Sustainable 3D printing using eggshells

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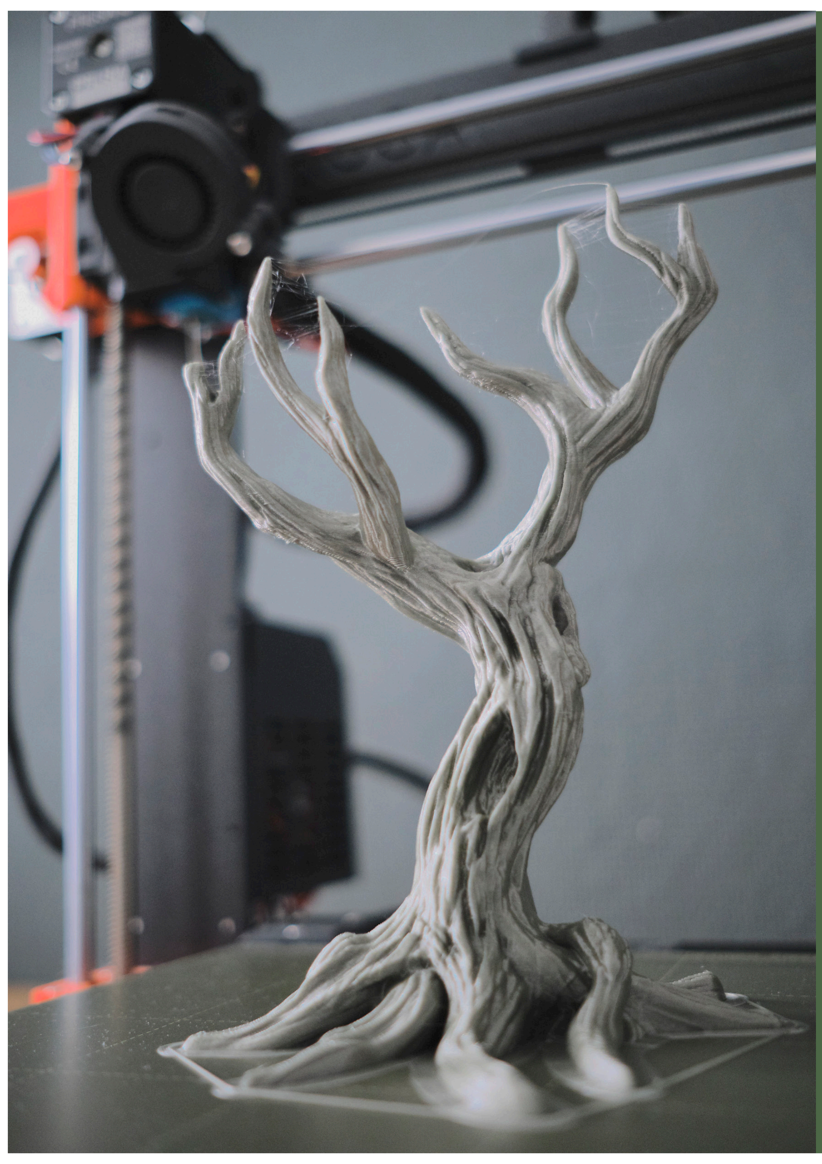


Project Introduction

Additive Manufacturing, or 3D printing, is a relatively new production metholodogy that is famous for its capability to create complex shapes and forms in a small amount of time. It has become a go-to for designers and hobbiest that want to create various and products for professional and personal use. Whereas the potential and opportunities of additive manufacturing are being celebrated by a lot of users, the sustainability side of the methodology does not get that much attention.

While additive manufacturing is faster and consumes less energy than many of the formative and subtractive methodologies when only single items are being made, for the production of larger amounts of products, the methodology is not sustainable at all. For large production numbers, the specific energy consumption (SEC) of additive manufacturing is one hundred times higher than that of formative production methodologies and fifty times higher than that of subtractive production methodologies (Yoon et al., 2014).

In FDM, the major part of energy consumption is used for heating up the heater, which melts the material, and the printbed, with 25.5% of the total energy consumption of the printer being spend on heating up the heater and 47.4% of the total energy consumption of the printer being spend on heating up the printbed (Nguyen et al., 2021).

