‘Closed Loop’ 3D Printing from waste packaging: How to Case Study

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Abstract

During the period 12/12/13 – 25/04/14, Co-oproduct CIC led a project in collaboration with Nestlé Research and NTU to explore the feasibility of a small scale ‘Closed Loop’ 3D Printing solution, using recycled/waste plastic as feedstock for educational use.

With support from the Technology Strategy Board, Nestle’, UnLTD and Nottingham Trent University; we carried out research and development work and built our own first stage prototype 3D printing system, which was capable of printing from recycled plastic waste.

We made various developments and innovations for the successful production of printable filament from recycled Polypropylene (PP) packaging/waste. To our knowledge, we are the first to document/publish printed objects from this particular waste packaging polymer, which may otherwise go to landfill.

The solution aimed to maximise the embodied energy of ‘waste’ polymers, through clever re-use of them, thereby reducing carbon emissions through the on-site ‘closed loop’ innovation. In addition, we wanted to reduce water consumption, since the most popular feedstock used is PLA and has a very high water footprint. We commissioned an independent report by 3DP/AM experts Econolyst to evaluate our work by carrying out Life Cycle Assessments (LCA) and Market Research.

According to our independent LCA (March 2014), our proposed closed loop reuse of PP packaging via 3D Printing, potentially uses 20 MJ less energy and 50% less water per 1Kg than the current, most popular 3D printing solution.

Additionally, our report estimated that there is a market for some 10,000 3D printing machines within UK industry, 4,000 within UK secondary schools and some 1,400 within Universities and Colleges, giving a total market opportunity of 15,400 units.

In April 2015, for our work on this project, we were declared winners of the ‘Responsible Waste Management’ category of the RSA City of London Sustainable City Awards and runners up for the ‘Resource Conservation’ category.

The majority of the knowledge required for the successful development of the solution was acquired without cost, via global community sharing networks and forums. Most of this information was new to the team and all major developments were achieved through ‘hands-on’ practice, crafting and experimentation. This is our story.

Introduction to Project

In Sept 2003, when I was first appointed as Senior Lecturer in Product Design at Nottingham Trent University, during a tour around our workshops I was introduced to a brand new 'powder' 3D printer. I was amazed at the implications and potential of this new technology and immediately, without hesitation, I turned to my colleagues and said: "In 10 years time, we'll be printing houses?" At the time, it generated a lot of blank faces and perhaps it seemed like a silly idea – although I actually meant it!

On reflection, this 'prediction' was really quite an obvious guess because as we were all later to realise, in principle 3D Printing (3DP) is just another extrusion device, controlled by software and we've been working with these types of machines for a very long time.

As luck would have it, in March 2014, WinSun, a private company from east China successfully used a giant 3D Printer set to print out ten full-sized houses within just one day[1] . When I discovered this, I turned to my colleagues and said: "In 11 years time, we will be printing cities". Once again I meant it.

During the twelve plus years, since my first introduction to 3DP technology, a lot has changed, as have my aspirations. Today, to paraphrase Google Ventures Design Partner, Braden Kowitz (Design Disruptors 2016) I'm not so interested in whether we can build something, because more and more we are realising that we can build almost anything. Today, along with many other designers across the world, I'm far more interested in exploring what kind of future we want to build together.

Context: Open Information Changing Design

The growing attitude in what might be described as the 'social potential of design' has been motivated by an explosion in technologies that have enabled very easy access to information and knowledge on a huge range of subjects - covering almost anything. Resources such as You Tube, Instructables, Thingiverse, Twitter, Instagram, Facebook, etc. and all the other 'social' platforms and forums have been slowly influencing many other areas of our lives and changing our perception of ourselves and the world around us. Although public 'sharing' culture isn't really a new phenomenon[2] , the technology that supports it is and the way in which new information is so rapidly delivered, so easily accessible and so seamlessly woven into our everyday lives means that in theory, anyone can access any of it, at anytime and from anywhere.

