Development of a Plastic Shredder

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MASTER THESIS

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Abstract

This report covers a project for the Division of Product Development at Lund University to build and further develop a plastic shredder. It was based on open-source blueprints from the Precious Plastic machine series, a nonprofit project by Dave Hakkens to reduce plastic waste. Its purpose is to shred common plastic waste so that the shreds can be remelt to create new products by students in the subsequent machines of the series. The main goals of the project were to build the shredder at minimum cost and to develop an improved version after testing it. It was built using in-house machines at the schools workshop and is powered by a gearmotor build from parts found at a local junkyard. Minor modifications were made of the original designs to improve handling and assembling of the machine. The gearmotor and its electronics were also built on a separate platform to create a modularized unit that is easily detached if desired to be used in other applications.

The shredder worked as intended but caused some difficulties during assembly. The redesign addressed this issue aswell as increased the rate of cutting action by modifying the knives and counterknives. Due to lack of time and restricted funds, an actual version of this redesign was never built and tested.

Keywords: Product Development, Plastic, Waste, Shredder, Recycling

Sammanfattning

Den här rapporten behandlar ett projekt hos avdelningen för produktutveckling vid Lunds Universitet för att bygga och vidareutveckla en flismaskin för plast. Den baserade på open-source ritningar från Precious Plastics maskinserie, ett ideellt projekt av Dave Hakkens för att reducera plastavfall. Dess syfte är att flisa vanligt plastavfall så att flisorna kan smältas om för att skapa nya produkter av studenter i de följande maskinerna i serien. Projektets huvudmål var att bygga flismaskinen till minimal kostnad och att utveckla en förbättrad version efter att ha testat den. Den byggdes med hjälp av lokala maskiner i skolans verkstad och drivs av en växelmotor som byggdes av delar som hittades hos en lokal skrothandlare. Mindre modifikationer av originalritningarna gjordes för att förbättra hanteringen och monteringen av maskinen. Växelmotorn och dess elektronik byggdes även på en separat plattform för att skapa en modulariserad enhet som är enkel att avskilja om den önskas användas i andra syften.

Flismaskinen fungerade som tänkt men skapade vissa svårigheter under monteringen. Den nya designen adresserade detta problemet såväl som ökade skärfrekvensen genom att modifiera knivarna och motknivarna. I brist av tid och begränsat kapital byggdes och testades aldrig en faktisk version av den nya designen.

Nyckelord: Produktutveckling, Plast, Avfall, Flismaskin, Återvinning

Preface

I would like to thank Professor Olaf Diegel for giving me the opportunity to do this project for the Division of Product Development and for the assistance he gave me as supervisor of this project. Im also grateful to Johannes Ekdahl du Rietz and Giorgos Nikoleris for helping me with the electronic connections, in which I realized I was hopelessly lost.

A special thank you is in order to all the instructors of the ID-A workshop at IKDC who helped me untiringly. Whether I needed parts machined that I could not do myself or just someone to discuss technical difficulties with, they were there.

Lund, March 2018

Rasmus Ekman

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Introduction

This first introductory chapter is meant to give an insight into the company from which the basis of my master thesis stems, the goals of this project and the limitations to how far the development process will be completed.

1.1 Precious Plastic

Precious Plastic is an open-source project that was started in 2013 by Dutch designer Dave Hakkens [1]. The idea was to make a series of machines that were to decrease the problem of plastic waste throughout the world by reshaping it into new products on a local basis. Hakkens suggested that people all over the world could build their own production line and pay the local citizens a small fee according to the weight of the raw material they bring to the workshop [2].

Version 1.0 was merely a proof of concept for his graduation project at Design Academy in Eindhoven. More people got involved to help develop version 2.0 to make them easier to build using basic materials that are available worldwide [1]. The blueprints and instructions were then shared freely at his website and he made a forum to form a community of machine developers that give feedback and help each other with problems that may arise during the construction phase and as a source of inspiration for further uses. The machine that was built and developed in this thesis is based on this version.

1.2 Background

The machine series was noticed by Olaf Diegel, Head of Division of Product Development at Lund University. He wanted students to build the machine series for the benefit of the school so that other student could make simple products out of recycled plastic for other project courses. The series comprises a total of four machines: shredding, injection, compression and extrusion machines. The three latter are dependent on the output of the shredder. They melt and reshape the plastic flakes that the shredder creates from the plastic waste. As this would be the first machine of the series to be built at the school, our top priority was therefore to build a good and functioning shredder to have a foundation for other students to build upon.

1.3 Aims and purpose

Hakkens was clear in his instructions that the Precious Plastic machines are not perfect and so is under ongoing development by the community. Consequently, problems were expected to arise during construction and testing since variations in dimensions and tolerance will depend on the precision of the material supplier and manufacturing methods. Since the blueprints only cover the actual shredder-part and a general framework, the actual setup would have to be modified to fit whatever power supply unit (PSU) that was finally used.

To summarize, the main objectives of the project were to:

- Build a functioning shredding machine for plastics waste.
- Make an easily detachable modular PSU that can be used for other future applications.
- Redevelop the shredder to improve performance, output quality, assembly and/or user-friendliness, after testing of the machine.
- If possible, rebuild the machine with the new improvements.
- Minimize building cost.

1.4 Scope

The project ranged from the complete building and testing of the plastic shredder provided by Hakkens to development of a new design of the shredder. Ultimately, the goal was to build a physical and functioning version of the new design of the shredder.

No deeper analysis was made of the throughput of the machine in any of its versions other than a cursory examination if the desired functionality is fulfilled.

To keep the costs to a minimum, the building of the machine was exclusively done in the schools workshop at IKDC, Lund.

1.5 Limitations

The costs were not calculated as a considerable part of the machining was carried out by the supervisors of the workshop when they were available. This was done inbetween other work which made it difficult to assess the time spent on my project and the corresponding costs. Besides, the majority of the costs were that of the PSU and as such is highly dependent on what is available and varies greatly.

The project did not comprise any type of manual for the machine or protocols regarding safety in operating or handling the machine. It is up to any user of the machine to use it responsibly and exercise caution on personal safety and integrity of the machine.

No CAD models were analyzed by FEM-based programs as the forces acting on the shredder would be too difficult to anticipate and model which would likely lead to irrelevant results.

2 Method

The purpose of this chapter is to give insight into the methodology used during the course of the project. As it was of a more practical nature than most other master theses, the methodology that was found best suited turned out to be less theoretical and strict than what might normally be the case.

2.1 Project Plan

The actual building of the machine involved several manufacturing steps that I lacked practical experience with and so had to be done in part by the workshops supervisors. The unregular accessibility of certain machines made it difficult to nail down a precise project plan to follow. Consequently, at the start up of the project a very loose plan was made, see Appendix A, with expected milestones to aim towards. This was intended to be amended as the project progressed.

2.2 Pre-Study

2.2.1 **Provided Material**

Before construction of the individual parts of the machine, it was decided that a study of the provided blueprints and CAD-drawings would be undertaken. This would give better understanding of how it was constructed and an oppotunity to discover areas that could potentially cause problem during assembly. The Precious Plastic forum, where other machine builders around the world post about their progress and problems that they encountered, would also be studied to this end.

2.2.2 **Industrial Shredders**

During construction phase of the provided original design, a study of current in-use shredders designed for different purposes would be made to draw inspiration for the following redesign of my own shredder.

A study of the machine builds posted on the Precious Plastic forum by other people could also give valuable insight into positives and negatives on the current design and ideas for change.

2.3 Development Method for the Redesign

After a cursory study of the way these machines are built, it was realized that the different possibilities of configuration are considerably limited. Therefore, it was decided not to use the typical product development process taught by the school and formulated by Ulrich & Eppinger [3].

2.3.1 **Gradual refinement of a new design**

It was concluded that the most practical approach would be a very simple design strategy. A few general construction ideas would be formulated and then evaluated at that level. The ones that suited the projects particular situation and limitations would then be refined further until a final version could be devised.

2.3.2 **Building the new design**

Ideally, there would be enough time to build the previously mentioned new design in actual scale and materials. Assuming that the original design would function despite prospective flaws, the option to build this new version would largely come down to a matter of cost. If built, the new design would be tested and compared to the previously built version.

2.3.3 **Final Design**

If needed, a final design would be made to solve any resulting problems arising in the previous testing. This last version were, however, not planned to be built due to the aforementioned financial limitations. An illustration using a CAD model would likely suffice to show any design changes at this stage.

3 Pre-study

This chapter presents the result of the pre-study described in chapter 2.2.

3.1 Provided Material

The material provided by Precious Plastic to build the shredder can be found at https://github.com/hakkens/precious-plastic-kit/archive/master.zip and contain everything needed to build any of the four machines, complemented by the instruction videos on their homepage https://preciousplastic.com/en/videos/. See Figure 3.1 for an overview of a shredder built by Precious Plastic.

Figure 3.1 A general view of the shredder as built by Precious Plastic.

3.1.1 Framework

The first observation made while studying the material was that the framework would have to be modified to fit whatever setup of PSU was to use. Furthermore, the raised platform that is meant to support the shredder sub-part (SSP) would have to be either very carefully measured to maintain axis alignment of the SSP shaft and the PSU output shaft or another design should be used. Any misalignment would cause unnecessary strain on the bearings. A, by such radial forces, gradual loosening of the bolts securing the positioning of the SSP shaft could, in a worst-case-scenario, cause the knives to strike solidly into the counterknives, see Figure 3.2, and destroy the machine.

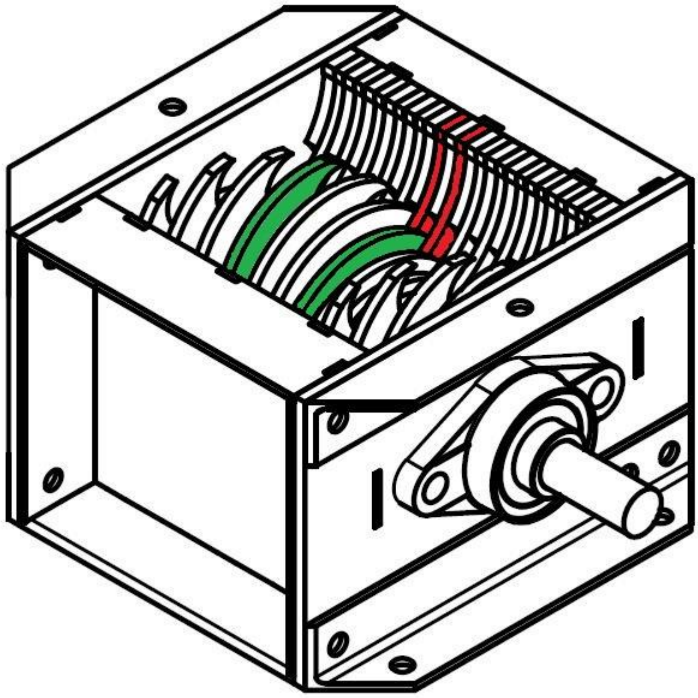

Figure 3.2 SSP where knives (green) and counterknives (red) are marked.

3.1.2 Shredder Sub-part

The main issue seen in the SSP were the puzzle shaped connectors between the different parts of the housing, as seen in Figure 3.3. Many of the parts that are supposed to fit together tightly are designed with no gaps, i.e. a 10.0 mm wide male part is designed to fit with a 10.0 mm wide female part.

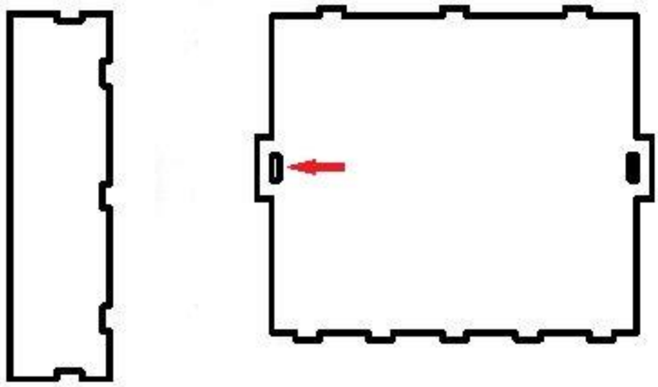

Figure 3.3 Two pieces with puzzle shaped connectors. Slits dependent on sheet metal thickness marked by arrow.

The precision of the manufacturing method would greatly influence the outcome of the fitting. Another influencing factor is the precision of the manufacturer of the sheet metal as some fittings were dependent on this, i.e. the slits marked by a red arrow in Figure 3.3 where the width of the slits corresponds to the sheet thickness of the connecting part.

3.1.3 PSU

As noted in the Bill of Materials from Precious Plastic, see Appendix B, the specifications of the PSU call for a motor with a power of ~ 2 kW and an output speed ~ 70 RPM. That would result in a torque of around 300 Nm at the output shaft. Posts at the Precious Plastic forum told of builders that used other configurations with less power and had mixed results. My conclusions were that 300 Nm is probably more than what is actually necessary. I would, however, try to get as close as I could to ensure that the machine does not clog and stop if I try to shred thicker pieces of plastic.

3.2 Industrial Shredders

By investigating a multitude of different industrial shredders I realized that they all build on the same principle, with different configurations of two key aspects based on the application of the machine.

3.2.1 **Shafts**

The most basic disparity between the different designs is the number of knife shafts. Most of the shredders studied were either single or double shafted but some heavy-duty ones were even made with four. The obvious advantage of having several knife shafts is of course that the number of cutting actions at any given time increases with the number of shafts which increases the speed of the process. The major advantage with several shafts, however, seemed to be a noticable increase in its ability to pull material through the machine. When comparing them to videos of Hakken testing his machine, they appear to have much less problems with the material to be shredded skipping on top of the knives.

Figure 3.4 Four shaft shredder

3.2.2 **Knives**

The second attribute that usually differs is the design of the knives themselves. This is highly dependent on the application they are to be used for. Heavy-duty shredding such as cars, engine blocks, transmissions and other large metal pieces require the knives to be thicker and smaller, coupled with a slower speed to increase torque.

The number of teeth also affects the performance of the machine. More teeth mean faster cutting; but it also increases the risk of the object to be shredded skipping on top of the knives, as well as the risk of clogging the machine and thus forcing a reverse of the spin direction. If the knives have too many teeth the machine may not be able to shred tougher objects as more teeth will be engaged at any time.

Most machines use one of two tooth designs with minor variations. The first is in the general shape of a hook where the cutting edges are square. The Precious Plastic knives are based on this design, albeit a bit different than most other blades, see Figure 3.5. Typically, the hook is made with a straight cutting edge and a straight or rounded supporting back, as seen in Figure 3.5. Hakkens used a curved cutting edge instead. The other type uses triangularly shaped teeth and similarly shaped counterknives, see Figure 3.6.