On top of that, the plastic filaments that are used in FDM printing are made from various valuable, and often non-renewable, resources. Some of the more commonly used filaments are PLA, PETG. PLA is made from valuable, natural resources such as corn, potato, cassave and sugarcane (Castro-Aguirre, 2016), which could also be used as food for people and lifestock. The material is technically recyclable, but is barely done due to a lack of infrastructure to collect and sort PLA products and waste. PETG is made from crude oil and natural gas, which are non-renewable sources. As the material is more commonly used for the production of products and food packaging, it is more commonly recycled. However, most filaments are made from virgin material as recycled plastic often has worse mechanical performance than virgin plastic.

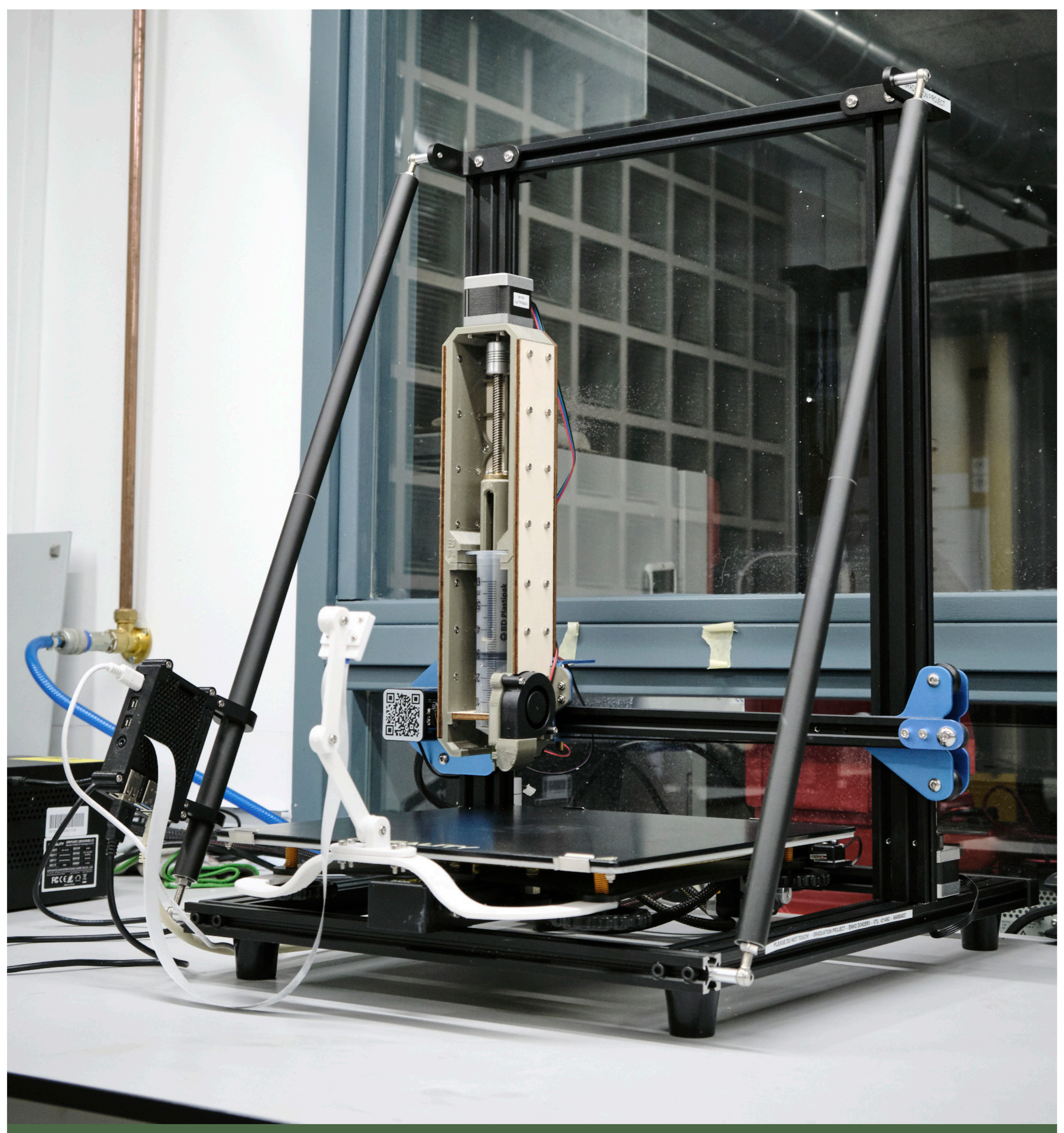
In order to decrease the environmental impact of FDM, new materials should be developed that do not need to be heated up during the printing process, in order to decrease energy consumption of the printer, and are not as reliant on valuable and non-renewable resources, fitting it into a circular economy.