If we look for it, more likely than not, we can find information on any subject. So many of us use these types of information portals to fix our phones, laptops and other domestic devices, make home improvements and some of us learn new skills, both physical (making) and virtual (software). Today, it is easy to accept that we can build almost anything, but still just as difficult to have the vision of what future we might want to build together?

The reality of design is the production of material culture. We can observe how a range of open information made available to us through these types of networked digital environments, are influencing design thinking and changing design education programmes. In establishing the new BA (Hons) Design programme at Plymouth College of Art, we have incorporated 3 principle phenomenon's evident in open sharing cultures ('Environmental Degradation', 'Social/Open/Frugal Innovation' & 'Interaction') and these are central to the entire programme framework, conditioning how the programme prepares the designers of the future.

Environmental Degradation

Designers play a very central role in contributing to environmental degradation, since design and the production of material culture drives consumption. Consumption requires a constant flow of resources and infrastructure - currently estimated at 50 per cent more than the planet can provide (The World Counts 2016) and the majority of designers haven't proved very prolific in influencing a sustainable balance of natural resources against manufacturing demand.

A global approach to sustainable design practice is necessary through the re-evaluation of existing resources and ethical practice. This will include considerations of alternative systems, materials, resources and processes - such as design for reuse, upcycling, recycling, repair, disassembly, remanufacture, upgrade, sharing and other logistical or unconventional creative innovations.

Social/Open/Frugal Innovation

There are many new emerging trends, cultures and methods that actively seek to disrupt the status quo, by challenging existing conventions and ideologies. Designers need to understand how the global phenomenon in new democratic, open, social and frugal forms of innovation such as ‘Making, DIY and Sharing Culture’ are changing and shaping the traditional role of the designer.

It is important to note here that open and free sharing of information is potentially good for innovation and new ideas development. Author of Democratizing Innovation, Eric Von Hippel discusses how Intellectual Property Law, though the creation of ‘Patent Thickets’ actually stifles innovation and creates a risk adverse culture. von Hippel gives an example of some corporations’ R&D budget reducing, when its registration of Patents increases (von Hippel 2006) and this indicates that there may be more commercial interest in protecting ideas, rather than developing them? However, the free sharing of ideas means that intellectual property cannot be monopolised in this way; since it is already in the public domain. Actually, there are countless examples of where open sharing of ideas has resulted in innovation and design realisation (Billing and Cordingley 2011).

Interaction

The recent explosion and convergence in software and data production, means that objects and information are fluid ‘tangles’ of complex and responsive systems. The evolution of architecture and infrastructure to support this data means that networks are comprised of multiple, evolutionary layers of dynamic and intelligent platforms. To date, designers and the design profession haven’t established themselves as a vital influence in the manifestation of software and data production, yet all of design history and research indicates that designers could have significant positive influence in the evolution and experience of these new products. The bridging of digital and physical environments through interaction design methods would include, 3DP software and app. development as well as an appreciation of how design thinking can influence systems, network design and global infrastructure solutions.

There are examples of mainstream traditional undergraduate design education and training producing very able design practitioners, who are well equipped with the necessary skills and knowledge to develop creative solutions for current demands. However, this conventional design education and training framework has not been as effective in equipping designers with the appropriate skills and knowledge to address many of our emerging future demands. In particular, designers need a much better understanding of their relationship with the resources and communities that they so heavily rely on. This is necessary in order to create more harmonious and sustainable use of existing resources and to explore potential alternatives for constantly emerging new design solutions. We need educational programmes for design that will introduce these new evolutionary changes; helping develop designers who can reflect and respond to the challenges they present.

