Developing a plastics recycling add-on for the RepRap 3D printer

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Abstract

The main theme of this paper is using domestic waste plastic to create new plastic products. A brief research is conducted in the granule-making field. This research functions as the foundation in selecting the right domestic appliance for creating granule of the right size for a small extruder. This had to be done in a way that regular people must be able to copy this process, so this should be as easy as possible.

Parallel to this a literature review was conducted to find the right extruder principle for the creation of a mini extruder. A principle was selected and with the help of experts in the field of 3D printing and extruding this principle was evolved to a design. After lots of trial and error this design has been transformed into a working prototype.

With this prototype five tests were conducted. These tests proved to be very valuable in obtaining new insight in problems that still have to be overcome. The most important problems that were faced are getting the right accuracy in the tolerances, heat development in the granule making process and creating a good granule feed flow for the extruder. While trying to solve these problems other point of interest came along. This research can be seen as the starting point of the development of a new kind of domestic extruder.

Keywords,
Extrusion, granule extruder, mini extrusion, RepRap, 3d printing, domestic, plastics, recycling
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1. Introduction

The RepRap is a 3D printer that is available for Western households. The technology behind the RepRap is open source and thus available online for free. All the printer’s plastic parts can be printed by the printer itself.

The idea behind the RepRap is that it can produce products based on digital files one can download from the Internet or on CAD models which can be created by the owner of the RepRap. This way of producing articles will reduce transportation cost and the 3D printing process is efficient in material use. The big drawback, however, is that when people start to design products themselves with CAD software, the chance of misprinting objects increases. Misprints will result in waste. Next to this, lots of homes produce a giant amount of plastic waste. It would be very interesting to use these two waste flows to create new products.

Therefore the purpose of this research is to explore the possibility to use domestic waste plastic as input for the RepRap. This exploration will be extended by an experiment involving two steps. The first step is creating granule sized material from a commercial product that can be used as input material. The second step is using granule to create an extrusion flow. The result of this research is an idea of the feasibility of this concept and a conceptual printer head design. The next step is fitting the prototype to the RepRap. The final printer head should only consist of parts that are either printable or easy accessible for normal consumers, to fit the RepRap philosophy.

This research is carried out for the Bachelor elective course ‘Prototyping Lab’ at the faculty of Industrial Design Engineering of Delft University of Technology. In 10 weeks, the project was executed by a team of 4 students working half-time on it.

Since all team member were new in the world of rapid prototyping and the RepRap, first a literature review was carried out to determine interesting fields for a research, of which the granule extruder was chosen. In chapter 2 of this report, the findings of our review about the RepRap can be found. In chapter 3 the process of converting a plastic object to granule can be found. The process of changing this granule into an extrusion, actions and tests carried out for developing the extruder can be found in chapter 4. A vision on how the results of this project can be adapted to an extruder that can be placed on the RepRap are found in chapter 5, while conclusions and recommendations of the project can be found in chapter 6 and 7, respectively.

Our special thanks go out to Adrie Kooijman for his supervision, Jouke Verlinden for coordinating the course, Martin Verwaal for helping us with the test setup, Rolf Koster for his advice on the properties of plastics and extrusion characteristics and Kevin Kamman from the TU Delft PMB for helping us with machining the different parts.
In the beginning of this project, a literature review was carried out. The goal of this review was to gain some insight in the RepRap project and to determine a goal for the project. After the review, the subject of creating a recycling add-on for the printer was determined. An extract of the review, with a focus on the parts about the RepRap project, can be found in this chapter.

The RepRap 3D printer project is, according to their creators, "a project to save the world... or at least to improve it". The project is initiated by Adrian Bowyer, member of the Department of Mechanical Engineering at the University of Bath, United Kingdom. The first RepRap machine was the Darwin, completed in October 2008, see figure 2.1. Recently a new version, the Mendel, was released, having various improvements like a bigger print area, simpler assembly and a higher efficiency.

At Delft University of Technology, a Darwin printer created from a Bits from Bytes kit, is assembled by a previous project group. Bits from Bytes is an online reseller, selling complete RepRap kits made from plexiglass. The available printer is a RepMan version 3.1.

Building a complete printer costs about $400 when producing all the parts at home, while commercial kits are available starting from $1200.

2.1 RepRap philosophy

No current engineering manufacturing process is capable of exponentially expanding production, because none use self-replication. John von Neumann was the first person to propose self-replicating machines back in the 1960s.

The RepRap is built on the idea that anyone could manufacture products, anywhere in the world. It is an open-source project, with the goal to enable relatively low-cost 3d printing. This is realized by engineering a printer, using mostly simple standard components and of course the fact that both soft- and hardware are open-source. The hardware blueprints are available for free, so parts for the printer can be produced at home. This leads to the next characteristic of the RepRap. Its name stands for REPlicating RAPid-prototyper: this means that the machine should be able to print the parts for a new printer. At this moment the RepRap can fabricate up to 50% of its own components. To create the first RepRap of a family one can use a so called RepStrap.

The RepStrap project has been set-up to help people build there own RepRap machine without using an already existing RepRap machine. The goal of RepStrap is that anyone (no matter what education) can build his own complete RepRap only using tool and materials commonly available. Once someone has built his own RepRap machine, the printer is able to replicate itself and produce other useful parts. In this philosophy, the number of RepRap printer should be able to grow exponentially.

2.2 Working principle

The machine is composed of a frame, built out of standard thread rods and printed parts. A platform, where the parts are meant to be built on, can move in the frame along the vertical axis. A stepper motor drives this platform up and down by using movement threads. On top of the frame rests the print head, which extrudes a thin layer of molten plastic to form a layer on the base platform. The extruder is moved along the horizontal axes by two stepper motors and toothed belts.
The RepRap project

2.3 Crowdsourcing

Since the RepRap project is open-source, everyone that wants to help should be able to share thoughts and knowledge about the process. This happens through various channels. The official website, RepRap.org, contains extensive user forums and a wiki about all developments. Next to that, various projects keep track of their progress on their own weblogs.

To incorporate this means of crowd-sourcing in this project, an online weblog was set up at WordPress.com. It is available at http://reprapdelft.wordpress.com. This weblog was updated regularly with updates on the progress and results of the process. Comments were posted by other RepRap enthusiasts, which varied from encouragements to fresh ideas to serious feedback on the progression. All questions were answered and discussed, to accentuate that the message was read and processed.

At the end of this project, this report will be put online on the weblog, to ensure it is available for everyone that is willing to further investigate the subject and to emphasise on the open-source character of it.
3. From product to granule

The first part of this research is based on the question how a common, thin walled, plastic product can be turned into granule. This granule should be used in the extruder head that is being developed. In this chapter, the milk bottle and its properties, different shredding methods, the conducted tests and the issues that emerged will be discussed.

3.1 Background

Chosen product
For this research, it was chosen to deal with a specific product, since this enables a focus on processing one specific material instead of all plastics in general. A milk bottle was chosen because it is a common object and made of a recyclable plastic, which also can be extruded on the RepRap\textsuperscript{14}.

![Figure 3.1 - Examples of the milk bottles used.](image)

In the 20th century, milk was delivered to consumers in glass milk bottles. Today, plastic bottles are more common. These bottles are often made from high density polyethylene (HDPE). In contrary to the glass bottles, these bottles are only used once and can be collected afterwards for recycling. The milk bottles are made from HDPE using a production process called blow molding \textsuperscript{15}, in which the material is heated and blown in the correct shape by using a mould.

Material
High density polyethylene is a type of grade of Polyethylene (PE). PE is widely used because it is resistant to a lot of common influences in daily life. It is cheap and easy to fabricate. HDPE has longer and less branched chains of molecules than, for example, Low density polyethylene (LDPE). Because of this, it is stiffer and stronger and therefore used for all kinds of containers\textsuperscript{16}.

Below follows a table with important material properties\textsuperscript{16}.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength</td>
<td>17.9 - 29 (MPa)</td>
</tr>
<tr>
<td>Density</td>
<td>939 - 960 (kg/m\textsuperscript{3})</td>
</tr>
<tr>
<td>Melting point</td>
<td>125 - 132 (°C)</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1.81e3 - 1.88e3 J/kg.K</td>
</tr>
</tbody>
</table>

When recycling thermoplastics, the material has to be heated again to be able to transform an object into a new shape or object wanted. What is the influence of temperature changes on the material properties of plastics?