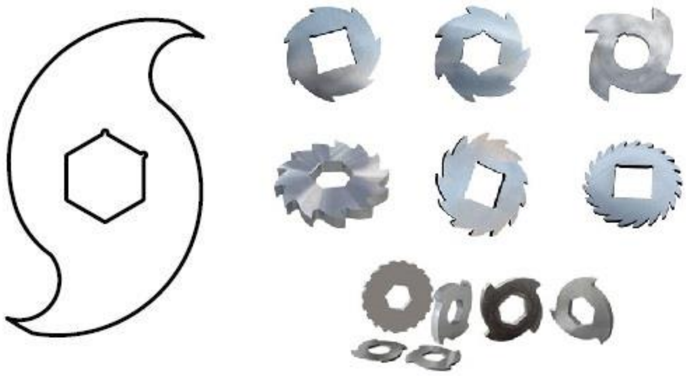

Figure 3.5 Left: shredder knives as designed by Precious Plastic. Right: Assorted industrial shredder knives.

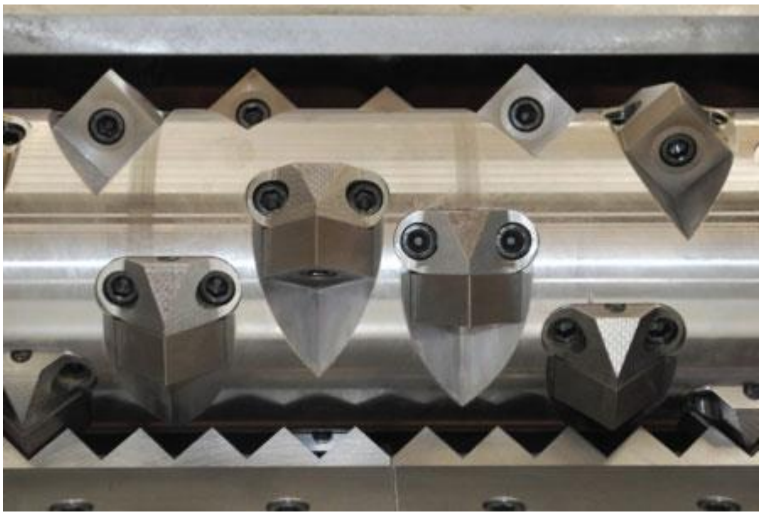

Figure 3.6 Triangular teeth and counterknives.

As seen in Figure 3.6 many high end shredding machines use easily replaceable cutting edges to improve maintenance and longevity.

There are a few other variations typically adapted to the specific task they perform. One such is a paper shredder. As the main purpose is not only to reduce it to smaller pieces but also to destroy the information contained on it, the paper needs to be reduced to small enough pieces that the text and images become unintelligible. As the paper does not cause much resistance, these machines can be designed with a larger amount of blades that are much thinner. If shredding the papers into strips is enough, a simple dual-shaft design with completely round knives would suffice.

Should a finer shred be needed, the previously described hook-blades are an alternative, see Figure 3.7.

Figure 3.7 Paper shredder with hook knives.

4 Building the Machine

This chapter covers the entire building phase of the shredder by Precious Plastic with some changes made to the design.

4.1 PSU

Based on the specifications and the load application it was decided that a geared motor would be best suited for the task. Dave Hakkens uses an angular geared motor in his setup, as seen in Figure 4.1, that he found on a local junkyard, albeit with a lower speed than the specified. Based on his instruction videos its speed was approximated to ~35 RPM.

Figure 4.1 Dave Hakkens angular geared motor.

4.1.1 **Worm Drive**

The first plan was to buy a used motor and connect it to a new worm gear from Liljenbergs AB, shown in Figure 4.2; they were reasonably priced and had high reduction ratios.

Figure 4.2 Worm gear from Liljenbergs AB.

A worm gear of similar type from Mekanex AB is supposed to handle max torques of 1050 Nm [4]. The output shaft would then be connected to the knife shaft using a jaw coupling, see Figure 4.3.

Figure 4.3 Jaw coupling.

These couplings are designed to be able to transfer large amounts of torque, as my application requires. The flexibility of the elastomer spider between the two claws also allow a maximum misalignment of the two shafts of 0.9° [5]. This would make the assembly a little bit easier. I found a motor, see Figure 4.4, at a local junkyard with adequate power, see Figure 4.5, for 200 SEK.

Figure 4.4 Used motor from a local junkyard.

Figure 4.5 Rating plate of the motor.

It had previously been used as a pump so the pump housing had to be removed. A lot of time was spent getting rid of the impeller that had rusted onto the motor, without damaging the underlying shaft, see Figure 4.6. After connecting the motor through a protective circuit breaker, see Figure 4.7, it ran without fault.

Figure 4.6 Motor after removing the pumphouse and part of the impeller.

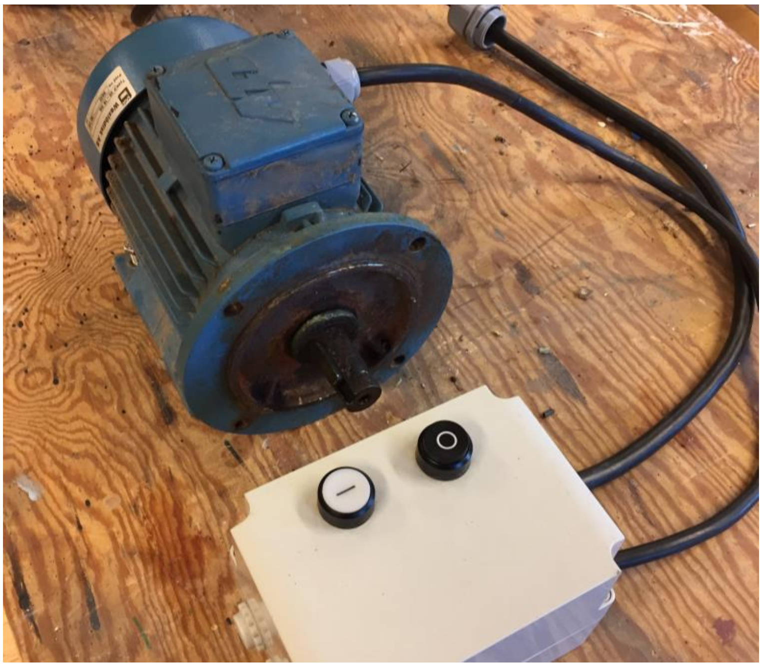

Figure 4.7 Motor connected to a protective circuit breaker.

However, when Liljenbergs was called to place an order for the worm gear, the sales representative informed that those were not dimensioned to handle such forces and that worm gears are unsuited for this application. They work by using a screw-shaped gear, called worm, to drive a larger gear, called worm gear, as can be seen in Figure 4.8. Ideally, the worm is made of hardened alloy steel and the worm gear of phosphor bronze [6].

Figure 4.8 The basic setup of a worm gear.

Besides offering a compact way to achieve high reductions ratios, this design works as a kind of brake. The worm can drive the large wheel in both directions but the output shaft cannot drive the worm shaft. The sharp angles of the worm's teeth produce enough friction to lock the two gears together, resulting in the worm gear trying to shear off the teeth of the worm. This function does not affect my particular situation though, as there is no risk of external forces driving the knife shaft. However, since worm drive works entirely through a sliding frictional contact between the gears, the system requires highly specified lubrication with high viscosity which makes it unsuited for this relatively simple machine [7]. According to Liljenbergs it would instead be better to look for a coaxial gearmotor, as seen in Figure 4.9.

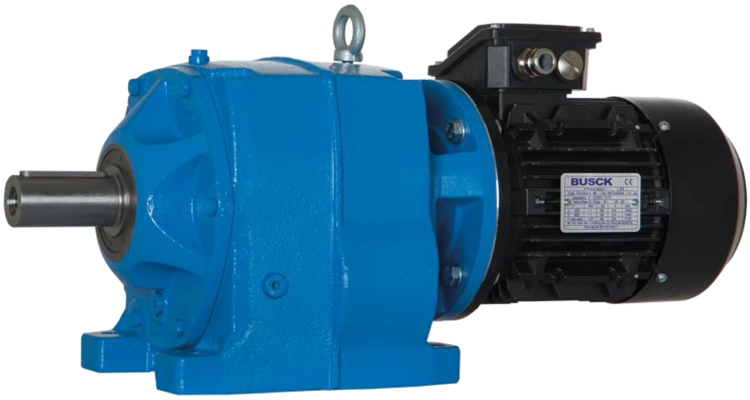

Figure 4.9 Coaxial gearmotor.

That turned out to be hard to find at low enough price. An offer for a new such from Liljenbergs showed a total cost of 13950 SEK + 25% VAT and additional freight cost, which would definitely be too much as the costs needed to be kept to a minimum. Most used gearmotors with a speed similar to the recommendation turned out to have too low power output. Alternatively, a used gearmotor could be found and then change the motor to the one already bought. Unfortunately, the motors speed of 2820 RPM, as seen in Figure 4.5, is unusually high which forces a higher reduction ratio of i:40 to reach 70 RPM on the output shaft. This turned out to be hard to find in a strong enough design.

4.1.2 Belt drive

It was decided to instead use a V-belt drive transmission, also called friction drive, see Figure 4.10 (left), as I could more or less easily modify the framework to accommodate the system of pulleys and belts. Besides being a common and economic way of transmitting power, belt drive offers the significant advantages of shock load dampening and not requiring lubrication [8]. It would also act as an additional safeguard if plastic were to jam the machine or the knives would strike the counterknives as the belts are free to slip if the resistance is too high. The downside of the belts ability to slip is that its unsuited to applications that need high precision of velocity ratio and timing, which fortunately, this machine does not. To solve that problem, one could use ribbed belts, as shown in Figure 4.10 (right) instead, as in the camshaft transmission of a car engine, see Figure 4.11.

Figure 4.10 V-belt drive (left) and Ribbed belt drive (right).

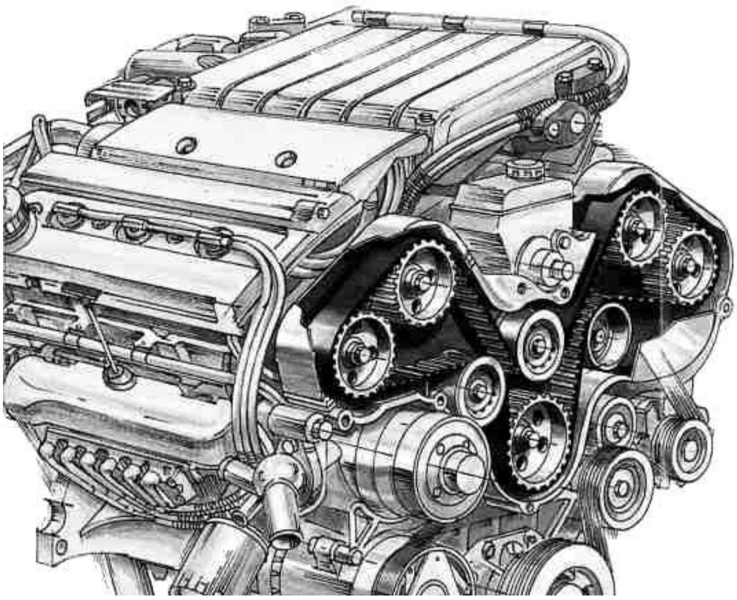

Figure 4.11 Ribbed belt as a timing belt for the camshafts of a car engine.

To calculate the size and position of the pulleys, length of the belts and number of belts in the transmission a handbook on belt drives from Trelleborg AB was used. The required high reduction rate means that if a small pulley with a diameter of 63 mm was used on the motor shaft, then the pulley on the knife shaft would have to be 2.5 m in diameter. Obviously, this would not be practical. The solution would be a setup of several subsequent transmissions via separate shafts. As seen in Appendix C the power that can be transmitted per belt is lower with decreasing speed and diameter of the smallest pulley. This mean that the last step of the transmission is the critical component. To avoid using very large pulleys, a balance would have to be found between the size of the last reduction and the size of the smallest pulley. As the availability of pulleys with more grooves than six is limited the first thing to calculate was the smallest size possible of the knife shaft pulley and then dimension the remaining transmission from that. After numerous calculations with the handbook, it was concluded that the most cost efficient way to achieve the required reduction would be to use a reduction setup of i:4:3:3. However, to make sure that the right amount of tension was applied on each belt, either a springed tensioner, as seen in Figure 4.12, would need to be used or the distance between the two passive shafts with pulleys had to be adjustable.

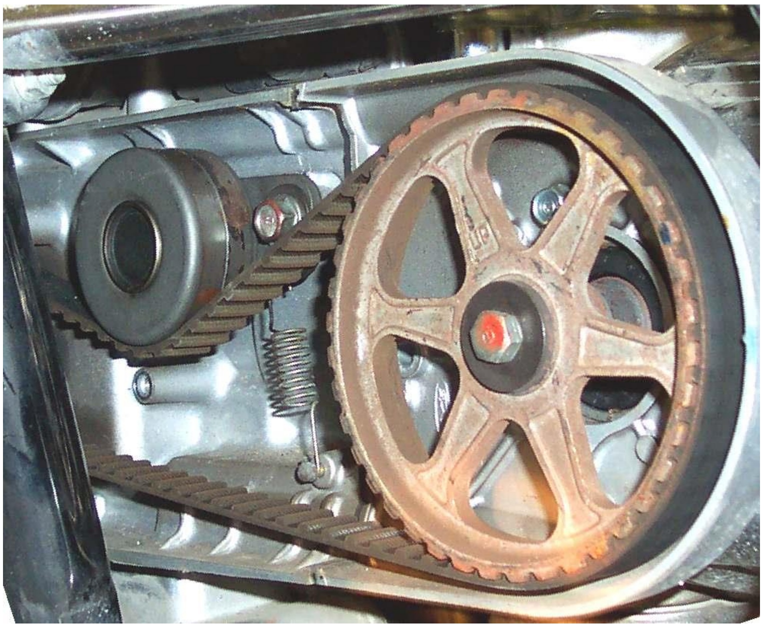

Figure 4.12 Spring tensioner on a ribbed belt.

This made the construction relatively complex and quite costly. Before ordering the parts for the complete belt drive another search was made at the different markets for used parts in hope of finding a gear reducer or a gearmotor with slower speed and lower power.

4.1.3 Gear Reducer

Fortunately, deep in the junkyard, a complete coaxial gearmotor was found, see Figure 4.13, that was not there the last time.

Figure 4.13 Gearmotor as found on the junkyard.

Figure 4.14 Rating plate on the gearbox.

The motor did not have any plate that showed its speed or power, but the gearbox just so happened to have almost exactly the right amount of reduction, as seen in Figure 4.14. Its output shaft could not be turned but the flange connection to the motor was damaged, as seen in Figure 4.15, and the fan cover at the back was buckled. In hope that it was the motor that was damaged and not the gearbox, or that any damage to the latter could be repaired, the gearmotor was bought for 250 SEK.

It was taken apart in the workshop, see Figure 4.16, and luckily the gearbox worked perfectly.

Figure 4.15 Damaged flange connection.