3D Printer Build

Without specialist 3DP experience, but inspired by open resources the project aimed to build a 3DP solution capable of printing parts from Polypropylene (PP) plastic waste, in order to demonstrate a ‘closed loop’ concept is in fact possible[4]. We chose PP because it is a very widely produced plastic, due to its fantastic qualities and applications and we suspected that the majority of it (about 95 per cent) goes to landfill. At the time of the project, there were limited, if any commercial 3DP activities who publicly shared any evidence of exploring the potential to recycle plastic waste as feedstock for 3DP. Many commercial organisations discussed it, but none, it seemed had proven the potential to actually achieve it. Only the Perpetual Plastic Project whose work explored new potentials for closed loop recycling of plastic waste, with their educational installation at Dutch Design Week in 2012 (Perpetual Plastic Project 2016) and others. The Perpetual Plastic Project openly shared their innovation and became an inspiration for our ‘Closed Loop’ 3D Printing from waste packaging project.

From the onset of the project it was obvious that, in a project of this nature, constant development changes to the prototype solution would be inevitable - both physically and in terms of its control through software. For this reason, the project adopted the open source 3DP RepRap Prusa and Arduino software platform as the test unit for all the work to come. The RepRap could be constructed from 'scratch' or built from a kit, for just under £500 and there was (and still is) a huge amount of data already freely available on the internet, which outlined how to build and set up the RepRap Prusa (RepRap 2016).

Building the 3D printer allowed the team to demystify the technology and understand how the printer functioned on a very practical level, since it was constructed from physical parts made primarily from metals and plastics. This approach allowed the team working on the project to get as close as needed to the basic technology; which offered significant control when making any necessary changes to demonstrate the principle, that 3DP from waste plastic is quite possible and may be easier than the team first thought.

3D Filament & Feedstock

Originally, the project proposed to mount a small 'oven' unit on to the gantry of the RepRap, where plastic waste parts could be discarded, heated, and then extruded directly on to the print bed as new 3DP parts. This was intended as an ideal scenario for proof of 'closed loop' potential, since it would have demonstrated conceivable circular economy usage; theoretically allowing anyone to recycle their plastic and turn it into new prints, without the need for any additional preparation processes (cleaning, shredding, extruding into filament etc). However, the very short project timeframe and relatively small budget made this particular proposal unrealistic. For this reason the idea was discarded and instead, the team turned their attention to researching suitable filament extruders; with the intention of creating filament from plastic waste, although at this stage it wasn't clear what problems this decision might also present.

Even in 2013, there was already a large choice of 3DP Filament Extruders although mainly developed, produced and exported from the US. The trend in small scale 3DP had already began and this had resulted in a number of crowd-funded Filament Extruders, which supported the growing demand for 3DP hobbyists who wanted to make their own filament to keep costs down.

However, the team were unsuccessful in locating a Filament Extruder designed to recycle (PP) plastic waste and even the 'Filabot' (Filabot 2016), which, at the time claimed to recycle plastic filament, didn't provide any evidence of successfully doing so. After some investigation and in the absence of any suitable 'off the shelf' solutions, the team realised as with the printer, that constant development changes and modifications to the filament extruder would also be likely. The possibility of building a bespoke filament extruder for the specific purposes of the project were not feasible, due to project timeframe and the decision was made to purchase a filament extruder from a UK based company called NozTek. This was the best option and NozTek were keen to help us explore the potential to create recycled filament from plastic waste.

Nestle' Research agreed to collaborate as a packaging sponsor and wanted to use their (PP) packaging material in the form of their well known Quality Street tubs, as the first test waste PP plastic which would theoretically be converted into new printed objects. Initial desk research into 3DP from Polypropylene revealed very little work had been carried out in the area and what little had been explored had been dismissed early, since at the time, the problems presented by PP were perhaps too great a challenge[5]. Other virgin polymers (ABS, HDPE and PLA) were much easier to work with and were already achieving easy 3DP results.

Its is interesting to note here that it is perhaps due to these early 3DP feedstock investigations by others and the very quick market adoption of alternative polymers (which were much easier to 3DP), that allowed us to innovate in this area. If the 3DP revolution had been less concerned with printing successful parts from plastics and a little more disruptive, others may have explored the possibilities of 3DP from PP in more detail, much earlier than our project did.