Plastics like PE, can be recycled (thus: heated) about 7 or 8 times before it is not useable anymore. Every time it is recycled its material properties like quality and appearance are getting degraded\textsuperscript{17}, yet in normal products this is not noticeable up till the above-mentioned amount. The reason why recycling in plastics is not widespread is just because of the costs: the use of recycled plastics is more expensive than the use of new plastics\textsuperscript{20}. Above that, the addition of fillers added to modify a plastic’s properties makes recycling more complicated.

Label
The bottles that are used in this research are HDPE milk bottles as described above, which are available at regular supermarkets in the Netherlands. These bottles all have a label attached to them, applied with sticker adhesive. Leaving the label on the bottle or just tearing it off will pollute the granule after shredding and therefore downgrade the resulting material after extruding. There are different ways to remove the labels: for example, commercial sticker remover or tricks found on various websites. Decided is to simply cut out the piece of the bottle with the label attached to it for our testing. Removing the label with chemicals is likely to affect the material and its properties. Some of the simple tricks, like removing the label with water or olive oil, were tried. However, they just did not work. Besides, simple cutting out the label is probably also the fastest way of obtaining a clean piece of material.
Table 3.1 - Possible techniques and products for plastic products

Different methods of shredding
Before being able to actually make granule out of the milk bottles, different shredding methods were analysed. Which method would be most suitable for both our and the RepRap project? A short brainstorm was held about breaking something into smaller pieces. The results are summarised in Table 3.1.
3.2 Creating a test setup

Juicer

After looking at different machines, decided was to perform some initial testing with a juicer, to see if that principle worked. The vision was, that because of the rotating blade and the ability to push the material in by using human force the juicer would be able to create granule. In a second-hand store, a juicer (brand: Braun, type 4154, model MP50 with 220 Volts, 50 Hertz and 300 Watts) was bought for €10, see figure 3.2.

A milk bottle was cut into pieces to try to shred it to usable granule. Soon it turned out the juicer was not able to shred the plastic to granule. Since the transition between the feed mouth of the juicer and the blade was a bit too wide, the material could slip trough it too easy. This way, it would enter the bigger compartment where it would not be pressed anymore, so it would just bounce around a bit. The efficiency of creating granule would be very low this way, because just a little bit of material is shredded. Even crumpling the pieces had little effect. There were some ideas to modify the juicer, mainly to close the gap between the mouth and the blade. However, the blade would probably scrape this modification, so the granule would be polluted with the modification’s material. Therefore, the juicer was found not usable to create granule.

Blender

The next effort was to try a blender. Again, a second-hand machine was bought for €10: a Bestron DBD101/BD101 blender with 350 Watts of power, see figure 3.3. With some initial testing, it was determined that shredding the milk bottle with a blender might actually work with a relatively high level of efficiency. However, the next step was to create a research setup and to actually perform tests to see what parameters are of influence when creating granule. From the RepRap Delft weblog and conversations with experts\textsuperscript{18,19}, some suggestions were already made about different issues that could appear. These are discussed below.

Table 3.2 - Different domestic appliances.

Although there are a lot of different methods that can be thought of, a lot of them are not suitable for use with the RepRap. It was first tried to come up with a method that could be integrated in the design of the extruder. However, this seemed not feasible in the given amount of time. To be able to do this, the shredded material should all be usable by the extruder, while it is not likely that all shredded pieces are of the right size. Therefore, the shredding results should be sieved. To make this process continuous, to be able to use it on the RepRap, would be too difficult.

The next consideration was to create a custom side machine, especially designed to create granule for the RepRap. However, it is plausible that this involves buying or creating some expensive parts, like blades, screws and a heavy motor, to shred the milk bottle to granule. Building the extruder would become too expensive in the philosophy Reprap is based on.

The conclusion was, that the creation of a custom machine would not countervail against the use (or misuse) of a common domestic appliance under some conditions. These conditions include the use of a cheap appliance, to ensure everyone can have access to it. It is believed the use of an appliance for this purpose makes it unusable for the processing of food or other domestic tasks, so the appliance has the sole purpose of creating granule for the RepRap. This means it is allowed to make slight modifications to improve the efficiency of the shredding. The next step was to look at different domestic appliances and try to acquire some for testing.

Domestic appliances

Diferent domestic appliances were looked into to determine which one would work best. Table 3.2 demonstrates some of the machines and their working principles that were considered.

Another plausible appliance to use for making granule would be a meat mincer, yet it is believed that the penetration degree of this machine is too low nowadays to expect that it is widely available, since everyone buys preprocessed meat at the supermarket. Of the 4 machines, the coffee grinder seemed the least suitable for the task of creating granule, because it would turn the plastic into dust, which is unwanted.
Cooling the input material

On the weblog and the RepRap forum, it was suggested that the material should be cooled in advance to make it more brittle and therefore easier to cut\textsuperscript{4}. This was looked into.

At room temperature, around 20 degrees Celsius, HDPE, among other plastics, shows a sort of flexibility, also referred to as the rubber phase. At a given temperature (range), the glass transition temperature, molecules in polymers are beginning to stiffen up. This is called the 'glass transition'. At the end of this temperature range, the plastic has become very stiff and brittle with glass-like properties. This is shown in figure 3.3\textsuperscript{24}.

This would be a good reason to put a piece of plastic in a freezer before cutting it, so it will be more brittle and would brake easier. However, the glass transition temperature of PE lies around -20 degrees Celsius. This would mean that for PE to become completely glassy, one would need a freezer that cools to this temperature. A commercial freezer can reach this temperature, yet the transition between the fridge and the blender has to be fast, because the plastic warms up fast. Tests have to point out if there is an effect.

Initial testing showed that the blades of the blender were getting hot, which could result in them getting blunt fast. This is why the idea came up to try to add a coolant to see if the blade temperature would be lowered. Two options were tried: both cooling with water as putting the pieces in a fridge before blending them. Temperature measurements were done with an infra-red thermometer through the top of the blender pitcher. The tests with the frozen pieces were cancelled shortly after the blending begun: the temperature of the plastic rose so fast, the effect became undone just seconds after the blending started. It was tried to shorten the time between getting the pieces out of the fridge and the starting of the blending, yet that did not help.

Other materials

Depending on the results of the first test, it could be considered to test other materials, more specific the waste from previous RepRap prints. This ABS material, made up from a mix of rafts printed under RepRap objects and failed prints, can also be recycled. Although our research still focuses on HDPE, which is a more soft material with a lower glass transition temperature, it would be interesting to see what happens.

Type of blender

While the first tests were conducted, a comment was posted about on the blog about a person doing the same test\textsuperscript{23}. His pieces of plastic were not shredded, just merely stirred around. The blender used, uses 350 Watt. This is pretty low, compared to other commercially available blenders\textsuperscript{4}. This may put the test results gained in a positive perspective, as a higher wattage seems to indicate higher power and thus better blending quality. So if the shredding of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure32.jpg}
\caption{The tested juicer.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure33.jpg}
\caption{The tested blender.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure34.png}
\caption{Graph of the stiffness of thermoplasts.}
\end{figure}
plastics works with this blender, why would it not with every other available blender with a higher wattage? However, although this is indeed what blender manufacturers suggest, wattage is not as important. A higher wattage can work better with harder substances\textsuperscript{25}, yet consumer reviews contradict the argument that a higher wattage also means better blending. In fact, tests show that wattage has little correlation to performance\textsuperscript{26}.

So, although this is subject to further testing, it is stated that the size of the pieces of plastic to be blended is more important than the power of the blender. Of course it may be the case that blenders with a higher wattage are too powerful and shred the plastic to dust instead of granule.

3.3 Research outline

During initial tests the use of a blender to create granule was found feasible. Next up were more structural tests to find out more about the ideal settings for creating the best granule. Note that during this test, it was not clear what would be the ideal output, since that depended on the size of the screw, which was unknown at this time.

Research goals:

- Investigate the wanted size and state of the input material.
- Look at good ways to cool the material while blending.
- Find out how much granule comes from a single milk bottle and under what circumstances it should be shredded.
- Try other materials to test the feasibility for these.

Test setup

A blender was bought for €10 at a second-hand store. Model details are as follows:

- Brand: Bestron
- Model: DBD101/BD101
- Serial number: 100165
- Voltage: 230V~50Hz
- Power: 350 Watt
- Blades: 4 blades in pairs of two

In total, 13 tests were carried out. In all situations, the blender was turned on to full power.