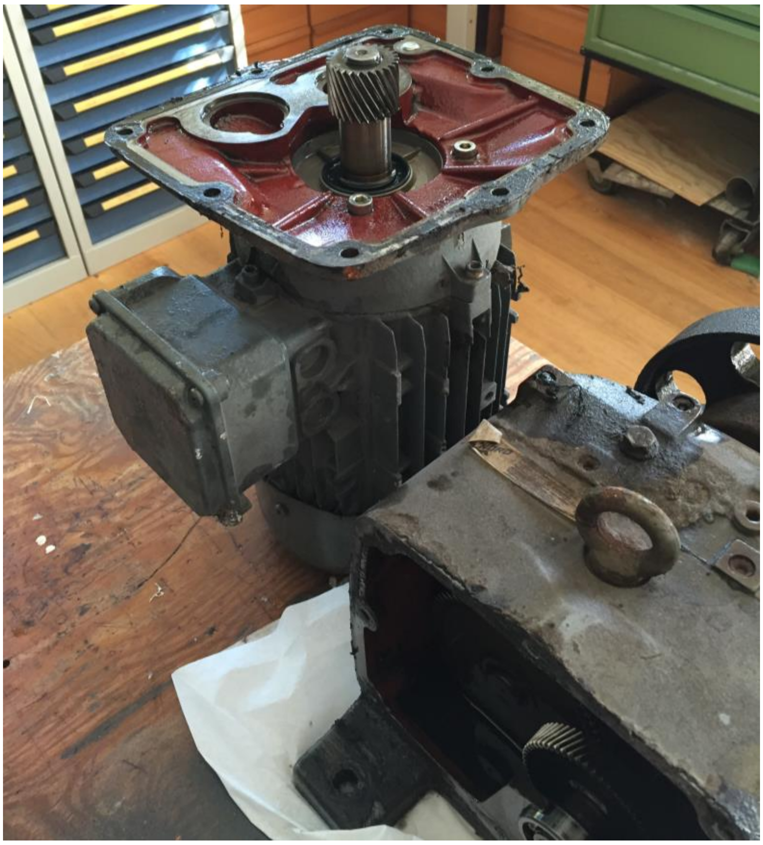

Figure 4.16 Motor separated from gearbox.

It did, however, have a large pulley, see Figure 4.17, on the output shaft that was fixed by rust from lying outdoors in the junkyard. Removing it turned out to be more cumbersome than expected. After several days of trying to disolve the rust around the set screw and intense efforts to remove the set screw the easy way, see Figure 4.18, the best way to go forward seemed to be to drill out the screw and try to pull off the pulley with a gear puller, as seen in Figure 4.19. Unfortunately, it would not budge. Half a day with the angle grinder, gear puller and a wedge, however, did the trick, see Figure 4.20.

Figure 4.17 Pulley on the output shaft of the gearmotor.

Figure 4.18 Allen key twisted from trying to remove the set screw.

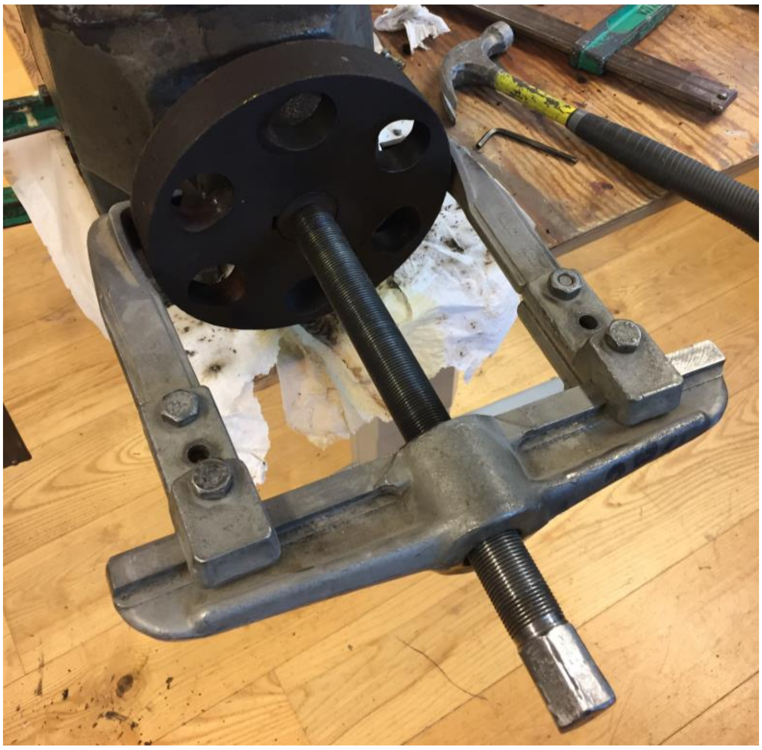

Figure 4.19 Attempting to remove pulley with gear puller.

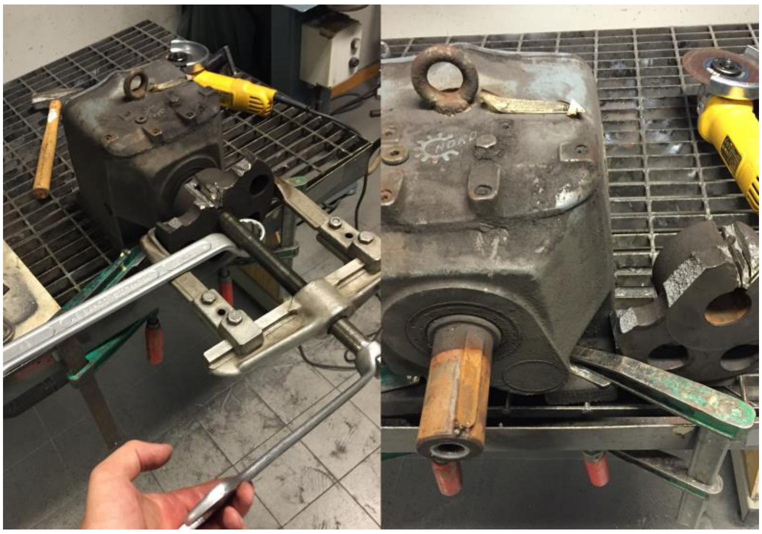

Figure 4.20 Successfully removing the pulley with an angle grinder.

4.1.4 PSU connection

Next was the issue of connecting the motors output shaft to the now ready gearbox. As seen in Figure 4.16, the helical gear at the end of the gearboxmotors shaft was designed to fit with the gearbox. The first plan was to use as much of the gearboxmotor as possible. It was disassembled and the shaft with the gear and flange was kept intact. That way the gears relative position to the flange would remain intact. As a result, only a connection between the motor and the gearboxmotors shaft had to be made. Then a simple cover of the moving shafts would be made by waterjet cutting two flanges that fit the gearbox and motor then weld them onto a steel pipe large enough to accommodate the old rotor still on the shaft, see Figure 4.21.

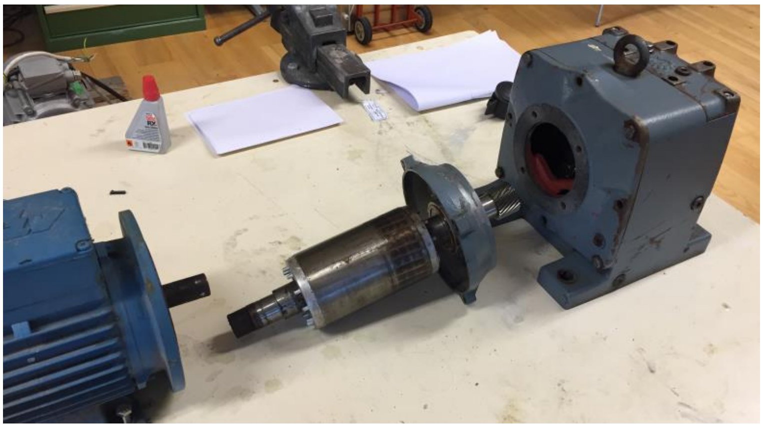

Figure 4.21 First plan of PSU configuration.

The major problem with this setup is maintaining the correct alignment between the two axes. A slight misalignment coupled with the high speed of the motor would most likely cause severe vibrations throughout the construction. To reduce this issue the rotor was cut from the shaft, see Figure 4.22, which allowed placement of the motor right next to the flange of the gearbox, barring space for the connection, as demonstrated in Figure 4.23.

Figure 4.22 The gearboxmotors shaft after cutting off the rotor and removing the flange and helical gear.

Figure 4.23 PSU configuration after removing the rotor with the remaining shaft connected to the gearbox.

Instead of making a simple connector between the two shafts and securing it with set screws in both ends, as first intended, Jonny Nyman, instructor at the school's workshop, lathed an entire new shaft with the connector integrated, as seen in Figure 4.24. This reduction of a fitting between shaft and connection further decreased the risk of misalignment.

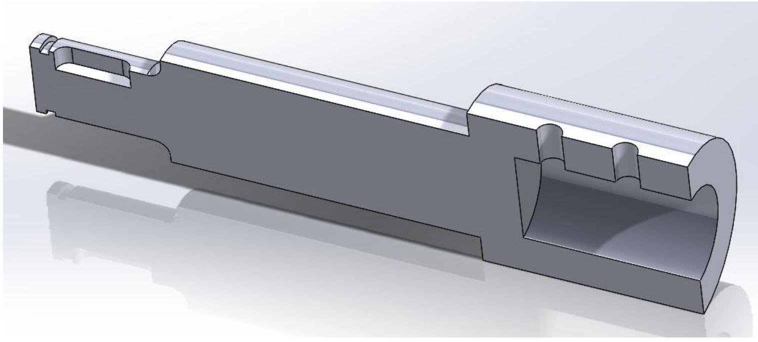

Figure 4.24 CAD model of the lathed shaft with an intergrated connector.

Lastly, instead of welding the cut flanges with a pipe and risk improper mounting, a solid connection was lathed to fit between the motors and gearboxes flanges with intakes for the spigot and socket of the flanges. As the spigot and socket, see Figure 4.25, are designed to be concentric with the output and input shafts respectively, a tight fitting would solve the issue of misalignment. The resulting flange connection is shown in Figure 4.26.

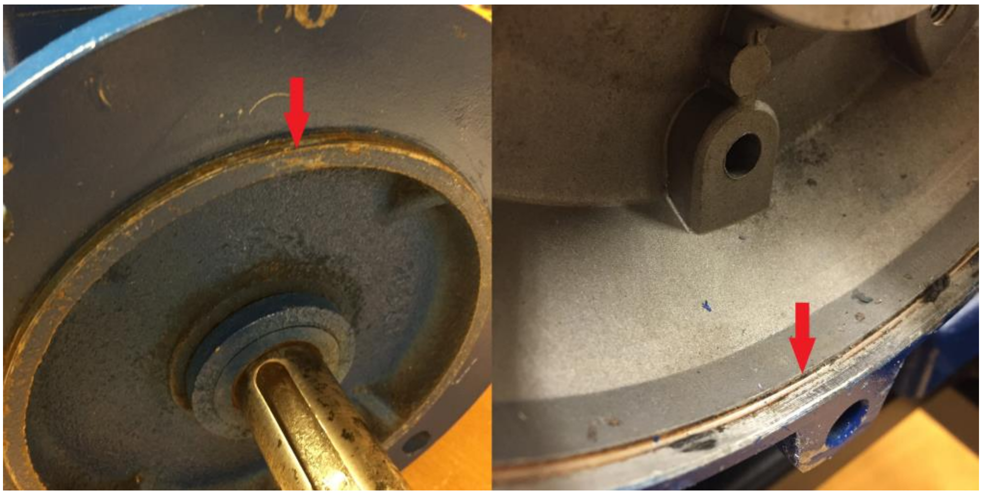

Figure 4.25 Spigot (left) and socket (right) of the flanges marked by arrows.

Figure 4.26 Lathed connection between motor and gearbox.

4.1.5 Paint and coating

Lastly the PSU needed a new finish. After thoroughly cleaning it, a gray primer was applied followed by a rich blue spraycolor, see Figure 4.27 and Figure 4.28.

Figure 4.27 Motor prepared for primer and paint.

Figure 4.28 Motor after painting.

The complete PSU were then assembled and tested after refilling the gearbox with new transmission oil. It functioned more or less perfectly. The finished PSU is shown in Figure 4.29.

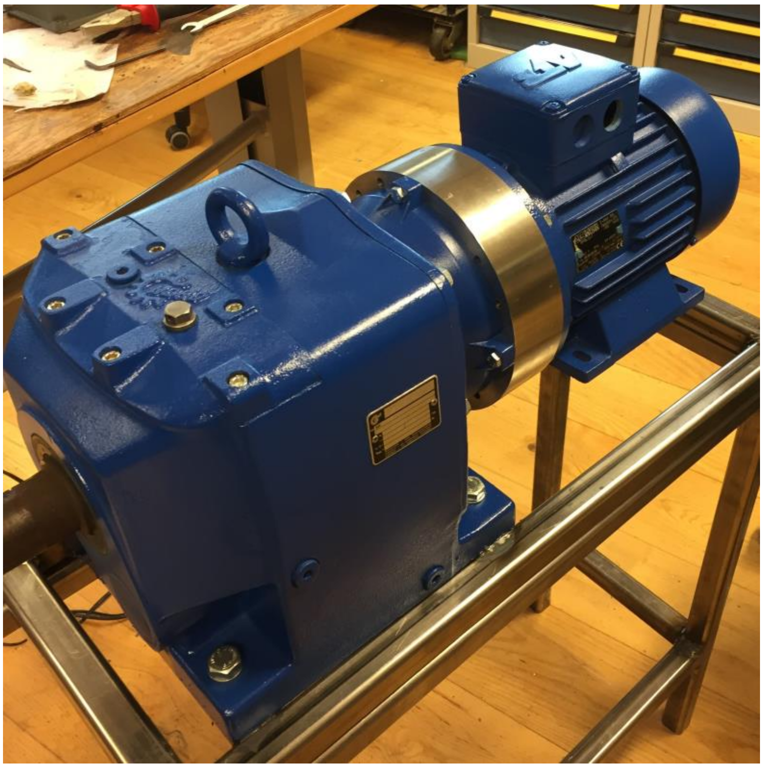

Figure 4.29 The finished PSU.

4.2 Shredder sub-part

4.2.1 Cutting the parts.

While finishing up the PSU work on the shredder sub-part was begun. As it turned out, almost all the files provided by Precious Plastic for cutting the individual parts had double lines that needed to be removed before they were sent to the waterjet cutter. These so-called double lines are two lines that are drawn on top of eachother. This would cause the waterjet program to want to engage each line twice from different directions,as seen in Figure 4.30, which would cut into the pieces that were being made.