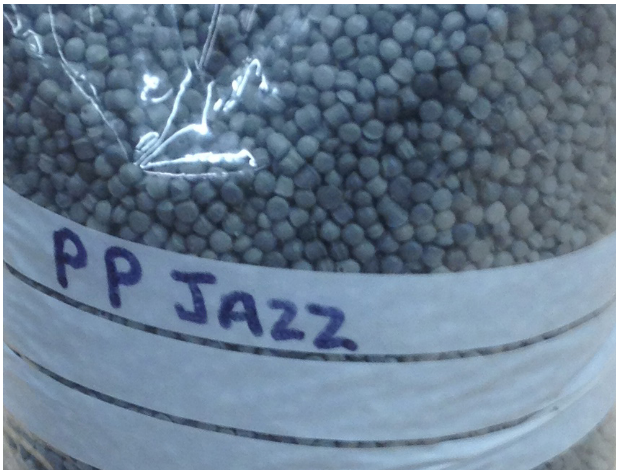
Preparing Waste Plastic for Filament Extrusion

Primary and secondary research into preparation processes and techniques for cleaning, shredding and extruding waste plastic packaging concluded in the team adopting a simple hand-cutting method, using scissors to create small plastic shards from the Quality Street Packaging.

©Co-oproduct CIC. Hand cut Quality Street Shards.

There were a number of alternative production methods explored, including mechanised shredding using sheet-based office paper and plastic shredders as well as industrial shredding units for larger and denser plastics. Of particular interest was the inspirational and pragmatic work of Braanker et al. in a project entitled Developing a plastics recycling add-on for the RepRap 3D printer exploring the potential of creating 3DP filament from waste HDPE (Milk Cartons), using a food blender and within a domestic environment (Braanker et al. 2010). However, the decision was made to discard mechanised shredding processes like this and adopt hand preparation methods since, they were quicker in the short term. In a project of this timeframe, it was not considered a priority to explore mass manufacturing techniques and pursuing this area of investigation would have consumed too much time and possibly compromised the overall aim of the project. The team felt that if the project could provide proof of concept using hand preparation methods, mass-manufacturing techniques could be explored at a later date.

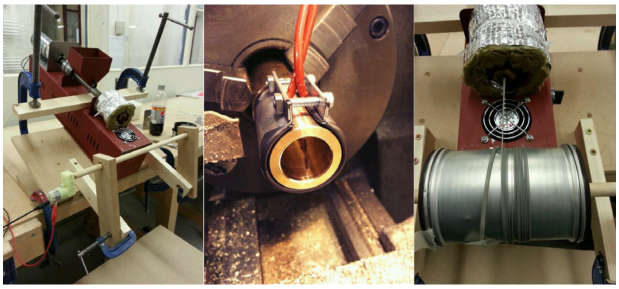
However, there were downsides of hand preparing PP packaging – particularly the time and skill that it takes to hand cut the Quality Street tubs into adequate quantities of shards, small enough to use in the filament extruder. Ideally, the plastic shards should be symmetrical and small enough to sit in the thread of the extruder screw. Each test would require a significant amount of work and results were not forthcoming quickly, since tests involved systematically exploring multiple extrusion speeds, temperatures, cooling methods as well as 'in' and 'out' feed control. The decision was rapidly made to obtain an alternative PP waste material; already in pellet/shard format and this manifested itself in as PP (Jazz) pellets made from crisp packet wrappers by Biffa Polymers in Redcar, near Middlesbrough.



©Co-oproduct CIC. PP Jazz Pellets made from crisp packet wrappers

Obtaining Printable Filament from waste PP Pellets

The PP pellets proved extremely useful and enabled the team to carry out multiple extrusion tests very quickly, in order to identify key innovations in working with the material in this way. Initial findings identified combinations of successful extrusion speeds, heating temperatures and out feed control innovations; all of which indicated the need for a number of modifications to the filament production process, in order to move the project forward.