Tests with different sizes, numbers and states of input material:

1. Blending 1 minute, one large flat piece (size around 13cm x 5,5cm)
2. Blending 1 minute, one large crumpled piece (size around 13cm x 5,5cm)
3. Blending 1 minute, four large flat pieces (size around 13cm x 5,5cm; ±10gram)
4. Blending 1 minute, four large crumpled pieces (size around 13cm x 5,5cm; ±10gram)
5. Blending 1 minute, a number of medium flat pieces (size around 5,5cm x 5,5cm; ±10gram)
6. Blending 1 minute, a number of medium crumpled pieces (size around 5,5cm x 5,5cm; ±10gram)
7. Blending 1 minute, a lot of small flat pieces (size around 1,5cm x 1,5cm; ±10gram)
8. Blending 1 minute, small amount of industrial granule (±10gram)
9. Blending 1 minute, large amount of industrial granule (±60gram)
10. Blending 1 minute, ABS RepRap waste (±10gram)

Test to determine amount of granule and the process of shredding 1 milk bottle:

11. Blending entire milk bottle, first in 1 piece, then cut into 2 pieces, then 4. Until the blender is able to blend the milk bottle into small pieces.

Tests with coolant:

12. Blending 1 minute, couple of large crumpled pieces (±10gram) inside a blender with water (in a way the pieces are just “below” water level, material floats)
13. Blending 1 minute, couple of large crumpled pieces (±10gram) inside a blender with water (in a way the pieces are above water level)

Some of these tests were added during the research, since new ideas came from the previous results.

3.4 Results and discussion

For an overview of photos and notes from all tests, see appendix A.

From the tests can be concluded, that the best way to create equal sized granule from milk bottles with a blender is by cutting the bottle in large, crumpled pieces of about 13 by 5.5 centimetres (test number 4). These pieces need to placed in such an orientation that the pieces cannot get stuck in the width of the blender pitcher.

Adding water

The testing with water was interesting. Aside from serving as a coolant for the blades, water should be added to the material to get the best results (test number 13, see figure 3.5), even better than the ones without water. The best results from the tests without water was now tried with water as a coolant. Aside from the water leading away heat from the blades, it also gave a better granule result then the testing without water. After 5 minutes of blending, the temperature of the blades was significantly lower: 65 degrees centigrade without water against 45 degrees centigrade with water. Only further testing can tell if the life of the blades is significantly shorter and if that is true, how much shorter.

3.3 Research outline

During initial tests the use of a blender to create granule was found feasible. Next up were more structural tests to find out more about the ideal settings for creating the best granule. Note that during this test, it was not clear what would be the ideal output, since that depended on the size of the screw, which was unknown at this time.
As for the reason why the resulting granule with water is better than without, it is assumed the water makes the plastic pieces move downward more and with a higher speed. This way, the plastic is making contact with the blades more often and therefore heightening the chance of having a successful, cutting impact. Without water, the pieces of plastic were more often just hit in an upward direction by the blades instead of making a cut. The water seems to prevent this by preventing the plastic from accelerating after impact.

Granule size
At the moment of testing the maximum size for granule was not known, since the process of creating granule and creating the extruder were carried out parallel to each other. That is why we made a sieve with holes of about 1 millimetre in diameter in it, to sieve out the pieces that were smaller than 1 millimetre wide each. This was done for both the test with and without water. Created with water, 27 percent of the granules was smaller than 2 millimetre wide, while the test without water only gave 13 percent of that size. These pieces were all usable later on in the extrusion process.

The remains of the sieving from the test with water as a coolant was later used for testing with the extruder. This were all pieces sized about 2 to 4 millimetres wide. Although this granule could also be extruded, it was noticed the extruder was subjected to higher forces, up to a point were. Therefore, it can be stated that it depends on the structure and assembly of the extruder if granule this size can be used. However, one should be careful with too large granule, since it can damage the extruder.

Another observation was what the blending of a batch of material a second time is far less effective than the first time. Because the material already exists of small pieces, the chance of having a successful impact with the blades is low.

Other materials
Both industrial granule, obtained from a shredder available at Delft University of Technology, as RepRap ABS waste were blended. Since the industrial granule already existed out of relatively small pieces, it could not be shredded to a smaller size aside from some small flakes. The ABS waste mainly existed out of rafts that were printed on the RepRap. These thin filaments were shredded to smaller pieces, yet not into ready to use granule. However, since it was decided to emphasize one specific material, not much effort was put into further testing these materials.

Concluding, it can be said blending crumpled pieces of material of about 13 by 5.5 centimeters, with some water added to the blender pitcher gives the best equal sized granule. This gives pieces with a width up to about 4 millimetres. When sieved, 27 percent of the granule turned out to be smaller than 2 millimeters.
4. From granule to extrusion

The goal in this chapter is to develop a granule extruder that can be placed on the RepRap 3D printing machine. With this in mind, it is important that the same printing method, Fused Deposition Modeling, can be maintained when the extruder is installed. To achieve this, the focus will be on extrusion in general and specific granule extruder projects that happened in the past. The output of the extruder should be the same as with the current RepRap thermoplastic extruder.

4.1 Background

Different ways of extruding

Extrusion is a process based on high pressure, because pressure generates heat that causes the plastic to change phase. There are different ways to generate the pressure needed to extrude material, yet most of the times an extrusion system uses a plunger or a screw to build up the pressure needed. For this research, air pressure, a plunger system and screw systems were evaluated briefly to choose which way is best for creating the RepRap add-on.

Air pressure systems

An air pressure extruder is based on a compressor that creates air pressure. This pressure is used to push the extrusion material trough an extrusion mould. This system needs lots of external heating, because both the friction involved and therefore the heat development will be low.

The benefit of an air pressure system is that the power source can be placed separately from the actual extrusion head. This can be of great importance because of the limited loading properties of the RepRap. A big drawback of this system is that it needs a tight fit to function properly. Next to the required tight fit there is a power loss due to the transportation of force and movement from the source to the extruder.

Plunger systems

A plunger system is the most low tech solution of the three solutions. It uses a plunger to push the material trough an extrusion mould. A similar system can be found in a combustion engine.

The fact that it low tech is a big benefit from RepRep perspective. However, this way of pressure building makes it very difficult to create a continuous extrusion process. Other problems that can occur during this kind of extrusion is unequal heating of the extruding material, the risks of air bubbles and non homogeneous distribution of material. These bottlenecks also apply to the air pressure systems.

Screw systems

This system is based on a screw that has a transportational and a compressive function. The screw transports the granule to the end of the extruder. While transporting the inner diameter reduces which cause high friction and temperature rise.

Screw systems are the most used systems to extrude materials. The reason for this wide application is the possibility to heat the material with friction instead of electro thermal energy. Plastics have a high specific heat capacity, which causes a relatively large amount of heat and time required to heat up the plastic. Because of the build in friction, less energy and time is needed for the extrusion. The downside of the screw systems is that the screw is a very complicated part, which can be hard to produce, in a way non-technical people that own a RapRap can do. A benefit of this way of extruding material is that it is quite easy to make a continuous extruder instead of a batch extruder.

Chosen system

The system that is chosen to function as our RepRap extruder is the screw system. The reasons for this decision are the frictional heating; the continuous process and the good heat and material distribution. The main drawback of this mechanism is the complicated screw. While it is possible to create such a screw on high-end CNC machines, this does not fit within the RepRap philosophy. To make this part fit in the philosophy, there is decided that the screw has to be bought for a reasonable price or has to be made on a machine that is available for most people in society, like a machine at a FabLab.

Mini extruders

This project is not the first in the field of small scale extrusion. So called mini extruders have already been developed for professional use. Mini extruders are mostly used when a certain plastic is very costly or scarce. Some extruders are specially designed to use only a few grams of granulate in order to save as much material as possible. Because RepRap requires a system on a domestic scale, there is looked into the field of industrial mini extruders to see what can be applied in this project. The two areas that will be evaluated in the research are scientific papers and already existing machinery.
From granule to extrusion

Existing machinery
Mini extruders are not only subject of research. They can also be found in specialised shops, both online and offline. Brands of mini extruders are for example Rondol; Mprus; FiveStarEngineers; Caleva; Brabender and Extrudex. These mini extruders are very expensive and therefore not suitable for the RepRap. Most of these mini extruders are too large for use on the Reprap. These producers do not share their information about the screws they use. What these product do prove, however, is that it is possible to extrude on a small to very small scale.