In order to built a frame of reference for newly developed materials, a comparison should be made with the more sustainable filaments that are currently available. These are filaments from recycled plastics. Reflow, the client for this project, manufactures recycled PLA filament (rPLA) and recycled PETG filament (rPETG), which are made from recycled food packaging and recycled serving trays respectively.

To summarize this, the goal of this project is to develop one or more new material mixes that are suitable for FDM printing, give similar or better results than rPLA and rPETG, while being less reliant on valuable and non-renewable resources.

Materials will be assessed on various criteria:

- Printability (ability to extrude, provide self-support, including starting and stopping cleanly, printing time)
- Dimensional Accuracy (not shrinking or warping, matching CAD model dimension)
- Resolution (primarily layer height in Z direction)
- Surface Finish (smooth and uniform surfaces, not rough or broken)
- Price (material cost per kg)
- Environment Impact (carbon footprint, water expenditure, reliance on non-renewable resources)



Printer Modificaton

The first challange in this project was to modify a conventional FDM printer to enable it to print with paste-like material mixes. Paste printers and modification kits already excist, but unfortunately no such printer or kit was available for the project. It was therefore chosen to create a custom modification for a Creality CR-10 V3. The modification consistent of three parts: the hardware, the software and the control unit.

Hardware

A complete new printhead was developed that could fit onto the mounting bracket of the printer. In the design, a stepper motor was used for extrusion, similar to the ones that are used for moving the X-, Y- and Z- axes, as well as extrusion of plastic filament on conventional FDM printers, including the Creality CR-10 V3. This stepper motor was used to drive down a custom plunger into a syringe, pressing out the material mix that is contained in the syringe. As the syringe was fitted with a Luer Lock connector, blunt needles of various sizes could be attached to it, providing users with a certain degree of freedom in playing with linewidth and layer height while printing. While prints were made at roomtemperature and no heat was added, a fan was fitted on the side of the printhead in order to provide prints with cooling. This helped the material to solidify at an accelerated pase in order to have it provide enough support for layers that are put on top of it.

Another adjustment was needed for the printbed. While plastic filaments solidify virtually instantaneously and can be removed from the printbed directly after the print has finished, prints made with paste-like material mix may need more time to dry, depending on their geometry. Therefore, printing directly onto the printbed is not recommended as it will render the printer useless until the print has dried enough to be removed. Instead prints were made on polyethylene sheets, so prints can be moved elsewhere to dry and can then be easily removed from the sheet.

Software

In order to make the printer work well with the newly developed printhead, adjustments had to be made to the printer's firmware. The most important adjustments that have been made were to decrease movement speed of the extrusion motor. Whereas plastic filament is shaped as a thin wire, that has to be pulled into the printhead at decent speed, filament of the modified printer works completely differently as it has a diameter equal to the inner diameter of the syringe, requiring a much lower speed for extrusion. In addition to that, 'cold extrusion' had to be enabled which is a safety setting that would normally prevent the printer to extrude if the heater and heatbed have not reached the elevated temperatures that are needed for printing with plastic filaments.

Control Unit

While the printer is provided with a control unit, it was chosen to use a Raspberry Pi with OctoPi to control the printer. Whereas the printer's control unit requires users to navigate through the menu to move motors on each individual axis and the extrusion motor seperately , OctoPi allows one to have full control in one overview, which was found to be essential for succesfull printing. Especially direct control over the extrusion motor is important in order to make sure is consistent before a print is started.