©Co-oproduct CIC. A number of modifications to the filament production process were necessary.

At this stage, the project was concerned with obtaining printable filament from the PP Pellets, in order to establish production methods and techniques that would work for other types of PP in particular the Quality Street tubs.

For a filament to be printable it has to be consistent. ‘Consistent filament’ must be of a constant fixed diameter and decent length as well as also being chemically consistent, without contaminants or pockets of air. This is important so that there are no surprises for the 3DP when running its programme; since the 3DP assumes that the material is constant in quantity and chemical makeup and cannot compensate for any differences to ‘the programme’. When inconsistent filament is used, it usually results in a ‘failed’ print job, due to either too much or too little material being extruded on to the print bed. This has the physical effect of the part having empty pockets (which can not be built upon) and/or a build up of too much material in one or more areas (again prohibiting build).

©Co-oproduct CIC. Failed print job, due to inconsistent filament.

Mass production of 3DP filament has evolved to a stage where successful production of consistent printable filament from virgin plastics is a well trialled operation. Producing consistent printable filament from virgin plastic pellets, using small-scale production technologies (like those used in this project) is not an easy feat and doing so from recycled waste PP is a real challenge! Most significantly, PP is a thermoplastic and as such, remembers its cooled state – which is literally woven into its molecules, causing it to shrink[6] when cooled. This is the predominant characteristic of PP and when working with it in this way, it seems that PP will fight very hard to do whatever it can to get back to ‘normal’, as it starts to cool down.

©Co-oproduct CIC. PP can behave in unusual ways when it begins to cool.

<u>Modifications to the NozTek Filament Extruder</u>

There were a number of modifications that were made to the NozTek extruder in order to test and trial alternative methods for producing consistent, printable filament. These included an additional heating element, the manufacture of a new die/nozzle for the extruder, various cooling (air and water), a number of out feed control systems and spooling as well as gravity-inspired mounting systems.

All of the modifications had a multitude of effects on the filament produced and each result was correlated against the differing modifications and methods. For example, allowing the filament to slowly cool naturally (by air) only achieved workable results if the out feed control operated at a particular speed and spooled according to specific gravitational circumstances.

We found success in 'stretching' the PP as it exited the filament extruder, but we had to be careful to adapt the out feed control speed, so as to not over-stretch the PP, which would make its diameter unsuitable/too thin. Likewise, if the PP were not stretched on its exit, it would be too thick and lumpy.

Since we were not treating the process as a science and as novices to the work we were carrying out, were instead tackling the problem head on - 'on the hoof', so to speak. We didn't meticulously record each experiment; we didn't have the experience, time or manpower to record everything, if we were going to achieve our main aim. Everything about our approach was practical and hands-on. We hacked a printer, we hacked a filament extruder and we were pretty sure that we could hack our way through these problems also. This practical approach enabled us to move faster in our work and we did get a 'feel' for what was working and when something good happened, we would seek specialist advice within Nottingham Trent University or search the vast amounts of data using Internet resources.

The team had already learned that the PP liked to cool slowly, which seemed to produce more consistent filament. The nozzle that we were using (already fitted to the extruder on arrival) was quite short in length, for use with PLA, which is a plant polymer with different characteristics to that of PP. Most notably, PLA doesn't requite such high temperatures to melt and dries very brittle, without the oily elastic quality to that of waste PP. Checking with our specialist advisors, we wondered whether a longer nozzle would 'encourage' the PP to extrude more consistently, since it should help stabilise the plastic by 'straighten' it as it cooled. Our specialist advisors confirmed that the PP perhaps needed to cool slowly and a longer nozzle would help us produce a straighter, more consistent filament.

©Jamie billing. New filament extruder nozzle produced at NTU by Kerry Truman.