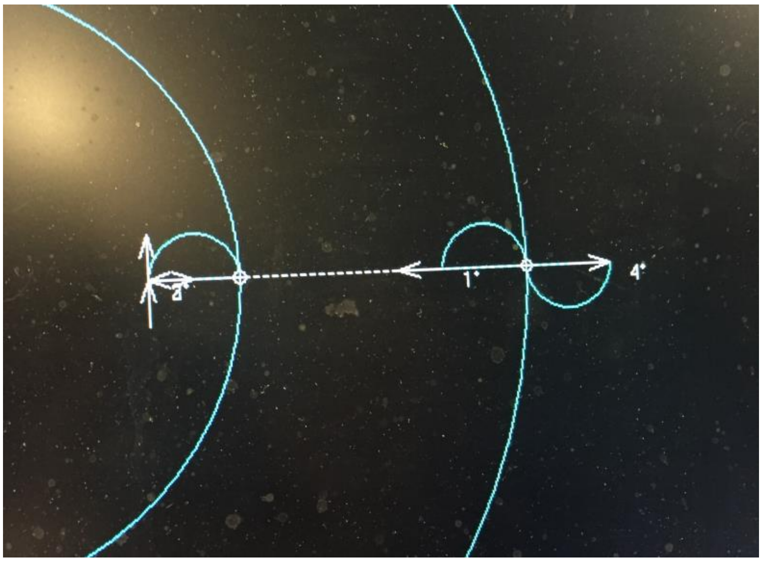

Figure 4.30 Double lines that cause double engaging points as seen on the rightmost line. The object to be cut is a ring between the two lines. The blue lines represent the cutting path of the waterjet cutter.

As anticipated in chapter 3.1.2 the fitting between most puzzle shaped connectors were too tight and had to be considerably reduced at both thickness and width using an angle grinder. The blueprints were not changed beforehand as the waterjet were thought to follow the path of the lines in the blueprints; making the width of the waterjet correspond to the gap between the connectors.

4.2.2 Knife shaft

As for the knife shaft, Jonny Nyman helped with the lathing of a hexagonal rod at the ends of the shaft. This needed a high degree of accuracy to produce a tight fitting with the bearings. He also helped with milling all hexagonal sides of the rod a small fraction as the hexagonal holes in the cut knives were slightly too small to fit.

4.2.3 Knife configuration

Regarding the configuration of the knives it was decided to use a different setup than Hakkens. Instead, each new knife was rotated “backward” a little until about halfway where they would start rotating “forwards”. This created a V-shape as seen in Figure 4.31. The idea was that the flow of edges would somewhat “push” the remaining plastic shreds toward the center of the SSP to avoid having too much material rotating along the outer wall as there are only one cutting action per teeth on the outer knives.

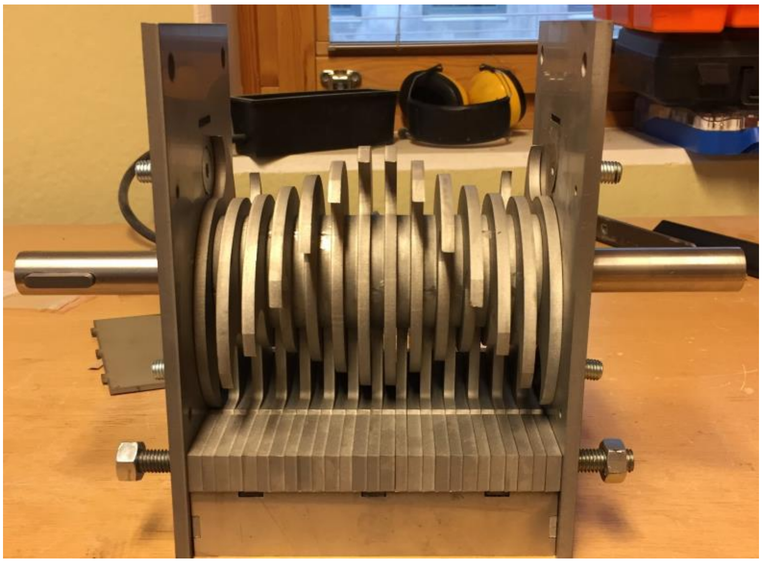

Figure 4.31 Knife configuration shaped like a V.

4.2.4 **Assembling the SSP**

The pieces were assembled according to Hakkens instruction videos and tightened so that the knives ran smoothly. The finished SSP is shown in Figure 4.32.

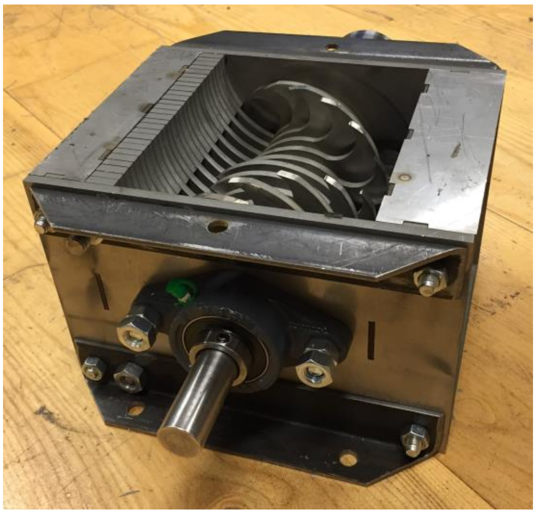

Figure 4.32 The finished SSP.

4.3 Framework

The building of the framework was done in stages as the other parts of the machine were completed. Firstly, since the PSU was to be detachable from the other parts, a separate frame was welded, see Figure 4.33. This was then to be bolted to the main frame, which was cut with angled ends to avoid open profiles at the corners when welded together. A simple shelf was made at the bottom for storage, e.g. containers of shredded plastic or raw material

Figure 4.33 Detachable frame for the PSU.

The original design called for the use of a platform of welded beams that the SSP would rest on, see Figure 3.1. Due to lack of experience with welding it would most likely not be perfectly aligned with the PSU. Instead, a modifiable solution was opted for where the SSP was bolted onto a separate frame which was then mounted on the main frame with four threaded bars. This allowed adjustment of the height of the SSP platform and the rotation around two axes by adjusting the position of the nuts on the bars, as seen in Figure 4.34. Lastly, the bottom nuts were welded to the main framework after connecting the SSP to the PSU. The complete framwork with SSP and PSU can be seen in Figure 4.35.

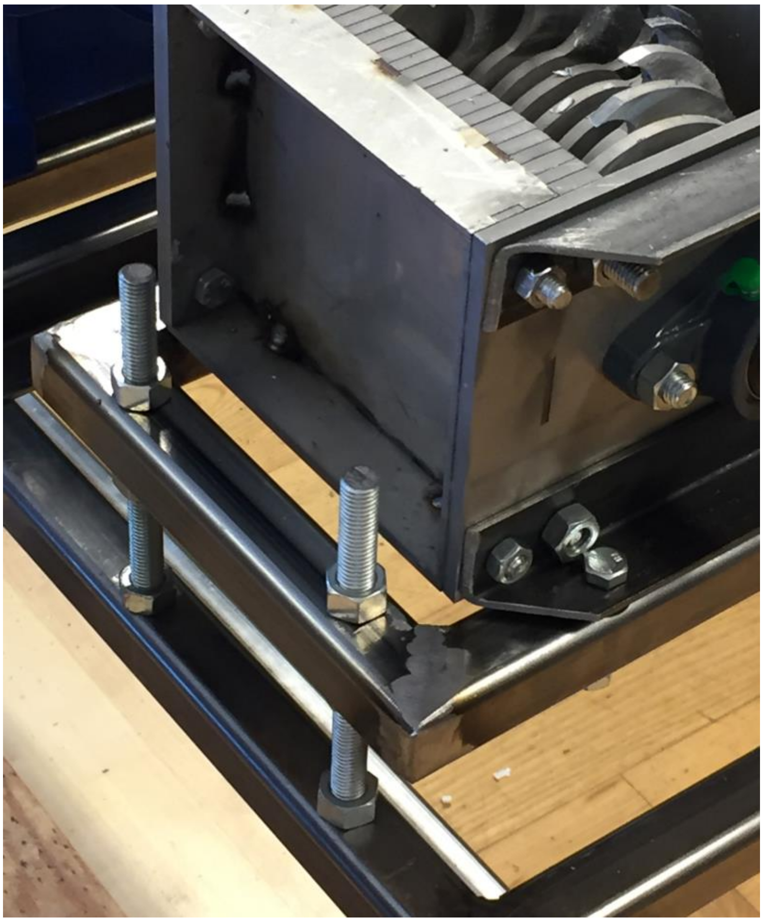

Figure 4.34 Adjustable framework solution for the SSP.

Figure 4.35 Complete framework with SSP an PSU.

4.4 PSU to SSP connection

The connector between the two shafts were lathed out of a solid block of steel. The schools workshop lacked the equipment to make a keyway at the large end that attaches to the output shaft of the PSU since the hole does not go all the way through. However, one could be made at the SSP-end of the connector. The large end were instead fastened by two set screws burrowing into the keyway left in the PSU output shaft from the previous key. The resulting connector is shown in Figure 4.36.

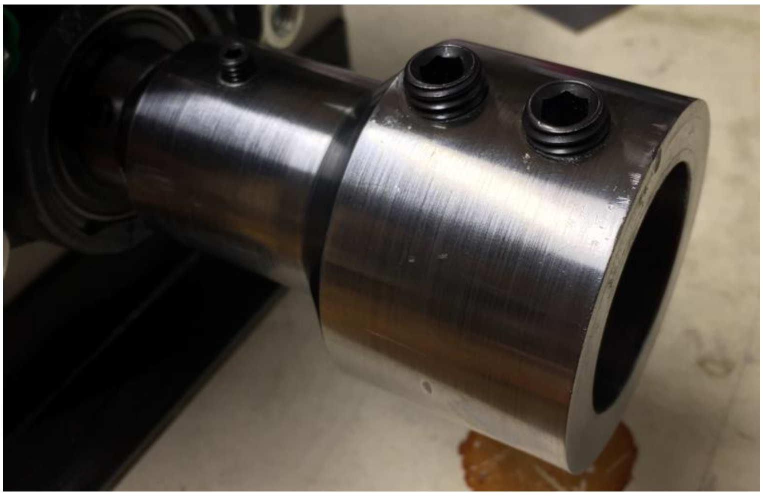

Figure 4.36 PSU to SSP connector.

4.5 Hopper

A crude hopper was made out of 1 mm sheet metal and welded together as seen in Figure 4.37.

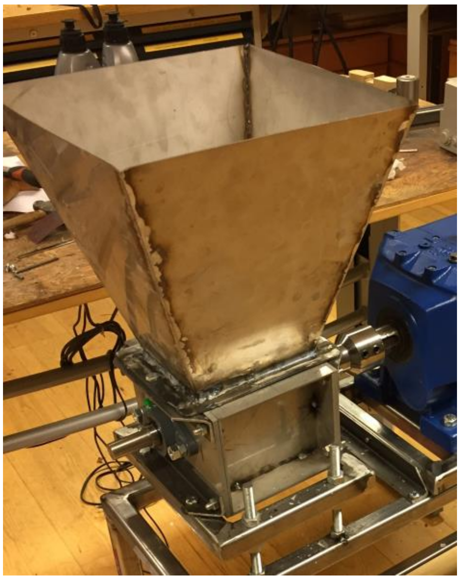

Figure 4.37 The hopper when mounted on the SSP.

4.6 Electronics

The basic electronic setup used to test the machine was a contactor and protective circuit breaker combined with on and off buttons. For the final system, however, the ability to run the shredder in both directions were needed in case the machine clogged. It would also be necessary to add an emergency stop button in an accessible position. The original plan was to place the box with the contactors more or less out of sight on the main frame, below the PSU. However, it was realized that removing the PSU platform would require either disconnecting the motor from the circuit breaker or make a limb on the platform that the box can be placed on. Such a limb however would make it difficult to store the disconnected PSU as it would have to be placed on a pallet or something similar. The most elegant solution seemed instead to place it level with the platform and on the backside of the motor, as seen from the operating side. To make the emergency button and spin direction switch accessible but still attached to the PSU platform, the only logical position seemed to be at the corner closest to the SSP on the operating side.

4.7 Finishing

To finish off the build the framework and hopper were sanded, primer was applied then painted and finished with a clear coat. The complete machine is shown in Figure 4.38-Figure 4.38.

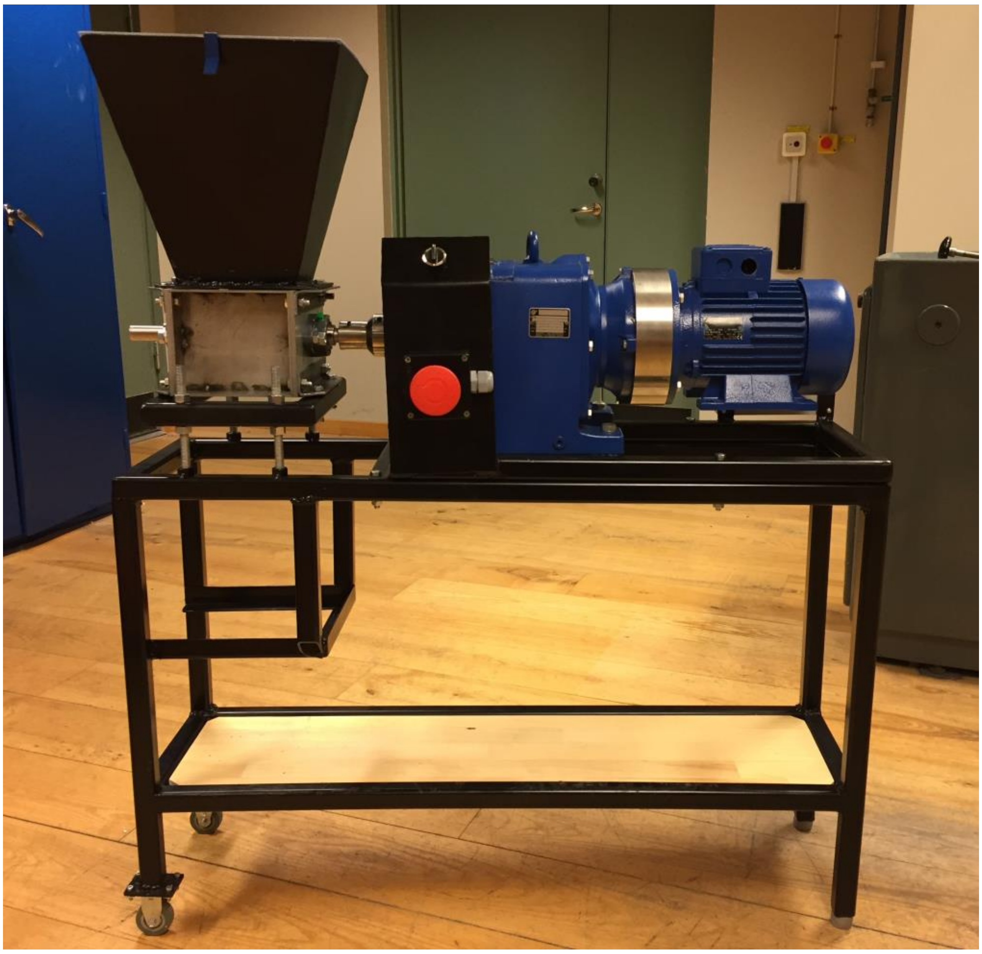

Figure 4.38 Finished machine.