Projects on a domestic level
In the past, three attempts were made to design a screw for domestic 3D printers. One of these attempts, by Adrian Tan & Timothy Nixon, was successful. They managed to create a fully operational extruder, while the others failed.

The first attempt is the one performed by Adrian Bowyer, the founder of the RepRap project. His extruder used 3 mm thick granules. These would be extruded using a variable pitch screw drive (see figure 4.2) and heated by a heating element. The main problem with this device is that the granule got stuck in the screw after a while. The problem may have been that the screw surface was too rough. Rough surfaces provide lots of grip for the melt. When the melt cools down it can block the screw by solidifying in the irregularities of the screw surface. For a new design of a mini extrusion screw it is important to find a way to create a screw having a smooth surface quality.

Another problem that has to be overcome is the fact that the screw needs to be easily producible considering the philosophy of the RepRap project. Therefore another possibility would be the use of a snake drill, like the one shown in figure 4.3. Forrest Higgs, who has tried to use this drill as an extruder screw, used the theory that if it would be able to ‘pump’ water, then it would be able to move the much

Figure 4.1 - Small screw design

Literature
The design of an extrusion screw is widely discussed. Lots of papers can be found about screws and extrusion machines. When the term “small” or “micro” is added to extrusion the amount of papers reduces quickly. Still, some interesting papers on the subject can be found. There are all kinds of ways to design a small extrusion screw. Some have tried it with the help of scaling rules for screws. This method is very primitive and does not lead to optimal results. Scaling rules are resulting in a very thin screw thickness that cannot function in reality. The forces needed to compress material are too big in relation to the thickness of the screw. This difference between large and small scale extruders is caused by the impossibility to scale material properties. The material can be downscaled, while the material properties will stay the same. This results in different situations for large and small extruders.

To avoid uncertainties caused by using scaling rules or difficult mathematical calculations, computer simulation is used to design a small screw. Covas and Costa made an extrusion screw with a diameter of eight millimetres, which is very small compared to other extrusion screws. An other design for a mini screw was made by Bin Liu, Yi Xie and Mingxing Wu. They tried to make a completely new design based on their own ideas (see figure 4.1). This kind of screw uses a melt as input. By making the channels of the screw very narrow, the melt does not have a big contact area. These kinds of channels make sure that there is less shearing in the barrel. Less shearing decreases the chance of decomposition of the material. The small channels are also causing a steady delivery of the melt and a raise in the melt pressure.

Figure 4.2 - Adrian Bowyer’s screw.

Figure 4.3 - Snake drill.

References
28. Covas and Costa
29. Forrest Higgs
30. Bin Liu, Yi Xie and Mingxing Wu
31. Adrian Bowyer
32. Adrian Bowyer
33. Adrian Tan & Timothy Nixon
more viscous polymers. The pumping did not work for water, although polymers might work after all, because the difference in viscosity between water and plastics is very large.

A third research, that has been performed by Adrian Tan & Timothy Nixon, is an extruder made for the Fab@home domestic 3D printer. This design, shown in figure 4.4, actually worked, with a different approach than regular extrusion, however. The Fab@home extruder is based on a principle with some sort of boiler in which the plastic melts. When it is molten, the plastic will be transported to the extrusion nozzle using a screw drive. This means that the screw drive can have a constant radius and pitch, which would make it much easier to produce. Although it is not a conventional extruder in which granules are transported and molten on the way, this system has to be considered as a possible solution for the RepRap.

4.2 Creating a test setup

Approach

The micro extruder is based on a theoretical design. This theoretical design will be tested by making it in real life. Instead of making a really detailed research plan there is decided to start with an experimental phase: design included research. While testing the first prototype it will be adjusted continuously in order to make it work. This kind of research is qualitative, it is not about conducting a lot of experiments to proof research goals set. It is about making the extruder work, and learning from the problems that have to be solved.

Extruder design

After research, the starting-point for the granule extruder design was established after a brainstorm and discussions with an expert. The goal was to create a working extrusion setup and to investigate its feasibility, before even looking at adapting it to RepRap. The key elements of the extruder are a extrusion screw, a funnel, a tube, a heating element and a nozzle, as shown in figure 4.5. Next to these specific parts, this system has to be built into a test setup to determine if the extruder works with our screw and what kind of motor, heating element and other features are needed for the extruder to work.

Screw

An extruder consists of many parts. The most difficult part to be produced would be the screw. Keeping in mind that the RepRap is an open-source project the screw needs to be easily producible by a broad public, for example in a FabLab. This requires the possibility to create the screw by machining on a small (CNC) lathe. During this research, different screws, with designs based on different sources, have been tested. All screws were machined on an EMCO PC turn 55, a CNC lathe. The machine was instructed to turn a helical thread with all the correct parameters filled in. The different parameters were the size of the inner
thread diameter at the start of the screw, the pitch, that size at the end of the screw and the number of steps the machine makes, thus the thread size.

The actual shape of the cross-section of the thread is determined by the shape of the chisel that is fixed in the lathe. This means that there is a limit to the angle the flank of the screw thread can have. This limit lies at 60° for the side in which direction the chisel moves. The other side can have an angle of almost 90°.

The programme that the EMCO lathe works with is essentially a piece of G-code, which is the same format the RepRap printer works with. The G-code file contains information about the wanted position and movement of the chisel and about other variables like speed. However, the process of writing and testing the programme code involved a lot of trial and error, which meant that there were a lot of failed attempts. The chisels needed for the screw designs that were picked were custom made and broke multiple times, which made the creation of the screw a labour-intensive process.

This, combined with the fact that the tolerances on the screw are small, makes it hard to say that the screw is an easy-producible part. It is more likely that in the future, the screw will be a buyable part for the RepRap, like the stepper motors.

**Extrusion tube**

The extrusion tube is a simple tube. Its main function is to force the granule and melt to stay within the spacing of the pitch of the screw. By forcing the material in the space, frictional heat development will occur. The tube can be bought or created by milling. It is important that the inside of the tube is as smooth as possible. The granule and melt have a downward motion; every scratch makes it more difficult to maintain this downward motion. To make sure that the inner surface of the tube is perfectly round and free of irregularity a high accuracy drill is used. The use of a high accuracy drill facilitates also a tight fit between the screw and the tube. M16 screw thread is applied at the end of the tube to make it possible to connect different nozzles. This tube was created specifically for our test setup.

For the final extrusion design, other aspects, like the ease to produce this kind of tubing, have to be taken into account. For example, the connection between the tube and the nozzle by screw thread is probably not necessary. At the moment, it is wanted to be able to change nozzles for research purposes. A picture of the tube as used in the test is shown in figure 4.6.

**Nozzle**

The nozzle is also machined. It is a simple conical piece of tube closed with only a tiny hole in it on one end and M16 screw thread on the other end. This is useful because the extruder can be tested with nozzles with different extrusion diameters. Figure 4.7 shows a picture of the nozzle as used in the test.

**Funnel**

The funnel used is a standard funnel available in numerous stores. The most important is that it fits on the extrusion tube. If necessary, a connector can be made to make it fit. With heat development in mind there is chosen to use a funnel made from steel.

**Heating element**

Normal scale extrusion machines generate most of the heat needed by friction between the granule and the screw tube combination. In the mini extruder situation, the heat development is estimated to be relatively lower in comparison to the normal situation. The amount of material will also be smaller, yet the melting temperature needed stays the same. Presumably, more energy is needed to make the granule extrude-able. For testing reasons a heating element is used that has a wide temperature range.

The heating element exists of glass fibre insulated thermocouple wire, winded around the end of the extrusion tube. Glass fibre insulation is used to overcome temperatures of 300 degrees centigrade and higher. By using a sufficient amount of windings the resistance can be made perfectly well fitting to the available 12 Volts power source of the Reprap, which comes down to 3 Ohms. Within the heating element a piece of thermocouple wire is placed. By connecting this piece of wire to a multimeter the temperature can be measured.
Test setup
While all the parts for the extruder were created for a first attempt, the rest of the test setup was assembled. A schematic overview of this setup can be found in figure 4.8, a photo can be found in figure 4.9.

Power supply
The variable laboratory power supplies used were two Voltcraft PS3610 units. One was connected to the motor, which was set on 12 Volts. The amperage was fluctuated to maintain a constant rotational speed, with an initial setting of 1.0 Ampere. This gave the motor about 12 Watts of power, depending on the extrusion stage. The other power source was connected to the heating element. Its values were determined on 12 Volts and 3.8 Ampere. This gave the heating element about 45 Watts of power and a maximum temperature of 250 degrees centigrade.