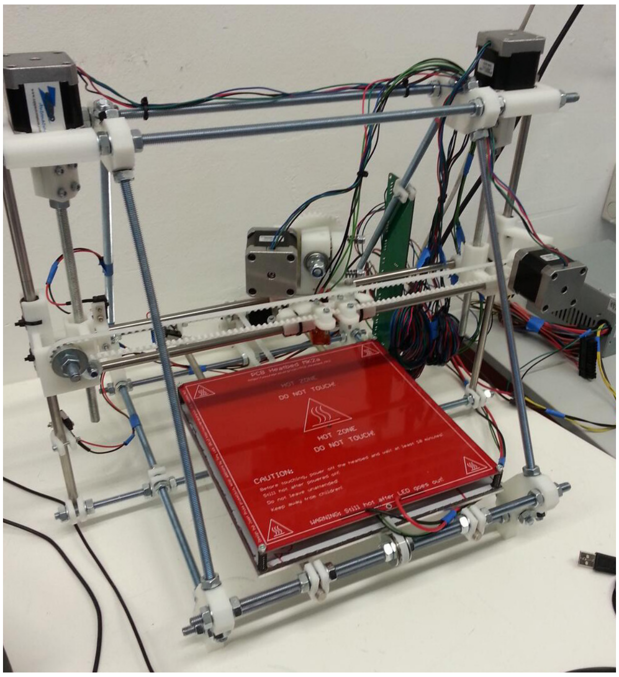
Finally, after making many modifications, trying many different methods and spending a long time watching filament cool, we managed to reach a system set-up that allowed us to produce several meters of consistent filament from waste PP Pellets, helped immensely by our extended new extruder nozzle.

©Co-oproduct CIC. Examples of successful production of consistent filament from waste PP

Printing

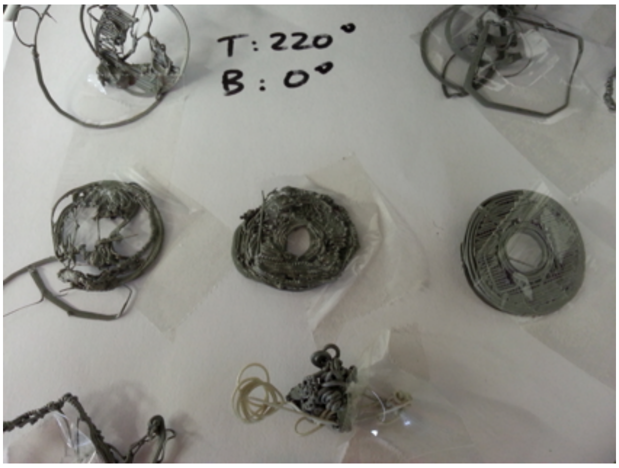
Most commonly, PP is used in injection moulding processes and its shrinking characteristics are well suited to moulding; since by shrinking in the mould as it cools, makes removing it from the mould a simple and smoother operation. However, its shrinking qualities are not so useful in the 3D Printing process, as the effect on the print bed, is 'contraction', 'movement' and 'warping', and as any hobbyist or 3DP specialist knows, its pretty impossible to build a 3D printed part if each layer is contracting, moving and warping! 3D printing is a precise 'additive' process and works by building 'layers' of material on top of the previous layer. Even if good quality 'consistent' PP filament can be produced from waste packaging materials, getting the plastic to 'behave' on the print bed is another matter entirely.

Once the RepRap had been constructed, Arduino firmware installed and control successfully tested through an application called Slic3r, the printer was calibrated using pre-purchased manufactured virgin PLA in filament form. Various calibration tests were conducted using free calibration files downloaded from Thingiverse and when the team were content with the quality of 3D printed calibration objects using the virgin PLA, we moved to experiment with the PP– initially first with recycled pellets made from crisp packets, but with the intention of moving on to the Quality Street tubs as soon as possible.