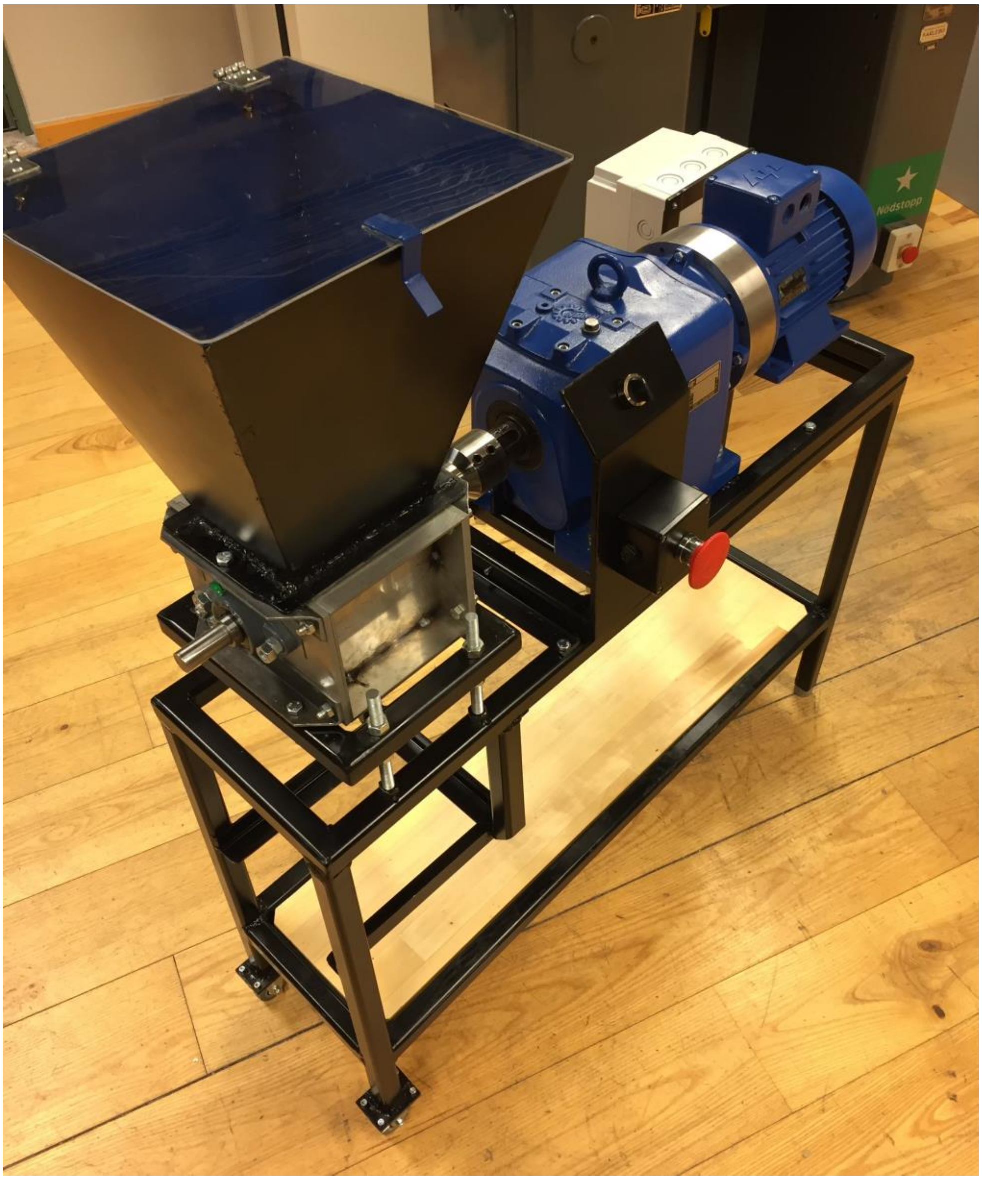

Figure 4.39 Finished Machine.

Figure 4.40 Finished Machine.

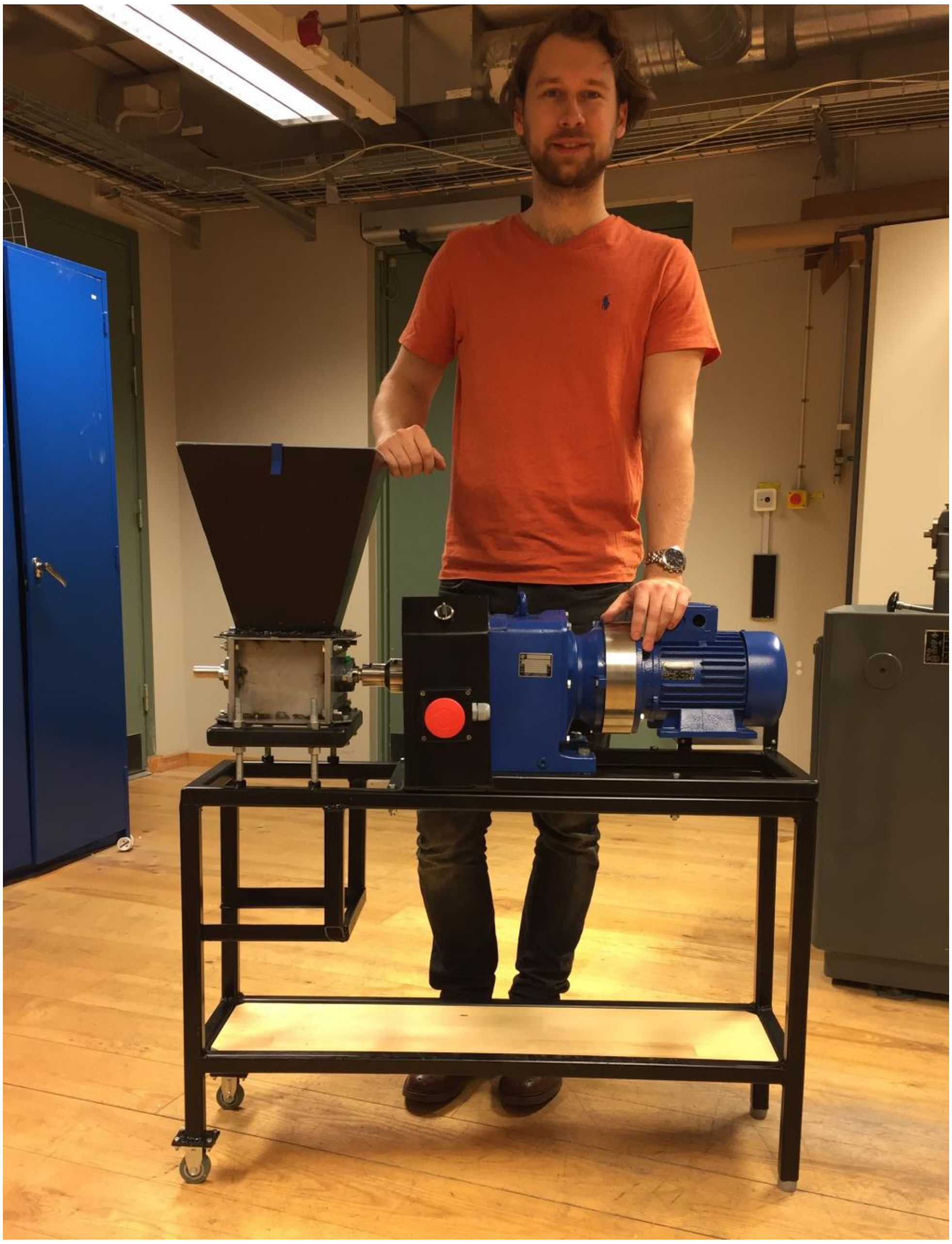

Figure 4.41 Finished machine, proudly presented by myself for scale.

5 Testing

5.1 Different sieves

The machine as designed by Hakkens uses a bent sieve made out of perforated sheet metal as seen in Figure 5.1 that attaches to the SSP under the knives. This is meant to keep the plastic inside the SSP till the shreds become small enough to pass through the holes of the sieve. Modifing the number and sizes of the holes changes the size of the shreds aswell as the processing time.

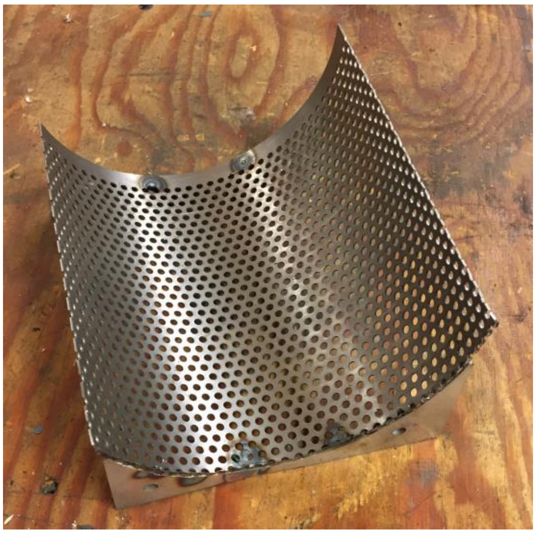

Figure 5.1 Sieve with a fine perforation.

As for the plastic that was shredded, plastic waste from the household was stored to this end. Most of it was made out of either PP, PET, PS or HDPE.

Naturally, testing the machine started without a sieve to see what size of shreds it would produce. As expected, the process was very quick and produced a wide range of shred sizes, as can be seen in Figure 5.2, where household waste made of PP were shredded. As the teeth of the knives are relatively long and there is little chance of cross-cutting, the pieces tended to be in the shape of long strands when shredding softer products with a lower material thickness, as compared to the seemingly random shapes seen in Figure 5.2. The wide spread of sizes makes it unsuitable for remelting in subsequent machines.

Figure 5.2 Different sizes when shredding without a sieve.

Not using a sieve turned out to be the prefered setup when shredding thin film of LD-PE. The shape of film when scrunched up to a loose ball made sure that the knives only cut small pieces at a time as they gradually pulled the plastic through the shredder. The film before and after shredding is shown in Figure 5.3.

Figure 5.3 LDPE-film before and after being shredded without a sieve.

The specifications did not state a recommended size of the perforation of the sieve so at first the smaller of two available sizes in the workshop was used. It had a hole diameter of 3 mm with a spacing and row distance of 6 mm. The resulting shreds turned out to be much finer compared to the un-sieved shreds. But the sieve turned out to be too fine for practical use. Instead of falling through the mesh at a reasonable rate, the majority of the shreds kept being swiveled around by the knives without noticable cutting action. As the shredder was fed more plastic, this mass of shreds became large enough to cause substantial sideways movement of the SSP. Increasing the clamping force on the rubber cushions that were installed between the SSP and its framework to reduce vibrations decreased this somewhat, but this means that the bearings absorbed those forces instead. This problem was attributed to two main issues. Firstly, the more obvious of the two, was that the perforation was simply too fine. The second was that the clearance between the knives and the sieve was too large for the knives to help push the shreds through the sieve.

The other perforation available had a considerably larger perforation than the finer one. Its hole size was 10 mm with a spacing of 20 mm and the same hole positioning as the finer perforation, as can be seen in Figure 5.4.

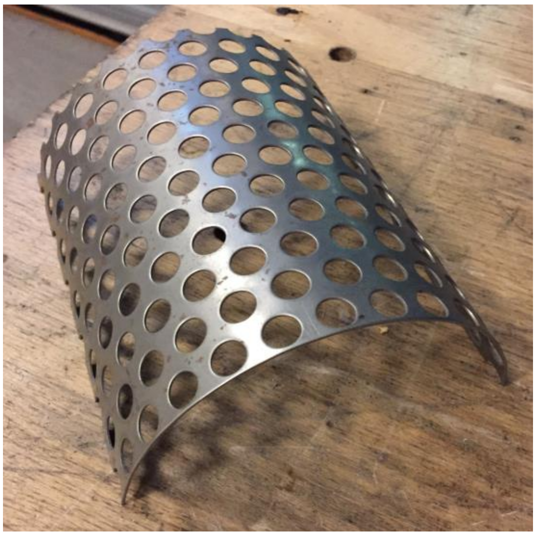

Figure 5.4 Sieve with a larger perforation.

The process time was, as expected, good enough for practical application and only had a minor buildup of material. The quality of the output, see Figure 5.5, turned out to be fine enough when shredding a mixture of PP, PET and PS.

Figure 5.5 Output quality from a mixture of PP, PET and PS when using the sieve with larger perforation.

5.2 Types of plastic waste

As this machine is meant to shred plastic waste, the different types of plastic that will be used in larger quantities is somewhat limited. Considering that the shredder will be located at IKDC, a majority of the plastic waste will most likely be made out of PET from plastic bottles and PP from assorted food containers. My understanding from reading posts at the Precious Plastic forum was that many of the machines with a weaker PSU had problems with plastic bottles. These are usually designed with thicker plastic at the necks which made the machines stop completely as the neck cloged the knives. The initial testing with softer PP waste showed signs of wear on the knives through chipping of their leading edge, as seen in Figure 5.6. It was decided to test PET bottles lastly in case they would cause any permanent damage. It turned out that worry was unfounded as no signs of trouble were noticed from the machine, even when shredding particularly thick bottles.

Figure 5.6 Chipping of the teeth after testing the shredder.

5.3 Result of knife configuration

During testing with the fine sieve it was noticed that the flow of edges worked better than anticipated as the vast majority of the buildup of material was pushed towards the center of the shredder.

6 Redesign

Even at the early stages of testing it was realized that despite whatever flaws had been found while building and testing the machine, it worked well enough not to warrant the cost and time it would take to build a new version of the SSP. The updated version would have to be limited to a detailed CAD model.

6.1 Number of shafts

The first design choice was whether to continue using a single shaft, as Hakkens did, or add a second shaft rotating counter to the first to reduce the problem of skipping mentioned in Chapter 3.2.1. Any more than that would be superfluous to the task that the shredder would be used for.

It was decided that the added complexity and cost of another shaft simply would not be worth the advantages it provides. Having dual shafts would also mean that the sieve would be more complex as it would need to be made almost in the shape of a “w” as opposed to a half circle. It would also make the shredder considerably bulkier. Large pieces of plastic would simply have to be cut into smaller pieces beforehand or be handled differently.

