.05	3.38	370.2	243.4	86.5	123.0	202.7
0:33	5.78	4.19	1.69	2.24	3.57	346.8	251.4	101.2	134.6	214.4
0:34	5.65	3.97	1.99	1.89	3.59	339.0	237.9	119.1	113.2	215.4
0:35	6.25	3.80	2.18	2.20	3.49	375.0	227.8	130.6	132.0	209.7
0:36	5.81	3.67	2.26	2.07	3.69	348.6	220.0	135.5	124.5	221.7
0:37	5.64	3.54	1.25	1.41	2.80	338.4	212.2	75.1	84.5	168.3
0:38	5.55	3.42	1.29	1.64	2.82	333.0	205.1	77.5	98.4	169.0
0:39	5.49	3.17	1.88	1.43	3.01	329.4	190.3	112.6	85.7	180.6
0:40	5.19	3.16	2.11	1.90	3.13	311.4	189.5	126.5	113.7	188.1
0:41	4.97	3.08	2.94	1.99	3.51	298.2	184.9	176.3	119.3	210.6
0:42	4.92	3.26	3.07	2.10	4.11	295.2	195.8	184.4	126.0	246.4
0:43	5.27	2.94	3.03	2.18	4.05	316.2	176.3	182.0	130.5	242.8
0:44	5.09	2.93	2.43	0.99	2.38	305.4	175.5	146.1	59.4	142.8
0:45	4.85	3.21	2.67	0.98	2.56	291.0	192.7	159.9	58.6	153.8
0:46	4.61	3.17	2.73	1.07	2.96	276.6	190.3	164.0	64.2	177.4
0:47	4.72	2.81	1.99	0.77	2.74	283.2	168.5	119.1	46.3	164.3
0:48	4.66	2.70	1.67	0.43	2.66	279.6	162.0	100.4	26.0	159.4
0:49	4.52	2.87	2.64	0.69	2.92	271.2	172.2	158.3	41.5	175.3
0:50	4.41	2.78	3.20	0.61	2.82	264.6	166.8	191.8	36.5	169.4
0:51	4.32	2.50	3.63	0.76	3.17	259.2	150.0	217.9	45.4	190.0
0:52	5.47	2.85	3.54	1.14	3.25	328.2	170.8	212.2	68.3	194.7
0:53	5.16	2.83	3.64	1.03	3.22	309.6	170.0	218.7	61.7	193.1
0:54	5.09	2.96	3.41	1.19	3.31	305.4	177.8	204.8	71.4	198.3
0:55	4.87	2.29	2.56	0.78	2.50	292.2	137.3	153.4	46.6	150.0
0:56	4.68	2.50	2.68	0.82	2.48	280.8	149.8	160.8	49.5	148.9
0:57	4.43	2.86	3.10	1.00	2.85	265.8	171.6	186.0	60.0	171.0
0:58	4.34	1.29	3.09	0.57	2.58	260.4	77.2	185.2	34.0	154.7

	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
0:59	4.39	1.82	2.96	0.77	2.55	263.4	109.2	177.9	46.3	152.9
1:00	2.76	1.64	2.71	0.74	2.39	165.6	98.3	162.4	44.3	143.3
1:01	0.64	1.22	2.65	0.50	2.19	38.4	73.3	159.1	30.2	131.6
1:02	-	1.50	2.35	0.54	2.11	-	89.7	141.2	32.3	126.7
1:03	-	1.51	2.18	0.65	2.12	-	90.5	130.6	38.9	126.9
1:04	-	1.22	2.27	0.54	2.24	-	73.3	136.3	32.2	134.5
1:05	-	1.00	2.07	0.39	1.71	-	60.1	124.0	23.3	102.7
1:06	-	1.05	2.08	0.56	2.00	-	63.2	124.8	33.4	120.2
1:07	-	1.12	2.18	0.42	1.79	-	67.1	130.6	25.4	107.6
1:08	-	1.99	1.31	0.42	1.46	-	119.3	78.3	25.2	87.5
1:09	-	2.26	1.36	0.55	1.70	-	135.7	81.6	33.2	102.0
1:10	-	2.30	1.94	0.77	1.83	-	138.1	116.7	46.3	110.1
1:11	-	2.38	1.46	0.49	1.62	-	142.7	87.3	29.4	97.2
1:12	-	2.37	0.15	0.39	1.17	-	142.0	9.0	23.4	70.2
1:13	-	3.03	0.03	0.50	1.17	-	181.7	1.6	30.2	70.4
1:14	-	2.37	-	0.38	1.05	-	142.0	-	22.8	62.9
1:15	-	2.43	-	0.46	1.57	-	145.9	-	27.7	94.0
1:16	-	2.46	-	0.43	1.36	-	147.4	-	25.8	81.9
1:17	-	2.38	-	0.26	1.28	-	142.7	-	15.5	76.5
1:18	-	2.31	-	0.28	1.20	-	138.8	-	16.7	71.8
1:19	-	2.22	-	0.23	1.02	-	133.4	-	13.8	61.1
1:20	-	2.18	-	0.19	1.30	-	131.0	-	11.5	78.1
1:21	-	1.98	-	-	1.04	-	118.6	-	-	62.6
1:22	-	2.18	-	-	1.31	-	131.0	-	-	78.7
1:23	-	2.39	-	-	1.08	-	143.5	-	-	64.8
1:24	-	1.90	-	-	0.56	-	113.9	-	-	33.4
1:25	-	1.89	-	-	0.82	-	113.1	-	-	49.2
1:26	-	2.03	-	-	0.58	-	121.7	-	-	35.0
1:27	-	2.07	-	-	-	-	124.0	-	-	-
1:28	-	2.12	-	-	-	-	127.1	-	-	-
1:29	-	2.11	-	-	-	-	126.4	-	-	-
1:30	-	2.12	-	-	-	-	127.1	-	-	-
1:31	-	1.01	-	-	-	-	60.8	-	-	-
1:32	-	0.16	-	-	-	-	9.4	-	-	-
1:33	-	-	-	-	-	-	-	-	-	-
1:34	-	-	-	-	-	-	-	-	-	-
1:35	-	-	-	-	-	-	-	-	-	-
1:36										