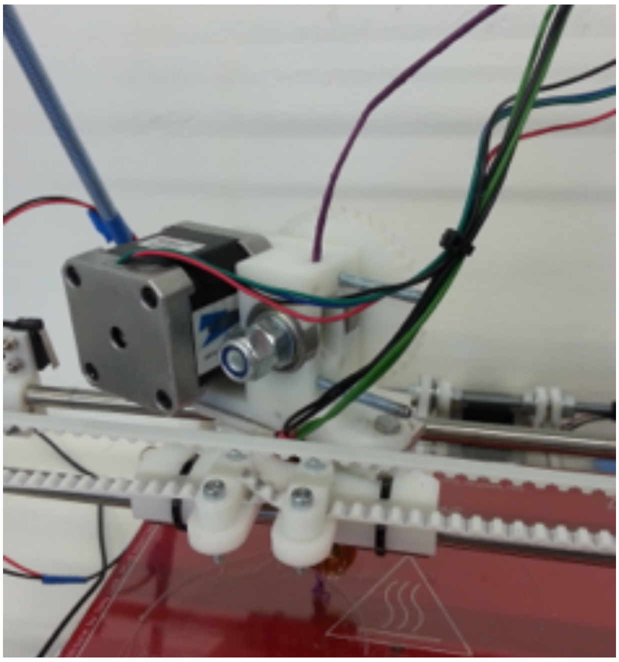


©Co-oproduct CIC. Completed RepRap Build.

Even with a calibrated 3D Printer, the 3D Print tests using PP proved challenging. The PP shrank, contracted and warped as it cooled on the print bed and this made it impossible to accurately build anything meaningful. We made numerous changes to the many variables in the Slic3r application (wall thickness, filament temperatures, sizes, speeds etc) and trailed varying print files from a number of different sources (including our own), but we could not entirely stop the PP from moving as it cooled.



©Co-oproduct CIC. Range of failed print tests.



RepRap print head.

We tried many ways to control the PP by changing the material of the print bed – we even tried 'keying' it into 'breadboard' used for electronics prototyping, but the PP still moved too much for us to run a print job for long enough. Additionally, whilst we had managed to produce a consistent filament, the waste PP would often jam in the print head, forcing the job to fail.

The elasticity of PP is a wonderful thing. It makes it a very popular plastic for all sorts of manufacture. Even when it has completely cooled, it still moves a little and it doesn't fracture as easy as other polymers do. This is incredibly useful with many, many applications for its use. However, its elasticity causes a problem when you try to feed it through the 'Hot End' of a 3D printer. In filament form, as the mechanisms in the print head clamp and push it into the Hot End, towards the 3D printer nozzle, the PP is heated and begins to melt. The principle is that the melted plastic builds up in the small chamber of the Hot end and the backpressure caused by the constant feeding of new hard filament, forces it forwards where it is heated and extruded through the very small (0.4mm) nozzle, then on to the print bed. But these mechanisms move the material according to a programme that has been pre-defined, according to all sorts of variables, usually previously set for other polymers (ABS, PLA). These polymers are harder and do not usually bend under this type of pressure, when they are cool. PP does and as it does so, the backpressure is reduced and it stops extruding. We found that, even when we got some success with the PP stabilising on the print bed, often the job failed because the PP would build up and jam in the hot end of the print head.