6.2 Knives

Secondly, the teeth of the knives needed a remodeling. As the cutting edges are the ones that work in conjunction with the counterknives of the housing, there were no discernible reason why they should be designed the way Hakkens are. His knives have a rounded leading face that ends in a very sharp point, as can be seen in Figure 6.1. Making it that sharp also makes it weak, which is apparent from the jagged cuts seen on the knives after testing. The round face likely mean that the material will also get pushed towards the middle of the teeth. The teeth have more cutting power closer to the shaft, similar to a pair of scissors, so they were simply redesigned with a straight leading face instead, see Figure 6.2.

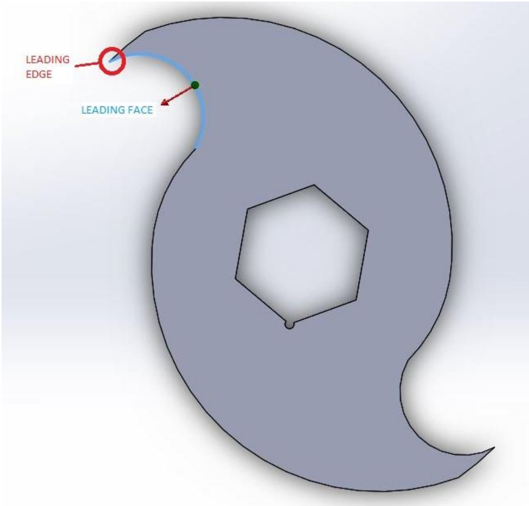

Figure 6.1 CAD view of Hakkes knives.

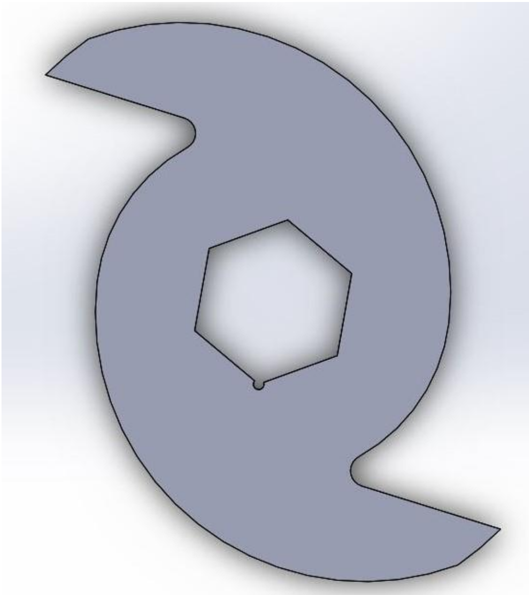

Figure 6.2 Redesigned knives with a straight leading face

6.3 Increasing the speed of the process

While Hakkens shredder may work adequately to what it is to be used for and produce fine enough shreds, it may be improved upon to provide even finer shreds at a reasonably rate. As mentioned in Chapter 5.1 using a finer sieve will provide finer shreds, but the process will take too long if theres not enough cutting action. The clearance between teeth and counterknives will also set a limit to how fine shreds you can make. To increase the number of cutting motions, however, only two options presented themselves: increase the speed and power of the PSU or increase the number of teeth and/or counterknives.

During the testing of the shredder it was observed that the recommended 70 RPM of the motor may be a bit high. Some of the stronger waste products created considerable forces when cut. Pieces could be thrown more than 2 meters away from the machine. Based on this, a slightly lower speed would be recommend; probably closer to 50 RPM.

Using knives with two teeth on the infeed seemed appropriate though. Any more than that would most likely make it more difficult to shred larger pieces.

6.3.1 More cutting actions

The conclusion was made that the infeed and outfeed needed to be separated to increase the number of cutting actions. The first idea was to extend the shaft and gradually increase the number of teeth on the knives, as can be seen in Figure 6.3. The eight-teethed knives at the end would significantly increase the number of cutting motions. Hakkens design uses counterknives on only one side of the machine. In addition to more knives the idea was to improve upon this by providing more counterknives per rotation after the infeed. One way to do that was to use spacer disks with holes cut into them in a circular pattern around the shaft hole to function as counterknives, see Figure 6.4.

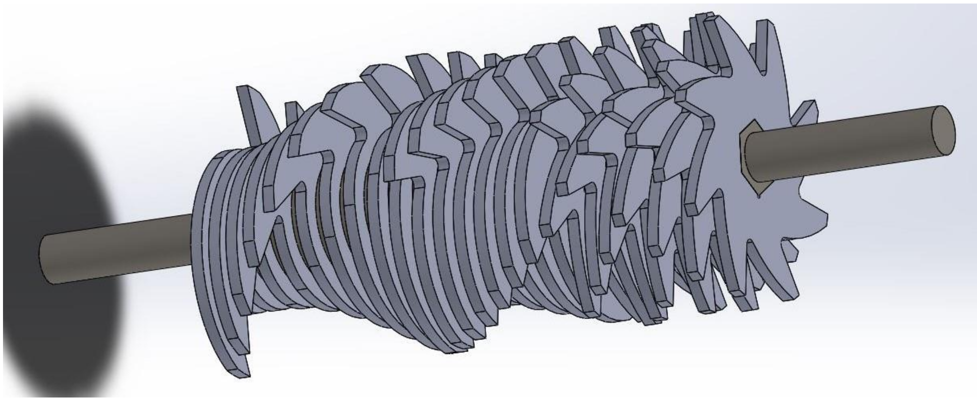

Figure 6.3 Extended shaft with increasing amount of teeth.

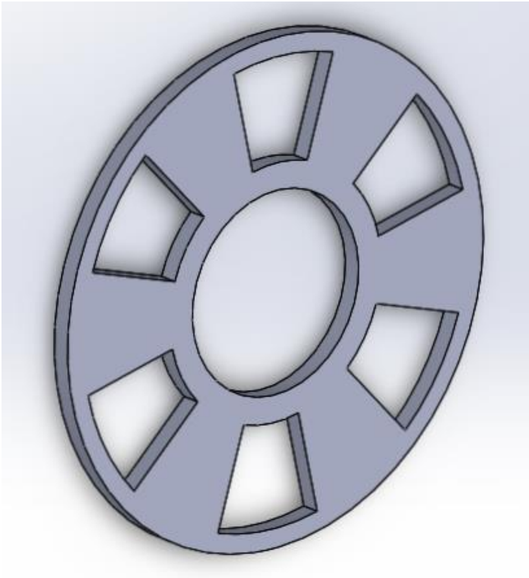

Figure 6.4 Redesigned counterknife.

6.3.2 Housing

This would then be mounted inside a pipe, with an opening cut into one end for infeed and another at the opposite end and side for outfeed, see Figure 6.5. Two major issues were noticed with this design. The first was that the counterknives would be very difficult to mount inside the pipe. Welding them on would be very difficult if not impossible. Heating the pipe before inserting shaft and counterknives could possibly hold them in place but maintaining their correct positions in regard to the knives could prove even more difficult. It would also mean that you could not disassemble the shredder without cutting the pipe open.

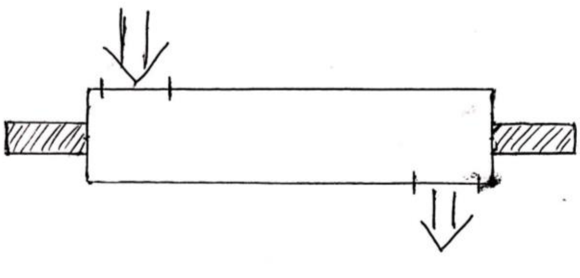

Figure 6.5 Conceptual image of knives mounted in a pipe where infeed and outfeed are marked by arrows.

It was decided instead to integrate the housing with the counterknives by adding outer spacers and ears to the counterknives where threaded bars would be used to tighten the design, see Figure 6.6. The idea was to use the configuration of the knives to push the shreds through the pipe-like design to the end with more teeth and the outlet; alternatively while also tilting the shredder at a slight angle so that gravity would help aswell.

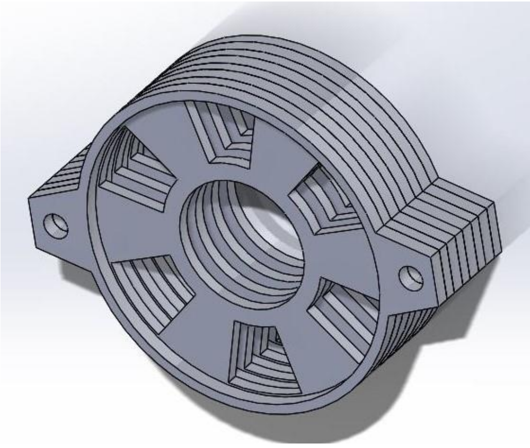

Figure 6.6 Integrated housing with spacers and counterknives.

Finally, the middle step between infeed and outfeed that had four teeth per knife was removed to make more room for the infeed. There were some problems during testing with large pieces of waste skipping on the knives of Hakkens design due to the infeed being too small. Modifying a spacer created the infeed, outfeed, endplates and ears were added to attach a hopper, see Figure 6.7.

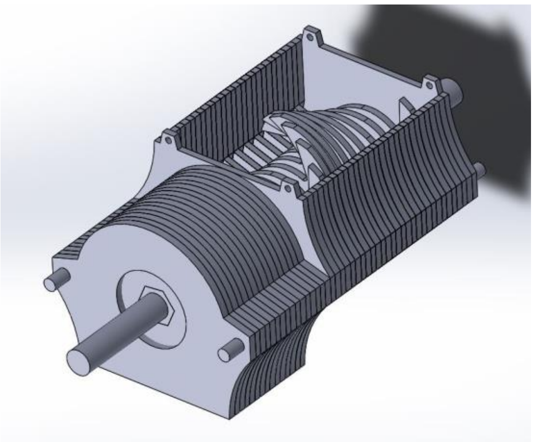

Figure 6.7 Extended infeed and modified housing.

6.3.3 **Bearing bolts**

As seen in Figure 6.8 the heads of the bolts that hold the bearings in Hakkens design rests right where the outer knives rotate. There was some worry that the vibrations of the machine might eventually loosen the bolts enough to put them into the path of the knives, which would most likely destroy the machine. To avoid this, the bearings were mounted on an external bracket that would in turn be fastened to the outer endplate by the same threaded bars that held the rest together to maintain alignment. Furthermore, the hole sizes for the bolts were changed to match those of the bearings since this caused a lot of trouble during assembly, see Figure 6.9.

Figure 6.8 Bearing bolts.

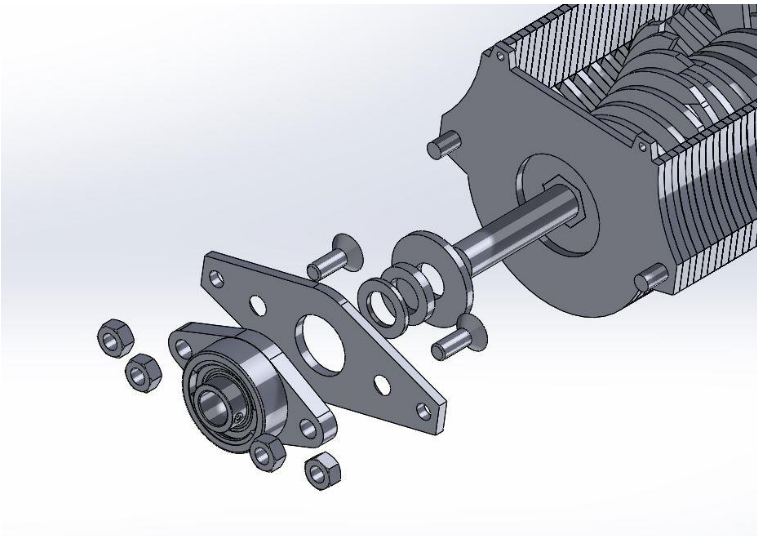

Figure 6.9 Exploded view of redesigned bearing assembly

6.3.4 **Sieve**

While the sieve in Hakkens shredder is fairly easy to remove and attach, it is slightly more complex to fit while building it. Welding the perforated sheet to its supports also splashed small beads of metal on the knives and knife spacers, see Figure 6.10. These were difficult to remove and they ground against the housing and counterknives.

Figure 6.10 Splashed beads of metal from welding the sieve to its supports.

To improve upon this, the idea was to design a sieve that you could somehow slide into the machine without having to weld it to anything. By adding slits in the spacers, a sieve with bent ends should be able to be slide in and out with an end cap to keep it in place, see Figure 6.11.

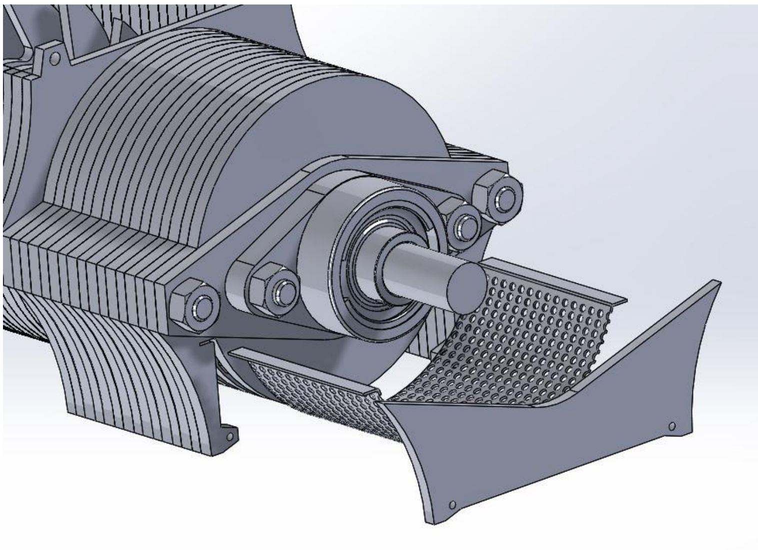

Figure 6.11 Exploded view of the redesigned mesh assembly.

6.3.5 Final design

This resulted in a new and final design shown in Figure 6.12-Figure 6.14.

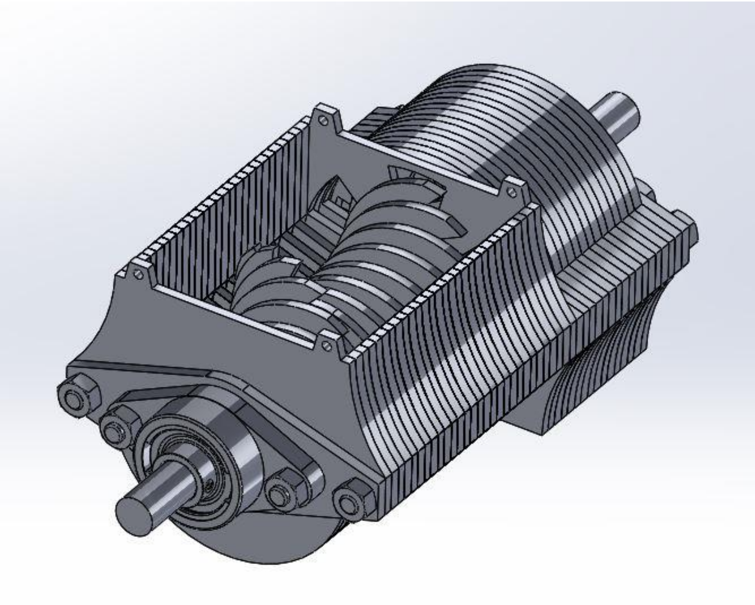

Figure 6.12 Final redesign.