Motor
The idea was to use a drilling machine, which was connected to a computer. This setup was made for another experiment and could be used easily. The only problem was that the drill was left turning and the drilling claw could not handle power in that direction. When the machine was turned on and torque applied by the extruding mechanism, the screw loosened in the claw due to the left turning mechanism. Unfortunately, this drilling machine could not be used for further testing.

The motor used for this experiment is made by SPG, type 59D 120-24CH, which can have 120 Watts of power, a Voltage of 24 (DC) and Amperage of 7.1 Ampere. It is able to reach a speed of 2920 rpm. The motor is connected to a gearbox; also made by SPG, type S9KC36BH. This gearbox has a ratio of 1:36. With the used preferences, the screw reached a speed of 44 rpm.

Multimeters
To determine the temperature of the heating element, a small piece of thermocouple wire was attached to both a multimeter and the tube. The multimeters were of the brand Iso-Tech, type IDM106M. In later tests, not only the tube temperature, but also the nozzle temperature was measured, since it was figured out this was important as well. Temperature measurements are just a rough indication, since it is measured on the outside of the setup instead of the inside.

4.3 Initial experimenting
After completion of the test setup, experimenting could begin. In total, five attempts for a successful extrusion have been undertaken.

First attempt
During the first three attempts, a steel screw was used. The screw design was based on the desing of
The screw that was created, however, was slightly different because it needed to be produced by the CNC lathe. The pitch, length and diameter of the screw were the same as the original design. The shape of the screw thread and the thread depth were slightly differed. The depth that was machined varied from 1.25 at the top end to 0.4 millimetres at the bottom. Both thread edges have an angle of 60 degrees and a width varying between 4.25 to 2.35 millimetres at the smallest part. This screw is turned using a symmetric chisel with an angle of 60°. For a photo of the screw, see figure 4.10.

Second attempt
After the first attempt, some improvements were made. There were small vertical channels created at the end of the funnel to prevent the material from ending up in a circular motion and the inner surface of the extruder tube was smoothed to have less friction between the tube and the screw. During the second attempt the material got dragged in more easily but still not sufficient enough. With a screwdriver sufficient material was pushed into the machine. The possible reasons for the jam were insufficient heat production, too little space between screw and tube, too large granule or the roughness of the inside surface of the tube.

Third attempt
The tube, made out of steel, was heated up to 180 degrees centigrade, through 14 windings of glassfiber insulated thermocouple wire around the tube, having a total resistance of 3 Ohm. After a few minutes, the setup was ready for the first test. There was no nozzle attached at the bottom of the tube, because of the experimental nature of this first test.

The motor turned smooth, until pressure started to build up in the tube. After 2 minutes, the material came out of the top end of the tube and the test setup started deforming. It seemed the pressure in the tube got too high. It was clear the material could not reach the bottom end of the screw. Since the beginning of this test, a better way to shape a mini extrusion screw was found in literature.

Fourth attempt
The fourth experiment was conducted using an aluminium screw. The design of the screw is a simple downscale of an existing extrusion screw which was available at the faculty of Industrial Design Engineering at Delft University of Technology, which was made in the beginning of this project while literature review was not finished. Although scaling rules are not optimal, it was decided to try one because some other option had to be tried. The screw was made of aluminium because it was intended as prototype of a steel screw. It turned out later that it would not be possible to create this design out of steel with the CNC lathe, while aluminium would be a disadvantage because of the softness of the material. Also, if this type of screw would be made out of steel, it would be too large and too heavy to use on the RepRap without making any adaptations. Because of the rapid wear aluminium would cause upon itself, an
aluminium tube was also made out. The disadvantage of the combination of the original steel tube with an aluminium screw is that when damage occurs, it would be on the screw instead of the extrusion tube. Because of the deep grooves in the screw, it was believed the material would build up less cylindrical pressure in comparison to the first experiment, because small granule was used. A photo of the screw can be seen in figure 4.12.

A nozzle was mounted, the heating element was heated and after a few minutes, when the temperature reached 200 degrees centigrade, the motor was switched on. Soon, the whole setup started to deform again, as a result of the high forces that acted upon it. It seemed it was a bad idea to put a nozzle on the extruder. The material got through the screw, but cooled down once it reached the nozzle. There, an accumulation of material was created, see figure 4.13.

Fifth attempt
The fifth attempt was conducted using a steel screw, turned with a non-symmetrical chisel which has an angle of 90° on one side and an angle of 60° on the other. The design of the screw was changed again. Since a steel screw is wanted because of the high forces that are released, the design of the second attempt is not suitable for this, the design of the first attempt was used again with a few adaptations. Since the first attempt was not successful, this time the grooves in this screw were made between 1.35 to 0.55 mm deep, to ensure material could enter it. The chisel used to make this screw had an angle of 60 degrees on the downside and a 90 degrees on the upper side. This causes a cutting motion with respect to the granule. The screw can be seen in figure 4.14.

So far, the heating element was only used to heat the extruder tube, while it turned out in the second attempt the material cooled down in the nozzle, where it congealed. To prevent this from happening again, the thermocouple wire was also wired around the nozzle. An extra multimeter was added to measure the nozzle temperature, next to the tube temperature. In this setup 10 windings were placed around the tube and 4 windings were placed around the nozzle. The total resistance remained 3 Ohm.

Because of time restraints, this was going to be the last experiment. To make sure this one would work, the diameter of the hole in the nozzle was enlarged from 1.5 millimetres to 2.3 millimetres, these dimensions are based on the impute diameter of the RepRap. This way, it was made sure the material would be able to flow through the nozzle once it reached it. Also, to lower the viscosity of the material some more, the temperature of the heating element was set to 240 degrees centigrade.

After preheating the extruder, the motor was switched on. The first few minutes, nothing visually happened. When it seemed the experiment would be over, a small piece of plastic came out of the nozzle. When this started, the process started to run.

Because of gravitational force, the plastic pulled itself downward reaching extrusion speeds of about 25 millimetres per minute at a motor speed of 43 rpm.

A problem during the experiment was feeding the screw through the funnel. This was first done by hand, stirring the material and ticking the funnel to shake the material intro the entrance of the screw. Later, a piece of steel wire was attached to the drive shaft, to stir the material automatically, which worked well.

Some days later, a small second test was performed to check if the extruder could be started again by just heating the tube and nozzle again. This
thin. This variation can be explained by the fact that some space is located between the end of the screw and the end of the nozzle. This space functions as a pressure vessel, while the nozzle opening functions as a valve. When the pressure reaches a certain level the material accelerates through the nozzle opening, resulting in a thicker material. After a certain time the pressure has dropped and the material output declines, resulting in a thinner material flow.

When the extruder was disassembled after the extrusion, it became clear that this explanation is plausible. The nozzle contained a piece of plastic, see figure 4.17. The thin front of the piece is caused by the shape of the nozzle. More interesting is the backside of the specimen. One can see that the backside does not contain any imprint from the extrusion screw. This means the backside is not touched by the screw, which means there is indeed space between the melt and the screw. This is in harmony with the stated theory of the pressure vessel and the valve.

Unstable extrusion speed
The unstable extrusion speed noticed is linked to the thick-thin relation described above. When the pressure is low in the gap between screw and nozzle, the extrusion speed is low as well. When the pressure reaches a certain point, the extrusion speed increases to release it.

Slow start
It took a very long time before the extruder started giving results. The reason for this slow start also has something to do with the gap between screw and nozzle. Before pressure could build up in this vessel it has to be filled completely with material. Since the extruder was empty it took some time for the whole system to fill. Only after this, the extrusion started.

Varying colour
The first extrusion sample was darkish grey. An easy explanation could be that the material was burned at that point because of too much external heating. Another explanation could be that metal parts of the extruder have polluted the extruded material. Because none of the samples smelled burned there was decided to test the filament with a magnet, see figure 4.16. The material clearly responded to the magnet, thus it is clear that there was ferrous pollution in the extruded material. When the filament was examined 20 centimetres from the starting point, the colour of the sample changed from darkish grey to lighter gray, see figure 5.16. In this part little metal pieces, still visible with the bare eye, could be found. These pieces might be found due to two reasons. The first reason might be that the metal bits were still in the extrusion tube or the screw when the granule was fed to the machine, because these parts where not cleaned before extruder assembly. However, this would count mainly for the first sample of extruded material, while that is not the one being of darker colour. The second explanation might be that the machine was not aligned well. The wear that occurs.