Material Mix Development

The second challenge of the project was the development of a suitable material mix. From other researches into printing with paste-like material mixes it was found that components can be divided into three categories: fillers, binders and additives. Fillers ingredients that are generally used for their low price and are (partially) responsible for the material mix's colour, texture and mechanical properties. A binder provides the material mix with a matrix which the other ingredients latch onto. Additives are optional ingredients that can enhance specific properties of the material mix.

Eggshells as a filler

Initially no ingredients were specified yet and there was full freedom to test fillers, binders and additives. Later on in the project, it was chosen to use eggshells as a filler. Eggshells would considered to be a very suitable ingredient for a material mix as

- They're available worldwide, making them fit well in a circular economy as eggshells should always be available locally and little transport will be needed.
- There are only a few usecases for eggshells currently, meaning that a lot of the material will be available for use. Some of the current usecases are as a calcium supplement for pets, as a stabilizer for soil and as a ingredient for contruction.

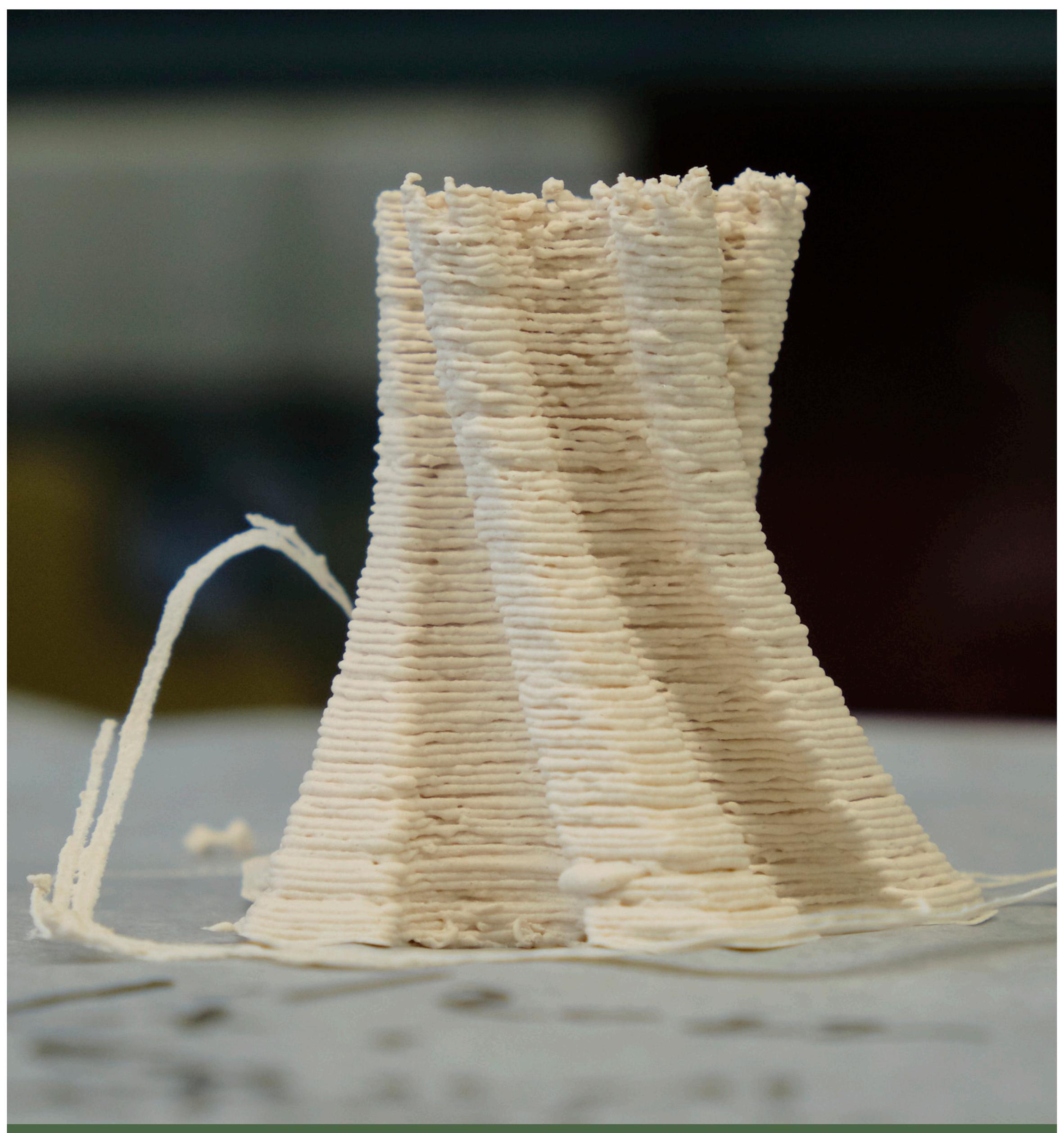
They're considered waste and breaker plants, industrialized plants that seperate the egg from its shell, currently dispose them in landfills, costing them around $100.000 annually.