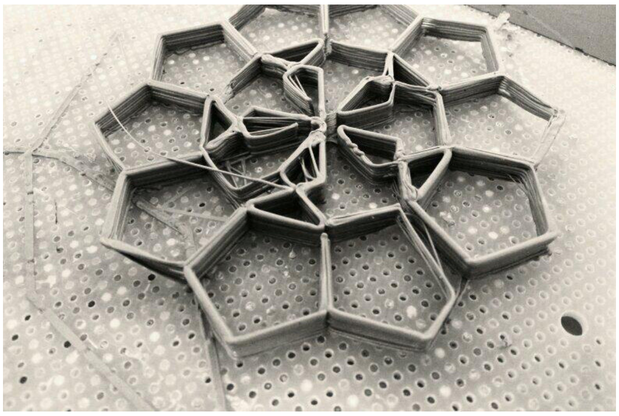
<u>Quality Street</u>

Primarily, for the most part of the project duration, we had been working with the waste PP Pellets (Jazz) due to previous rationale regarding the convenience of feedstock available through our established ability to bulk produce consistent and printable filament. However, we did carry out some early tests using the Quality Street tubs, which behaved in the same way to that of the PP Pellets and at the very end of the project, we successfully shredded, extruded and printed from the Quality Street tubs.

©Co-oproduct CIC. Quality Street shredded & extruded into printable filament.

<u>Stabilising PP with Minerals, Fillers & Reinforcements</u>

Eventually, with the project deadline approaching and because of the bending behaviour the PP often displayed in the Hot End of the 3D printer extruder, we began to manually feed the waste PP filament into the print head, (using our own hands and fingers). This allowed us to prevent the PP from bending and failing the print job. We hadn't fully resolved the issues caused by the PP warping on the print bed, but we did manage to complete a number of small jobs before the PP became unmanageable. Additionally, our resident Chemical Engineers suggested that we might overcome the warping and bending by experimenting with modifying the PP with minerals, fillers & reinforcements during initial extrusion into filament. By introducing Talc or Wollastonite filled PP for improved stiffness or Glass Fibre to increase the tensile strength, we might be able to reach a compromise and get a more usable form of recycled PP filament.



©Co-oproduct CIC. 3D Printed part from Waste PP.

Evaluation

We commissioned a report from 3D Printer experts Econolyst. The aim of the report was to carry out Life Cycle Assessment (LCA) against the best in class competitor 3D Print solution at the time (Makerbot Replicator) as well as some initial Market Research into potential demand for our new 'Closed Loop' system. The results of the report were very favourable with some compelling research into the potential for such a system in the Education Sector[7] as well as some substantial energy and water savings due to our new proposal[8].

1 See http://www.cnet.com/uk/news/worlds-first-3d-printed-apartment-building-constructed-in-china.
2 Consider that we've been sharing information through publications such as journals, newspapers and more recently television for over 100 years.
3 The most popular example would be iFixit, which is a private company in San Luis Obispo, California. Founded in 2003 while the founders were attending Cal Poly, the company sells repair parts and publishes free wiki-like online repair guides for consumer electronics and gadgets on its web site.
4 By using a recycled feedstock, it is possible to offset up to 50% of the embedded CO2 in 3D printing material.
5 PP has a memory and when it cools wants to return to its previous state. When cooling on the print bed, PP will often warp upwards at the edges, which makes it impossible to build on.
6 Moulding shrinkage of polypropylene is typically around 1%, but prediction of the actual value is difficult due to the strong influence of moulding conditions. See http://www.bpf.co.uk/plastipedia/polymers/pp.aspx for more information on PP shrinkage.
7 Potential demand being 10,000 3D printing machines within UK industry, 4,000 within UK secondary schools and some 1,400 within Universities and Colleges, giving a total market opportunity of 15,400 units).
8 Proposed closed loop reuse of PP packaging via 3D Printing, could potentially use 20 MJ less energy and 50% less water per 1Kg than the current, most popular 3D printing solution.

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Acknowledgements

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i The Research Excellence Framework (REF) is responsible for appraising the impact of research in UK Higher Education.
ii See also Indra Kagis McEwen's book, Socrates' Ancestor: An Essay on Architectural Beginnings (MIT, 1993)
iii Marcel Proust in Remembrance of Things Past 1923
iv https://vimeo.com/9498805
v Anders Gammelgaard Nielsen, Aarhus School of Architecture, Denmark
vi See http://www.studioswine.com/can-city

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