Figure 4.16 - Reaction of a sample to a magnet.

Figure 4.17 - The accumulation of material.

was indeed the case, as the extruder was functioning again.

Technical drawings of the parts used in the final test setup are added in appendix B. More in depth details about the extrusion screw, like the used software and G-code, can be found in appendix C.

4.4 Results and discussion
In total, four samples were extruded. Every sample was cut off when it was going to touch the ground. Photos of the samples can be found in figure 4.15.

The extruded material was examined, both during and after the extrusion. Several aspects of the extruded rod were conspicuous. Among these elements were a varying extrusion diameter, an unstable extrusion speed, changing material colour, material pollution and diameter expansion of the extrusion right after exiting the nozzle. These aspects are discussed more elaborately below.

Varying extrusion diameter
The diameter of the extruded material varied in two different ways. The first is the extruded material becoming thinner from the beginning of the extrusion to the end. This phenomenon can be assigned to gravitational forces. In the extrusion process the gravitational forces build up as the extruded material gets longer. This force leads to faster extrusion and a thinner output of the material. The second variation in diameter is harder to explain. The type of variation is characterised by a waving motion from thick to thin.
4 | From granule to extrusion

can cause material to chip from the screw of the tube. When the extruder was disassembled it became clear that the screw was full of small metal parts, demonstrated by a piece of paper turning gray from the metal filaments when wrapped around the screw. This significant pollution is most likely due to the wear between the screw and the inner surface of the tube. These findings make it clear that is of great importance to produce the screw and extrusion tube with narrow tolerances.

4.5 Research suggestions

Because of time restraints, there was no time left for any structural testing. Therefore, some suggestions for testing the setup described before are given. When the extruder works well and controllable, different parameters have to be investigated: motor power, couple, motor rpm, external heating, kind of materials, nozzle diameter, screw design, density of the granule, screw size, screw tube fit, frictional heating, extrusion speed etc.

As one can see there are a lot of different variables, which makes testing a difficult and time consuming process. When conducting this research one should know that the expected controllable variables are: temperature of the heating element, type and size of the input materials and motor speed (depending on the kind of motor). The chosen input material will request certain circumstances, which can be met by adjusting the motor speed and temperature. This statement is only valid when one decides to use one kind of machine and one does not vary the extrusion screw.

At the end of this process the relations between the different parameters and the ideal values of the different parameters can be derived. The final phase of the research will be the exploration of things as accuracy, reliability and lifespan of the product.

Diameter expansion after exiting the nozzle

It was noticed that the material is expanding after it exits the nozzle. With the nozzle hole having a diameter of 2.3 millimetres, the extrusion rod has a diameter of 2.6 to 2.9 millimetres. This is due the fact that the material wants to get back in its original shape. The extrusion nozzle forces the material into a certain shape. When the material exits the nozzle, the forces of the extrusion tube disappear. The material tends to get into force equilibrium and expands a little.

Larger granule causing a darker output colour

When larger pieces of granule are fed to the extruder the extruded material becomes darker. This can be caused by two phenomena. The larger granules could have more problems to get into the extrusion tube, which can lead to less material in the extruder. The wear between the tube and the screw stays the same and therefore there are comparative more iron particles in the melt. The second cause is that the bigger granule causes the screw to bend a little, because of wrong alignment. This causes the screw to touch this inner surface of the tube, which causes a larger wear.

Concluding, it can be questioned if the argumentation for choosing a screw based extruder was solidified. It seems that due to the small dimensions of the screw the fractional heating is very low. Another reason for this can be that the screw is not stiff enough to counter the force put on it by the material. Still the material blending and heat spreading properties of the screw based design are big advantage.
Unfortunately, the time given for this project turned out to be too short to be able to adapt our findings for a RepRap ready prototype. A rough concept was created for our presentation, to show what the ultimate goal of the project is. This concept reflects our vision on how the extruder will look in a RepRap setting, yet it tells little about the actual feasibility of it. The feasibility will be discussed in our conclusion.

RepRap mounted extruder
In figure 5.1, a concept drawing of the granule extruder can be seen. For this concept, the design of the current Thermoplastic extruder has been analysed and adapted. The different parts will be discussed below.

**Base**
The base is the part that joins everything together. As with the current extruder, it should be designed to be printed with a RepRap, to maximise the number of parts that are printable. Most other parts in the extruder are not that likely to be printed, because of tolerances and heat development.

The mount displayed in the figure is based on the current mount to the so called ‘X carriage’, the module that makes sure the printer head can move in the X-axis direction. The Bits From Bytes RapMan, that is available at Delft University of Technology, has a different kind of mount. The base can be easily adapted or redesigned to fit everything on that (or every other) mount.

**Motor**
For this concept, we added a stepper motor to the side of the base. The size and weight correspond to the stepper motor that is currently used in the Thermoplastic extruder. However, it is questionable if this standard RepRap stepper motor is sufficiently powerful for this type of extrusion (see chapter 6. Conclusion and discussion).

**Electronics**
Little is known about the required electronics at this moment. The circuit board should take care of the communication with the main RepRap control board. It is wired to the heating element, a temperature control board for motor and heating control mounted to base.

**Figure 5.1 - Concept drawing of the extruder with different parts named.**
sensor and the stepper motor. It is possible that the current electronics system for the thermoplastic extruder is sufficient, with possibly some adaptations, because a different motor setup is likely to be used.

**Screw**
The screw is designed as said before. Attention should go to the mount and the alignment of the screw, since it needs to run without any irregularities. In the concept, the screw is driven by a worm wheel. It should be investigated what the most efficient drive is between the motor and the screw.

**Funnel**
The funnel is placed on top of the base. Since the granule feed is crucial, investigated should be how the funnel can be shaped best for the material to enter the screw. The size of the funnel should be big enough, since it is unwanted to refill the funnel every five minutes.

**External extruder**
The result that was obtained with the extruder test setup resembled the input welding rod for the RepRap. This raises the question if it is possible to create an external extruder, which indeed changes home-made granule into feed material for the RepRap, instead of directly printing the material. To see if this is possible, a completely other approach is needed than for this project. Weight and size limits disappear, while there should go extra thought in the question how the extrusion rod should be caught and stored for later use on the RepRap, since such an extruder can extrude faster than the RepRap needs input material.

**Tube/thermal barrier**
For our tests, a steel tube was used as a guide for the screw. For safety reasons (a heated metal tube can reach a very high temperature) and because the base might get too hot, it might be best to make it a thermal barrier, to isolate the heating element, as it is with the Thermoplastic extruder. This barrier consists of PTFE or PEEK rod. The rod should be a standard size in which the screw fits perfect.

**Heating element**
The heating element consists of thermocouple wire, wound around the tube. Nothing is changed in comparison to the prototype, because the wire is relatively cheap and accessible.

**Nozzle**
The nozzle in the original RepRap extruder is made from three parts, most notably a brass barrel, in contrary to the machined one from the prototype. It should be examined if the original nozzle can be adapted to fit the design, because it is easier to produce.
6. Conclusion and discussion

The main question during this project was if domestic waste could be used as input for the RepRap 3D printer. In short: yes, this is feasible. Although there were a lot of problems during this research, it is believed these are solvable.

At this moment, the total assembly is too big and too heavy to be placed on the RepRap, but since there was too little time to look at this problem extensively, it should be possible to make big improvements in this field. The motor used in the test setup also was too big and too heavy, but it used only 10 Watts, which can also be achieved by a motor that is suitable for the RepRap.

When feeding granule into the extruder it is important to use a small stirring device in the funnel. This way the granule stays in motion which causes the material to move towards the screw. Another important point with an axial feeding funnel is that the rotational motion has to be transformed into a downward motion. To create this motion, transition slots were created in axial direction at the end of the funnel.

In the extrusion result, metal pieces were present, which indicates that the screw was out of centre. The screw, being long because the initial idea was to use friction as a warmth source, has a high risk of warping at the moment, which can be prevented by making it shorter or thicker. Nevertheless, tolerances will be very important in a final design, as high forces are released on the construction. This tolerance will be important in the manufacturing of the parts but also in the assembly of the parts. It is highly questionable if these tight tolerances can be met if a number of parts is replaced by parts that are RepRap printable and assembled by “amateurs”. Another problem is that the extruder is quite fragile. When the different parameters like temperature and motor speed are controlled in the wrong way, the extruder will break down. This can be prevented by all sorts of electrical circuits which makes the extruder lots more complicated.