Finding compatible binders and additives

Throughout the project tests with various binders and additives have been performed at different ratios of ingredients in order to find a material mix that printed well. Some of the binders that have been tested are Elmer's Glue, different types of woodglue, cornstarch, potato starch, xanthan gum and waterglass (sodium silicate). During tests it was found that one of the main problems was drying speed. Most of the tested binders did not dry fast enough for the material mix to provide enough support for next layers, and prints would collapse during or after the printing process.

The Final Material Mix Recipe

The final material mix recipe that was developed throughout the course was a mixture of eggshell powder, sodium silicate and glycerine, at a ratio of 59.1% eggshell powder, 36.4% sodium silicate and 4.5%. In this mixture, the sodium silicate fulfills the role of a binder, providing the other ingredients with a matrix to latch onto. The glycerine was used as an additive and it gave the material mix a smoother texture. Whereas prints without glycerine would feel rough and dry, prints with glycerine were smooth. This mixture would dry fast enough in order to be able to create higher models without them collapsing. Thin-walled objects, such as the vase pictured above, would dry fast enough to be able to pick up the print right after it had finished. Prints with more dense volume, such as cubes, would require a longer time to dry.



Material Mix Assessment

Printability

Extrusion was decent and the material is able to provide self-support, but it is still recommended to supervise the printer while printing, as small inconsistencies in extrusion and other small issues could cause the print to fail. By supervising the print, these issues can be prevented or solved, potentially saving the print.

Dimensional Accuracy

Dimensional accuracy was considerably worse than for the plastic filaments. Whereas the plastic filament generally deviate less than 0.3% from the CAD size, deviations in prints with the material mix reached values of over 5%. Warping of prints was not really an issue as the material mix is quite dense.

Resolution

Resolution of the material mix was lower than resolution of plastic filaments. Whereas plastic filaments can be printed at layer heights of as little as 0.10mm, the lowest layer height that was succesfully printed at with the material mix was 0.42mm. This height is still good enough for getting a reasonable level of detail, but not as good as when printing with plastics.

Surface Finish

Prints were found to be quite wobbly, resulting in uneven surfaces. When printing at lower layer heights, the wobbliness is reduced, but still noticeable. Texture of the material itself is smooth due to the addition of the glycerine.

Price

Pricing for the material mix was based on the prices that were paid for the various ingredients. Based on this prices, it was found that one kilogram of developed material mix was, with a price of €23.60, cheaper than a 1kg roll of rPLA, which is sold for €26.62 and cheaper than a 1kg roll of rPETG, which is sold for €33.88. It should be noted that prices paid for the ingredients were commercial prices and not wholesale prices. At wholesale prices, the material mix should be a lot cheaper.

Environmental Impact

Environmental impact of the printing process should be greatly reduced as the material does not need to be heated up during the printing process. However, energy consumption of the stepper motors should be slightly higher due to increased weight of the modified printhead.

Environmental impact of the materials should also be lower in comparison with the plastic filaments. Eggshells are a natural material that can increase stability in soil and glycerine is a natural alcohol that is also found in the human body, that form little to no threath to the environment unless dumped in large quantities. Sodium silicate is slightly acidic and could be harmful to aquatic and terrestrial organisms, but turns in the harmless silica when dissolved in water.

Conclusion

All in all, the developed material mix performs mediocre at best and cannot be used as a replacement for the plastics. Although print results are interesting and shapes are clearly recognizable, their quality does not come anywhere close to that of print made with rPLA, rPETG or other plastic filaments. New, better recipes should be developed and the process of printing with paste-like materials should be made easier for it to become a suitable alternative for printing with plastic filaments.