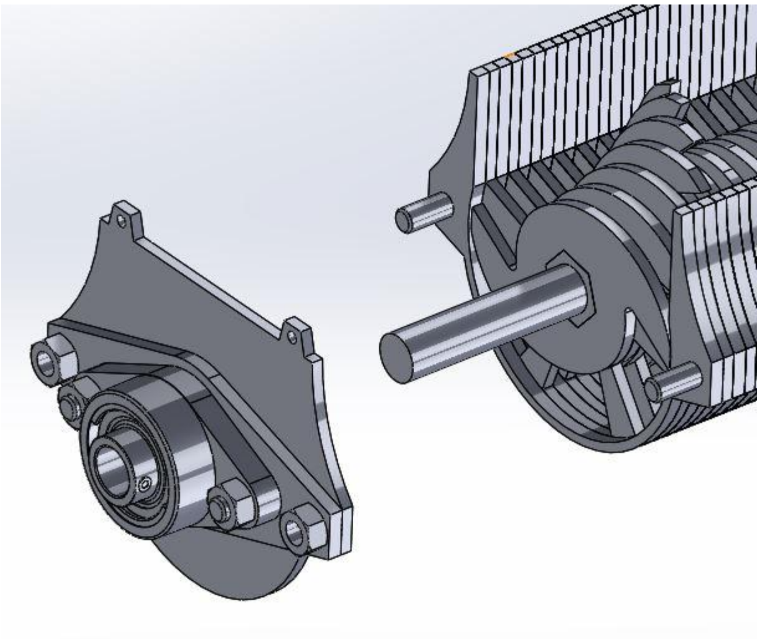

Figure 6.13 Final redesign - exploded view.

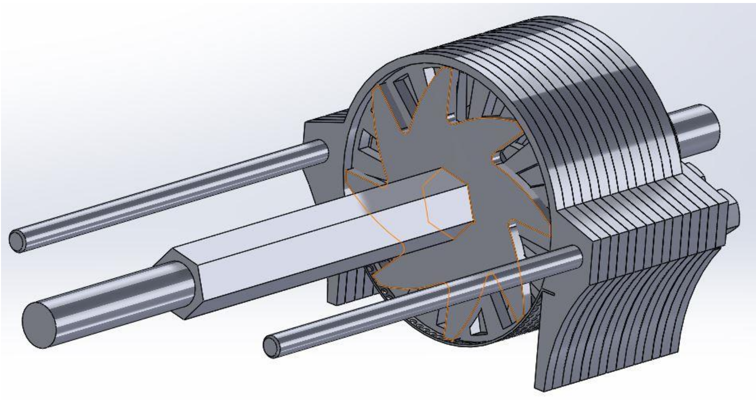

Figure 6.14 Final redesign - exploded view.

6.3.6 Additional changes made to Hakkens design during building

To make the machine more mobile the intended feet of the framework, see Figure 6.15, were changed to a pair of wheels in one end and rubber knobs in the other, see Figure 6.16. It is still cumbersome to move but certainly a lot easier than the original design.

Figure 6.15 Feet of the framework as designed by Hakkens.

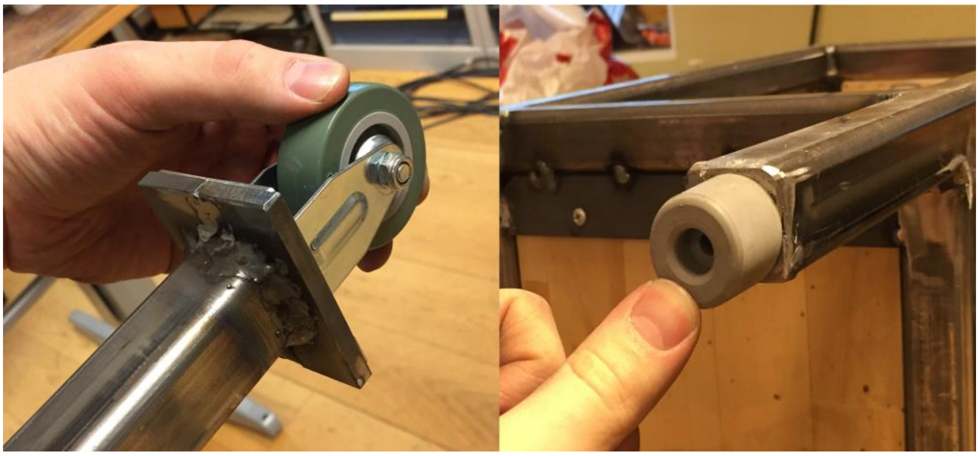

Figure 6.16 Redesigned feet of the framework.

For obvious safety reasons, a hinged transparent lid to the hopper was added with a small handle. This also prevents pieces from being thrown out of the machine. Also for the sake of safety an emergency stop button was added which Hakkens design did not have.

The very large collector that would stand at the shelf and reach up to the bottom of the SSP as Hakkens designed and shown in Figure 3.1 seemed unnecessary. To make it easier to handle, a simple rail to hold a smaller collector was opted for instead, see Figure 6.17. This had the added benefit of leaving more free space at the shelf.

Figure 6.17 Slide rail for a smaller collector.

7 Discussion

Early on it was realized that the total cost of 180 EUR projected in Appendix B would probably not be enough and seemed unreasonably low. Through sheer luck a motor and gearbox was found for a total of 450 SEK (~45 EUR) which was surprisingly cheap, while the Bill of Materials estimates the cost to only 30 EUR. Without that luck, the gearmotor or a motor with a different reduction would by far have been the driving cost of the machine. The total cost of the machine would therefore in most cases likely have been much higher than the projected.

Ideally it would have been preferable to play around with the configuration of the knives to see if a different setup might have worked better. Unfortunately, the margins were really small and the assembly was very difficult to get just right to make it run smoothly. It was simply not worth the effort to take it all apart again when it worked as well as it did.

During the planning phase a misstake was made in not checking that the holesizes of the shredders housing matched the holesizes of the bearings. The distance between the bolt holes of the bearing house for the shaft diameter was the same as the distance on the housing so it was assumed to be standardized. This caused a lot of trouble during assembly that would have been easily avoided had the holes of the housing been modified in the drawing.

As previously mentioned the plan was to get as close to the 2 kW and 70 RPM PSU recommendations as possible. Posts on the Precious Plastic forum told of some problems when using weaker setups. In hindsight though, a significantly weaker motor would likely have sufficed, coupled with a slightly slower speed to retain some of the torque. Plenty of weaker used gearmotors were found that might have worked fine but was ignored. Had a complete PSU with the right specifications been found, that would have been perfect. But as it turned out, connecting the motor and gearbox took a lot more time than anticipated. Using a complete and ready motor would have saved the roughly 7-8 weeks it took to design different setups of the PSU and ultimately building the final PSU. Granted, a few other parts of the project were worked on during this time. But as much of it was dependent on the PSU most of the time was dedicated to completing it. Considering the low price for the motor and gearbox a lot of money was saved compared to buying a new one or even a used one with similar specifications. In the end, it was probably not worth the time spent for the extra power gained and the money saved.

A considerable amount of time was also lost due to the fitting of all the different pieces. Increasing the margins in the drawings could have solved this but it could also have invited other troubles if they were made too large. As the schools workshop had a waterjet cutter it was decided to cut all the pieces in-house using this. Hakkens instructions however assume that a laser cutter is used which has a more precise cut. If the pieces had been ordered from an external company with a new laser cutter the margins as designed might have been sufficient.

By only adding wheels in one end of the framework it was thought to be easy enough to move around while also retaining some of the stability offered by stationary feet. Due to the weight of the machine being positioned as high up as it is, it is still a bit wobbly to move around. To anyone building a similar machine, it would be recommend to make the base a bit wider to improve stability. Wheels with brakes should also be mounted instead of the now stationary end to make it even more mobile.

Regarding the holes making up the circularly patterned counter knives in the redesign, it is possible that it was a bit too eager in create more cutting action. Without testing the design it is difficult to anticipate how it would behave, It is possible that the holes were made too small and that those same spacers would act more as a blockage in an actual live test. Unfortunately, the only way to get a realistic idea of how it would work is by building and testing it.

A considerable advantage of the new design is that its very easy to modify to your needs. With a strong PSU, as was used in this project, it would not take any effort at all to elongate it and create more space at both the inlet and outlet. If one did not want to separate the inlet and outlet it would still be recommend to somehow integrate the design of the new outlet and its sliding sieve with the inlet.

A thing to note is that all the plastic waste used during the testing was cleaned beforehand and most of the labels were removed. Using dirty plastic was never tested but as stainless steel was used for all the shredder parts, cleaning it should be as simple as placing a plastic container under the shredder and pouring water with perhaps soap added over it while running the machine. The shreds would of course also have to be cleaned before using them to create new products. Depending on the kind of dirt left on the waste however, it would likely cause problems with shreds sticking to the machine instead of passing through the sieve.

One thing that could be improved upon for any future versions of the machine is the lid. It sorely needs a lid to keep plastic from jumping out of the machine, but to help the shredding process the material often needs to be pushed towards the knives. Integrating some kind of tool to force the plastic when it skips on top of the knives with a sturdy lid would be a great improvement to its operation.

There are also likely numerous possible changes to be made when it comes to the safety of the machine. One would be a microswitch mounted in the lid to stop the machine when opening it. This would however require a solution to the previously mentioned problem of plastic skipping on top of the knives as the lid needs to be opened to force down the plastic. Another solution might be to build a different kind of hopper where the feeding of the machine is made in a way that you cant get your hands into the knives. There is also the safety concern of the open connection between PSU and SSP. Some kind of casing should be made to protect the operator from clothes and hair getting caught in it.

8 Conclusion

The goals of building a machine that can shred plastic waste into fine enough shreds to be usable in future machines for producing new products were met. The PSU was also made into a module by attaching it to a separate frame that fastened to the mainframe by three bolts.

The final redesign provides an increase in the cutting action rate which, if working as intended, should produce an increase in performance aswell as output. By integrating the housing with the counterknives and spacers, the assembly was greatly simplified through stacking of the knives, counterknives and different spacers on the knife shaft and then tightening it with two threaded bars after adding the endplates. The changing between different sieves to produce other quality of output should also see a substantial improvement for user friendliness.

The material costs of building the machine was managed to be kept to a minimum, though at a cost of greatly increased building time.

While unfortunately not being able to build the new design myself due to time and cost restraints, I am very proud of the results in both the machine that was built, the changes made from Hakkens design of it and the new design that resulted from the testing. The project has taught me a lot aswell as tested my abilities while still fulfilling the requirements set on it at the outset.

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Figures

Figure 3.1 A general view of the shredder as built by Precious Plastic. https://github.com/hakkens/precious-plastic-kit/archive/master.zip

Figure 3.2 SSP where knives (green) and counterknives (red) are marked. https://github.com/hakkens/precious-plastic-kit/archive/master.zip

Figure 3.3 Two pieces with puzzle shaped connectors. Slits dependent on sheet metal thickness marked by arrow.
https://github.com/hakkens/precious-plastic-kit/archive/master.zip

Figure 3.4 Four shaft shredder.
http://www.stokkermill.com/wp-content/uploads/2015/05/quadrialbero.jpg

Figure 3.5 Left: shredder knives as designed by Precious Plastic. Right: Assorted industrial shredder knives.
Left: https://github.com/hakkens/precious-plastic-kit/archive/master.zip.
Right: http://3.imimg.com/data3/BG/YM/MY-7296216/shredder-cutters-500x500.jpg

Figure 3.6 Triangular teeth and counterknives.
http://www.cmg-america.com/assets/images/loop-settori/single-shaft-shredders.jpg

Figure 3.7 Paper shredder with hook knives.
http://gsa.machine-solution.com/Shared/images/highsecuritypapershredders.jpg

Figure 4.1 Dave Hakkens angular geared motor.
https://github.com/hakkens/precious-plastic-kit/archive/master.zip

Figure 4.2 Worm gear from Liljenbergs AB.
http://www.liljenbergs.com/Images/products/snackvaxel_small.jpg

Figure 4.3 Jaw coupling.
Left: http://3.imimg.com/data3/NA/EE/MY-4199678/jaw-coupling-250x250.jpg.
Right:
http://www.abssac.co.uk/uploads/site/products/p_ye7di/img_CouplingKKa.jpg

Figure 4.8 The basic setup of a worm gear.
http://s.hswstatic.com/gif/gear-worm.jpg

Figure 4.9 Coaxial gearmotor.
http://www.busck.se/wp-content/uploads/ps-mi-t3a90s-4.png

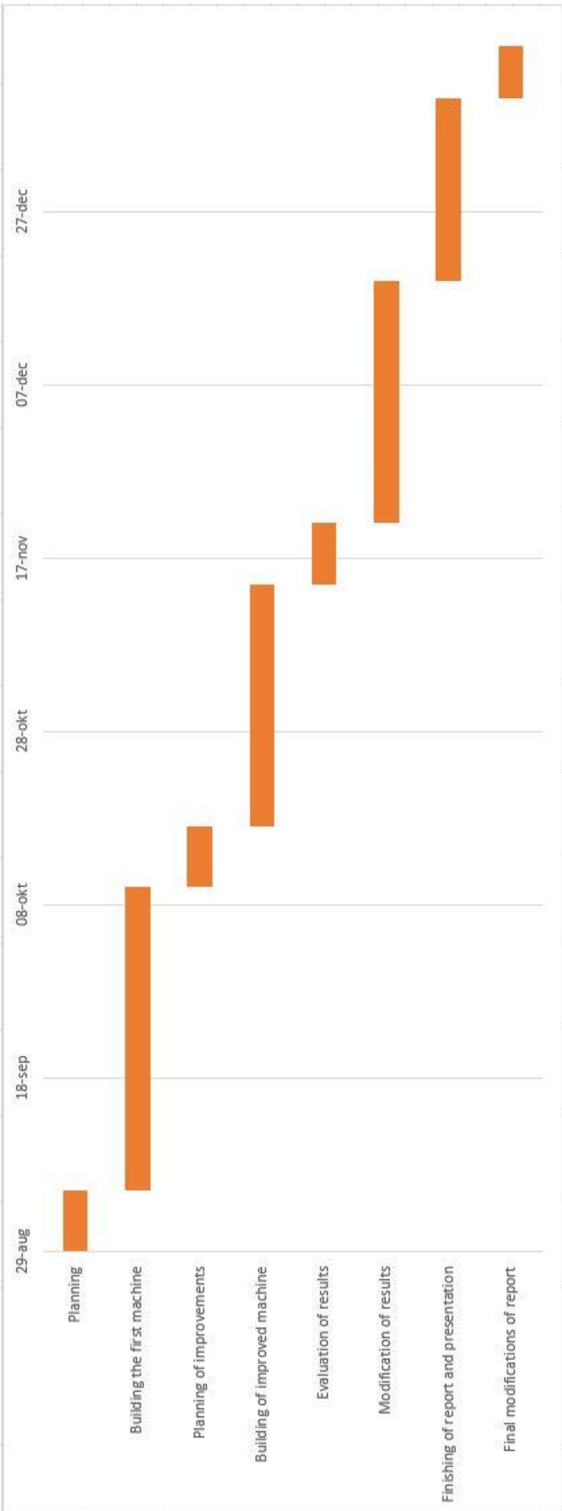
Figure 4.10 V-belt drive (left) and Ribbed belt drive (right).
Left: http://www.monarchbearing.com/images/import/images/poly-v-belt-drives.jpg.
Right:
http://4.bp.blogspot.com/_fEJbY0LcQ2w/TI9mZwW7TKI/AAAAAAAAACM/zu_-LpyAsIc/s1600/fenner-v-belts.jpg