The most doubtable part of a domestic extruder is the heat development in combination with the burnable plastics. When this kind of machine is expected to function in the domestic environment safety precautions have to be taken. It has to be absolutely sure that no toxic chemicals are released into the atmosphere by smelting the different domestic plastics. Even more difficult is the temperature safety. For example, PP and ABS have very melting temperatures. When the machine is set for ABS and a person decides to put PP in the machine problems can arise.

As mentioned in the report it's quite hard to create your own screw. First of all you have to gain access to a CNC lathe. Secondly you need to be capable of making your own chisel. When these to requirements are met it is important that you understand G-code to know what kind of file you can send to the CNC lathe. Finally, it is necessary to have some operating knowledge on the lathe that you are using, because it is possible that the turning and moving speeds have to be adjusted during the machining process. Because this process is quite complicated it is advisable to offer the screw as a buyable part or to look at using standard screws.

Overall, it can be concluded that it is feasible to create granule with a domestic appliance like a blender. However, it depends on the extruder which size of granule is needed and therefore how long it takes to obtain it. In this project, the best results were crumpled pieces of plastic with a size of about 13 by 5.5 centimetres, with some water added to the blender pitcher gave the best results of making granule. The drying of these pieces takes more time then the tests without water. If needed for the extruder, the result can be sieved. However, further and longer testing is required to determine if the concerning appliance does not break down or wear out too soon after one starts to use it for granule creating purposes. In the blender case, the heat development on the blades, although it was proven that adding water helps to minimize this effect, can be a serious problem, as it can cause the blades getting blunt. As long as a cheap appliance is used, this does not have to be a problem, depending on the worth of the objects being printed with the recycled material, but when a more expensive machine is used, one does not want it to last only a couple of weeks. An idea could be to use a food processor for the shredding, because this appliance uses replaceable blades. One could have a set of blades for food processing and one for making granule. However, this leads to another point. When making granule, a lot of plastic powder that has become electrostatic stays behind in the machine. It is very hard to clean this, because the dust just sticks everywhere. It is not plausible that an appliance that is used for making granule can ever be safely used for processing food, because of health reasons. Another
potential problem with the dust that stays behind is that material can get polluted when one tries to make granule from different kinds of plastics. Next to HPDE, there were also some tests performed with old ABS RepRap waste. It was very hard to get our blender clean enough. Thus, one can wonder if someone that wants to make his own granule should stick to only one kind of plastic of should have a different blender for every kind of plastic that can be recycled. In the future, education about different kinds of plastic should take place to ensure that people will not mix different plastics together and potentially danger themselves when heating that mix.
7. **Recommendations for further development**

To finalise this research, recommendations for further development in the field of a recycling add-on for the RepRap project were thought of, next to the execution of the research plan to determine temperature and motor characteristics. If someone wants to elaborate further on this subject, then these are interesting fields to look into.

**Test other domestic appliances**
With the blender tests, it was shown that creating extrude-able granule with a common domestic appliance like a blender is possible. However, there was only limited time and capacity to facilitate these experiments. Possibly, other domestic appliances like a food processor can work more efficient when creating granule. They can possibly cut the granule in a more equal size, in a shorter time, or in a way that the blades will last longer before they wear out. The most efficient way of granule making is needed to really be able to recycle plastic waste.

**The granule needed for an object**
For the size of the funnel, it is essential to know something about the amount of granule needed for a normal RepRap printed object. One wants to be able to start the RepRap and then leave it alone for some time while it prints. If the granule funnel needs to be refilled every five minutes, one should stay close. Also, if one needs to shred multiple milk bottles to create a small object, this would probably take too much time. In an ideal world, everyone would recycle his waste, but this is not going to happen if hours of free time need to be sacrificed.

**Degradation of the material**
As said, common HDPE can be recycled about eight times before it becomes unusable in a professional setting. Since the material in the process that is described in this paper is treated in a non-professional and non-sterile way, there is a high chance it gets polluted, for example by metal parts in this research. It should be investigated if the material degrades faster this way and on which scale. At first, normal material tests, like a tensile test, could be used. A more thorough approach would be to see the extruding result trough a microscope to check the molecular composition of the material.

**Test more standard extrusion screws**
Although the creation of an extrusion screw that anyone should be able to produce or get created was one of the main points of attention for the extruder, it turned out this was hard. The mini extrusion screws that were found could not be machined in a simple way. In the end, the most simple screw found that was specifically for extrusion needed a custom chisel to be machined. However, this screw did prove that the extruder concept could work. It should be interesting to see if the same result can be reached by using a standard DIY shop screw. This would save a lot of time and money.

**Harden the screw**
From the extrusion result, it was determined that the extruded rod was polluted with little metal parts, which probably flaked off because of some friction between screw and tube. If the screw, or any other parts, could be hardened in a simple way, this would prevent this kind of pollution and also create a longer lasting, more durable screw.

**Examine the possibility of extruding sideways**
At the start of this project, vertical extruding was chosen as the most logical solution because of size and moment of force reasons. However, there should be a reason all industrial extrusion machines work horizontal instead of vertical. This way, the granule gets pulled into the screw by force and gravity. It could be interesting to see if this procedure can also be applied to the RepRap. However, in this situation the extruded wire should be forced into a turn after the screw ends, to be able to exit the nozzle in the correct way.

**Possibility of an external extruder**
In this research, focused was on the creation of an extruder that could be placed on top of the RepRap. Although the conclusion is that this is a plausible solution. One could also investigate the feasibility of having an external extruder that extrudes the kind of welding rod the RepRap is normally fed with that was extruded with the test setup for this research. This eliminates some of the limitations of add-on extruder, like weight and size restraints.

A potential drawback of this approach, however, is that the input material needs to be heated twice, once to create the rod and once to be able to print the material. This way, the recycling costs two times more energy and the material degrades twice as fast as with an add-on extruder.

**Conduct an energy benchmark**
This project has mainly focussed on making an extruder that could be assembled to the Raprap. The main advantage of this, compared to an external wire extruder is that the material only needs two
transitional instead of four. The drawback of this system is that it can be very difficult to meet the tolerances required to use the friction screw extruder. A solution can be to use a transportation screw and melt the material by only using a heating element. Technically it would be more ideal to make an external wire extruder. The parts can made bigger, stiffer and stronger. It is strongly advised to conduct an energy benchmark between the extruder designed in this research and an external wire extruder in combination wit the RepRap.

Look at control software
One could also look at how the software that controls temperature and extrusion speed could be programmed. At first, one could think this is the same principle as the current software for the Thermoplastic extruder, but under a closer look, potential problems arise. Because the amount of granule in the funnel changes, the gravitational force with which the granule presses itself in the screw changes. Also, difference in the size of pieces of granule can cause a change in entrance speed. Because of this, the extrusion flow is probably not constant. One can look at possible ways to detect this and change settings trough software to make the extrusion stream more equal.
8. References


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Appendix A

Blender granule tests

1. Blending 1 minute, one large flat piece
   (size around 13cm x 5.5cm)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Input Image" /></td>
<td><img src="image2.png" alt="Blender Image" /></td>
<td><img src="image3.png" alt="Output Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

The result was not that good; the piece has only been cut a couple of times.
- Would the blades cut well if we crumpled the material?
- Would the blades cut well if we put more material into the blender?

2. Blending 1 minute, one large crumpled piece
   (size around 13cm x 5.5cm)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Input Image" /></td>
<td><img src="image2.png" alt="Blender Image" /></td>
<td><img src="image3.png" alt="Output Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

Result; there were still too many large pieces, but the result was a lot better.
- What size is small enough to extrude?
- How can we cut the remaining parts, putting more material into the blender?
3. **Blending 1 minute, four large flat pieces**  
* (size around 13cm x 5,5cm; ±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

**Thoughts**

More material does result into a higher number of smaller pieces and is therefore a better result than test 1, but still worse than test 2.

- What would happen if we filled the blender with the same amount material but then crumpled (larger volume, perhaps more impact).

4. **Blending 1 minute, four large crumpled pieces**  
* (size around 13cm x 5,5cm; ±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

**Thoughts**

The first good results are in, lot of small pieces but there are still some larger parts.

- The pieces bounce up and down, perhaps a smaller blender would fulfil better (might blend the material quicker). We think if we would fill the blender to the top the upper parts won’t hit the blender so a smaller blender would fit better.
- Some extreme small pieces become static and are sticking to the side of the blender.
- Longer blending could probably result into better pieces.
5. **Blending 1 minute, a number of medium flat pieces**  
(size around 5.5cm x 5.5cm; ±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

Tryout with smaller flat pieces reasonable result but still a lot of large parts.  
- These smaller pieces are blending better than the straight larger pieces (test 1 and 3), perhaps because they are small than the width of the blender container.

6. **Blending 1 minute, a number of medium crumpled pieces**  
(size around 5.5cm x 5.5cm; ±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4.jpg" alt="Image" /></td>
<td><img src="image5.jpg" alt="Image" /></td>
<td><img src="image6.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

The result shows less variation but there seems to be more not useful parts  
- Small crumple bounce more up and down then larger crumple, size of the crumple is too small for the blender.

7. **Blending 1 minute, a lot of small flat pieces**  
(size around 1.5cm x 1.5cm; ±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image7.jpg" alt="Image" /></td>
<td><img src="image8.jpg" alt="Image" /></td>
<td><img src="image9.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

The output looks nearl same as the input.  
- The input pieces bounce a lot, the blades hardly cut the material.  
- We are glad this does not work because it is a lot of work to cut a milk bottle as small as this.  
- Fumbling this size will not show a better result. The pieces would only bounce more up and down; it is not realistic for a consumer to put so much effort in recycling a milk bottle.

8. **Blending 1 minute, small amount of industrial granule**  
(±10gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image10.jpg" alt="Image" /></td>
<td><img src="image11.jpg" alt="Image" /></td>
<td><img src="image12.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

**Thoughts**

We wanted to try to blend the industrial granule, acquired by using the industrial shredder available at Delft University of Technology, to even smaller granule. The result shows that some of the granule becomes smaller but the rest remains the same.  
- A lot of granule becomes as large as dust and really static.  
- Granule bounce without being cut by the blades.
Thoughts
The output looks nearly the same as the input.
- The input pieces bounce a lot, the blades hardly cut the material.
- We are glad this does not work because it is a lot of work to cut a milk bottle as small as this.
- Fumbling this size will not show a better result. The pieces would only bounce more up and down; it is not realistic for a consumer to put so much effort in recycling a milk bottle.

8. **Blending 1 minute, small amount of industrial granule (±10gram)**

![Input Blender Output Images]

Thoughts
We wanted to try to blend the industrial granule, acquired by using the industrial shredder available at Delft University of Technology, to even smaller granule. The result shows that some of the granule becomes smaller but the rest remains the same.
- A lot of granule becomes as large as dust and really static.
- Granule bounces without being cut by the blades.
- What would happen if we put more granules into the blender?

9. **Blending 1 minute, large amount of industrial granule (±60gram)**

![Input Blender Output Images]

Thoughts
Result remains the same.
- Granule still bounces up without really being cut by the blades
- We felt that the blades of the blender can become really hot. So we wondered how that has impact on the material and on the sharpness of the blades.
10. Blending 1 minute, RepRap waste (±10 gram)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

Thoughts

The result of shredding the RepRap waste was a lot of small wires, which came out of the rafts of the prints. The (failed) RepRap printed objects that were also in the waste were cut into smaller pieces, but still consisted out of large parts.
- We wonder what would happen if we would cool down the material first.

11. Blending entire milk bottle, first in 1 piece, then cut into 2 pieces, then 4. Until the blender is able to blend the milk bottle into small pieces.

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

Thoughts

As we expected the first time we blended the material it was stuck, this effect remained until we cut the material for the fourth time into 8 pieces.
- The blades could not shred the screw thread part of the bottle.
- Small amount of material out of one bottle, what can you make out of one bottle?
- Pieces of the bottle cannot be bigger than the width of the blender
- Can a layer of water keep the material from bouncing up and down and cool down the metal blades and material.
11. Blending entire milk bottle, first in 1 piece, then cut into 2 pieces, then 4. Until the blender is able to blend the milk bottle into small pieces.

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

Thoughts
As we expected the first time we blended the material it was stuck, this effect remained until we cut the material for the fourth time into 8 pieces.
- The blades could not shred the screw thread part of the bottle.
- Small amount of material out of one bottle, what can you make out of one bottle?
- Pieces of the bottle cannot be bigger than the width of the blender
- Can a layer of water keep the material from bouncing up and down and cool down the metal blades and material

12. Blending 1 minute, couple of large crumpled pieces (±10 gram) inside a blender with water (so that the pieces are just “below” water level, material floats)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

Thoughts
We used as input the size and shape where we thought we had the best result with: the result of test number 4. The result was even better than that test. As result we had nearly only small parts.
- Water keeps the part from bouncing.
- Knifes didn’t feel warm, we wonder if this is also at the moment of impact and after a long time of use.
13. Blending 1 minute, couple of large crumpled pieces (±10g) inside a blender with water (so that the pieces are above water level)

<table>
<thead>
<tr>
<th>Input</th>
<th>Blender</th>
<th>Output</th>
</tr>
</thead>
</table>

**Thoughts**

We used as input the size and shape where we thought we had the best result with. As result we had nearly only small parts.

- Test result was a bit better than test number 12.
- Knifes did not feel warm, we wonder if this is also at moment of impact and after a long time of use
Sieve test

To determine an efficiency in creating granule with only pieces smaller than 1 millimetre, a test with water and without were compared.

Total weight:

<table>
<thead>
<tr>
<th></th>
<th>With water</th>
<th>Without water</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.8 gram</td>
<td>36.8 gram</td>
<td></td>
</tr>
</tbody>
</table>

Size > 1 mm wide (most between 2 and 4):

<table>
<thead>
<tr>
<th></th>
<th>With water</th>
<th>Without water</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.0 gram</td>
<td>36.2 gram</td>
<td></td>
</tr>
</tbody>
</table>

Size < 1 mm wide:

<table>
<thead>
<tr>
<th></th>
<th>With water</th>
<th>Without water</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.8 gram</td>
<td>5.6 gram</td>
<td></td>
</tr>
</tbody>
</table>

The percentage of small granule created with water, 26.6%. Without water it is 13.4%.
Appendix B.

Technical drawings of the parts used in the setup

On the next pages, technical drawing of the following parts can be found:

- The clamp used to mount the test setup
- Tube
- Nozzle
- Screw

On [http://reprapdelft.wordpress.com/](http://reprapdelft.wordpress.com/), STL files of these parts can be downloaded.
Clamp

TU Delft
Industrial Design Engineering

Jasper Flohil
4/14/2010

RepRap Delft

Datum: 4/14/2010
Groep: RepRap Delft
Tekeningnummer: A4
Maat: 1:1

Schaal: 1:1
Datum: 4/14/2010
Tekening: Jasper Flohil

50
50
10
25
R8
50
50
10
Tube

Dimensions:
- Diameter: 16 mm
- Length: 45 mm
- Thread: M16 x 1.5

Note: The drawing shows a 1:1 scale and is part of the A4 sheet with the name Jasper Flohil.
nozzle
screw
Appendix C.
*Extrusion screw manufacturing details*

As described in the report, the final extrusion screw was machined by a CNC lathe, using a G-code script. The script was created in WinCAM, a piece of software that comes with the EMCO lathe that was used. More information can be found at:  

The script itself is written below:

```
%MPF1
N0005 G54
N0055 G58 X0. Z172.
N0010 G96 S0
N0015 M3
N0020 G95 F0.100
N0025 G96 S180
N0030 G0 X50. D0
N0035 G0 Z50.
N0040 T6 D6
N0045 G0 X10.
N0050 G0 Z2.

N0060 G95 S50
N0065 R20=6.000 R21=7.4 R22=0. R23=1 R24=-1. R25=0
N0070 R26=1. R27=3. R28=100 R29=27 R31=5.8 R32=-91.2 L97 P1

N0075 M30
```

The first group of codes are standard written by WinCAM, the software in which the program is written. The second group of codes needs some explanation. The next rules represent the parameters for the screw, like depth and pitch.

N0060
G95 = Feed per revolution  
S50= Meter per Minute

N0065
R20=Pitch  
R21= Start of screw thread in X-direction  
R22= Start of screw thread in de Z-direction  
R24=Depth of screw thread  
R25=Surface depth

N0070
R26=Way in (amount of space)  
R27=Way out (amount of space)  
R28=Number of cycles  
R29=Angle of feed  
R31=End restraint of X  
R32= End restraint of Z  
L97=Screw thread cycle  
P1=Programme number