Figure 4.11 Ribbed belt as a timing belt for the camshafts of a car engine.
http://www.carscope.com/wp-content/uploads/2016/01/TimingBeltV6.jpg

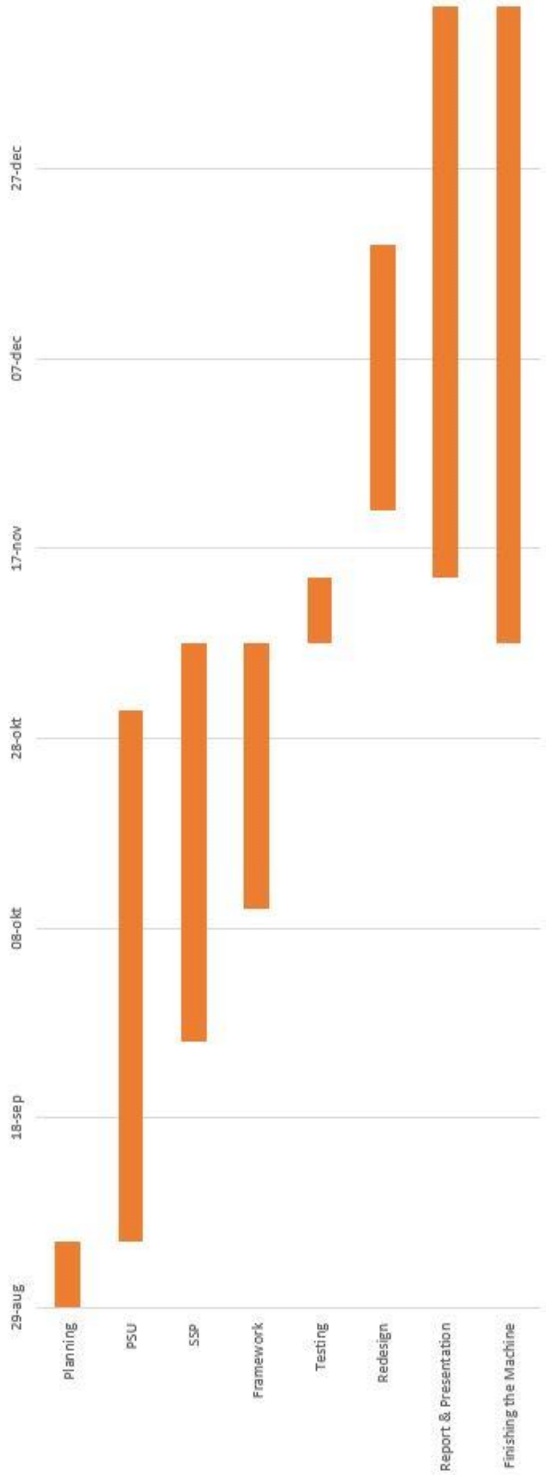
Figure 6.15 Feet of the framework as designed by Hakkens.
https://github.com/hakkens/precious-plastic-kit/archive/master.zip

Appendix A Project Plan

As can be seen in the following project plans they differ a lot. The first one shows the original plan before starting the project. When made, I had no idea how long time the different steps would take and tried to decide upon an ideal plan. The second one shows approximately how long the different steps took and when they were started. I was planning on building the machine from Hakkens in five weeks, which in actuality took 9 weeks (excluding the finishing steps that were not necessary to test the shredder). Although, as can be seen in the second plan, many of these weeks were spent on the PSU. Had I found a ready gearbox early on I could have spent all that time on the SSP and framework which would have shortened their build time significantly. In the first plan I assumed that I would be working on the report continuously throughout the project. I did not start on it until about halfway through the project. In hindsight I should probably have started a month earlier to give myself more time.



Planning
Building the first machine
Planning of improvements
Building of improved machine
Evaluation of results
Modification of results
Finishing of report and presentation
Final modifications of report
29-aug
18-sep
08-okt
28-okt
17-nov
07-dec
27-dec


29-aug
18-sep
08-okt
28-okt
17-nov
07-dec
27-dec
Planning
PSU
SSP
Framework
Testing
Redesign
Report & Presentation
Finishing the Machine

Appendix B – Bill of Materials

Bill of Materials as provided by Precious Plastic.

Bill of materials shredder

Description	Material	Details	Quantity	Where to get it	Remarks	Price
Machine parts						
3mm sheet	steel	cutted	1x	Scrapyard/Hardware store	optional stainless steel	30
5mm sheet	steel	cutted	1x	Scrapyard/Hardware store	optional stainless steel	40
6 mm sheet	steel	cutted	1x	Scrapyard/Hardware store	optional stainless steel	40
● Hexagon bar	Steel	27M	32cm	Metal shop		15
L Angle profile	Steel	30x30x3mm	100cm	Scrapyard		10
Mesh	metal	150x180x1.5mm		Scrapyard	perforated sheet or drill holes yourself	2
Sheet metal	Steel	1mm		Scrapyard		7
Electronics						
Motor	-	+/- 2kw	1x	Scrapyard	preferable +/- 70 RPM	30
Power switch	-		1x	Scrapyard/Hardware store		3
Led indicator	-	220V	1x	Hardware store		3
Powercord	-		5 M	Scrapyard/Hardware store		
				Total		€180 Price varies depending on where you live

Appendix C - Power transmission per belt

The following table shows the power transmitted per belt by speed and diameter of the smallest pulley for a profile SPZ belt from Trelleborg AB. Text of image in swedish.

Effektberäkning

Profil SPZ

Kraftöverföring (P_b) per rem för profil SPZ i kW (avser den minsta skivan i remtransmissionen)

Diameter / Varv/min	63	71	75	80	85	90	100	106	112	118	125	132	140	150	160	170	180
100	0,10	0,13	0,15	0,16	0,18	0,20	0,24	0,26	0,28	0,30	0,33	0,35	0,38	0,41	0,45	0,48	0,52
200	0,18	0,24	0,27	0,30	0,34	0,37	0,44	0,48	0,52	0,56	0,61	0,66	0,71	0,78	0,85	0,91	0,98
300	0,25	0,34	0,38	0,43	0,48	0,53	0,63	0,69	0,75	0,81	0,88	0,95	1,03	1,13	1,23	1,32	1,42
400	0,32	0,43	0,48	0,55	0,62	0,68	0,82	0,90	0,97	1,05	1,14	1,23	1,34	1,46	1,59	1,72	1,84
500	0,39	0,52	0,59	0,67	0,75	0,83	0,99	1,09	1,19	1,28	1,39	1,51	1,63	1,79	1,94	2,10	2,25
600	0,45	0,61	0,68	0,78	0,88	0,98	1,17	1,28	1,40	1,51	1,64	1,77	1,92	2,11	2,29	2,47	2,66
700	0,51	0,69	0,78	0,89	1,00	1,11	1,34	1,47	1,60	1,73	1,88	2,03	2,20	2,42	2,63	2,84	3,05
725	0,52	0,71	0,80	0,92	1,03	1,15	1,38	1,51	1,65	1,78	1,94	2,10	2,27	2,49	2,71	2,93	3,14
800	0,56	0,77	0,87	1,00	1,12	1,25	1,50	1,65	1,80	1,94	2,12	2,29	2,48	2,72	2,96	3,20	3,43
900	0,62	0,85	0,96	1,10	1,24	1,38	1,66	1,83	1,99	2,16	2,35	2,54	2,75	3,02	3,28	3,55	3,81
950	0,64	0,89	1,00	1,15	1,30	1,45	1,74	1,92	2,09	2,26	2,46	2,66	2,88	3,16	3,44	3,72	3,99
1000	0,67	0,92	1,05	1,20	1,36	1,51	1,82	2,00	2,18	2,36	2,57	2,78	3,02	3,31	3,60	3,89	4,17
1100	0,72	1,00	1,13	1,30	1,47	1,64	1,98	2,17	2,37	2,57	2,80	3,02	3,28	3,60	3,91	4,23	4,53
1200	0,77	1,07	1,22	1,40	1,58	1,77	2,13	2,34	2,56	2,77	3,01	3,26	3,54	3,88	4,22	4,55	4,89
1300	0,82	1,14	1,30	1,50	1,69	1,89	2,28	2,51	2,74	2,97	3,23	3,49	3,79	4,15	4,52	4,88	5,23
1400	0,87	1,21	1,38	1,59	1,80	2,01	2,42	2,67	2,92	3,16	3,44	3,72	4,03	4,43	4,81	5,19	5,57
1425	0,88	1,23	1,40	1,61	1,83	2,04	2,46	2,71	2,96	3,21	3,49	3,78	4,10	4,49	4,88	5,27	5,65
1500	0,91	1,28	1,46	1,68	1,91	2,13	2,57	2,83	3,09	3,35	3,65	3,94	4,28	4,69	5,10	5,50	5,90
1600	0,96	1,34	1,54	1,77	2,01	2,25	2,71	2,99	3,26	3,54	3,85	4,16	4,52	4,95	5,38	5,81	6,22
1700	1,00	1,41	1,61	1,86	2,11	2,36	2,85	3,14	3,43	3,72	4,05	4,38	4,75	5,21	5,66	6,10	6,54
1800	1,04	1,47	1,69	1,95	2,21	2,47	2,99	3,30	3,60	3,90	4,25	4,59	4,98	5,46	5,93	6,39	6,84
1900	1,08	1,53	1,76	2,04	2,31	2,58	3,13	3,45	3,76	4,08	4,44	4,80	5,20	5,70	6,19	6,67	7,14
2000	1,12	1,60	1,83	2,12	2,41	2,69	3,26	3,59	3,92	4,25	4,63	5,00	5,42	5,94	6,45	6,94	7,43
2100	1,16	1,66	1,90	2,20	2,50	2,80	3,39	3,74	4,08	4,42	4,81	5,20	5,64	6,17	6,70	7,21	7,71
2200	1,20	1,71	1,97	2,28	2,60	2,91	3,52	3,88	4,24	4,59	5,00	5,40	5,85	6,40	6,94	7,47	7,98
2300	1,24	1,77	2,04	2,36	2,69	3,01	3,64	4,02	4,39	4,75	5,17	5,59	6,05	6,62	7,18	7,72	8,24
2400	1,27	1,83	2,10	2,44	2,78	3,11	3,77	4,15	4,54	4,91	5,35	5,77	6,25	6,84	7,41	7,96	8,49
2500	1,31	1,88	2,17	2,52	2,87	3,21	3,89	4,29	4,68	5,07	5,52	5,96	6,45	7,05	7,63	8,19	8,74
2600	1,34	1,94	2,23	2,59	2,95	3,31	4,01	4,42	4,83	5,23	5,68	6,13	6,64	7,25	7,84	8,42	8,97
2700	1,37	1,99	2,29	2,67	3,04	3,40	4,12	4,55	4,96	5,38	5,85	6,31	6,82	7,45	8,05	8,63	9,19
2800	1,41	2,04	2,35	2,74	3,12	3,50	4,24	4,67	5,10	5,52	6,00	6,47	7,00	7,64	8,25	8,84	9,40
2850	1,42	2,07	2,38	2,77	3,16	3,54	4,29	4,74	5,17	5,59	6,08	6,56	7,09	7,73	8,35	8,94	9,50
2900	1,44	2,09	2,41	2,81	3,20	3,59	4,35	4,80	5,23	5,67	6,16	6,64	7,17	7,82	8,44	9,04	9,60
3000	1,47	2,14	2,47	2,88	3,28	3,68	4,46	4,92	5,36	5,80	6,31	6,80	7,34	8,00	8,63	9,22	9,79
3200	1,53	2,23	2,58	3,01	3,44	3,85	4,67	5,15	5,61	6,07	6,59	7,10	7,66	8,33	8,97	9,57	10,14
3400	1,58	2,32	2,69	3,14	3,58	4,02	4,87	5,37	5,85	6,32	6,86	7,38	7,95	8,63	9,27	9,87	10,43
3600	1,63	2,41	2,79	3,26	3,72	4,18	5,06	5,57	6,07	6,56	7,11	7,64	8,22	8,90	9,54	10,13	10,68
3800	1,68	2,49	2,89	3,38	3,86	4,33	5,24	5,77	6,28	6,78	7,34	7,87	8,46	9,14	9,78	10,35	
4000	1,72	2,57	2,98	3,49	3,98	4,47	5,41	5,95	6,47	6,98	7,55	8,09	8,67	9,35	9,97		
4200	1,76	2,64	3,06	3,59	4,10	4,60	5,56	6,12	6,65	7,16	7,74	8,28	8,86	9,52			
4400	1,80	2,70	3,14	3,68	4,21	4,72	5,71	6,27	6,81	7,33	7,90	8,44	9,01	9,66			
4600	1,83	2,76	3,22	3,77	4,31	4,84	5,84	6,41	6,96	7,47	8,05	8,58	9,14				
4800	1,86	2,82	3,28	3,85	4,41	4,94	5,96	6,54	7,08	7,60	8,17	8,69					
5000	1,88	2,87	3,35	3,93	4,49	5,04	6,07	6,64	7,19	7,71	8,26	8,77					
5200	1,90	2,91	3,40	3,99	4,57	5,12	6,16	6,74	7,28	7,79	8,33						
5400	1,91	2,95	3,45	4,05	4,63	5,19	6,24	6,82	7,36	7,85							
5600	1,93	2,98	3,49	4,10	4,69	5,26	6,30	6,88	7,41	7,89							
5800	1,93	3,01	3,53	4,15	4,74	5,31	6,35	6,92	7,44								
6000	1,94	3,03	3,56	4,18	4,78	5,35	6,39	6,95									

Anmärkning: Det gråfärgade området indikerar periferihastigheter större än 30 m/s. Det är därför nödvändigt att använda dynamisk balanserade remskivor.

En reduktion i kilremmens livslängd kan förväntas inom detta område. För remskivor som faller inom det färgade området är det rekommenderat att använda det lägre området.