Appendices to MRes Thesis of Andrew James Drummond, 2024 – Digital Edition

Appendix A: Information posters on common concepts, materials and processes in polymer science and engineering, prepared for the initial engagement event.
Pages 2-17

Appendix B: Transcript of the initial engagement event (not included in digital edition).

Appendix C: List of coded quotes from the transcript, and list of codes by frequency and order of mention.
Pages 18-28

Appendix D: Account of my visit to the Plastic@Bay workshop.
Pages 29-37

Appendix E: Ethics forms.
Pages 38-40

Appendix F: Transcript of interview with the staff of Plastic@Bay (not included in digital edition).

Appendix G: Material explorations – technical report on experiments with small-scale plastic recycling techniques at ReBOOT and Moray Reach Out.
Pages 41-60

Appendix H: ReBOOT Tour Video – a whistle-stop tour of the main recycling operations and plastic processing at ReBOOT, Forres, as of 2020. Backing music by Scott Holmes.
(MP4 file provided)

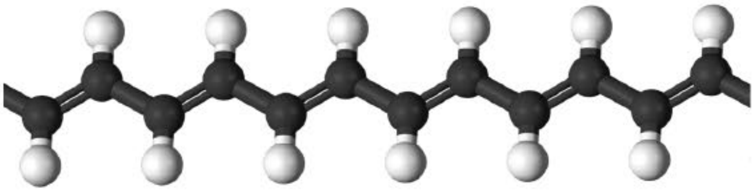
Appendix I: Transcript of the first online workshop and follow-up (not included in digital edition).

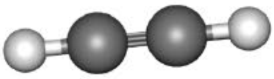
Appendix J: Transcript of the second online workshop and follow-up (not included in digital edition).

Appendix K: High-resolution screen captures of the Miro virtual whiteboard space and virtual analysis on the wall
(JPEG files provided)

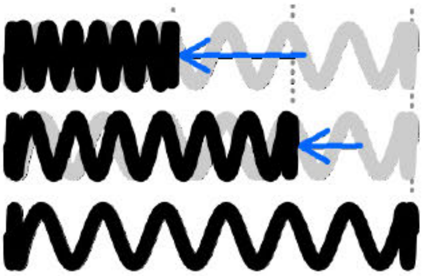
An Introduction to Plastic Mechanics

A polymer (from Greek poly + méros, literally "many parts") is a material made up of very long molecules, constructed as chains of smaller molecules (monomers) joined with chemical links.





We call these *plastic* materials due to their physical behaviour:



In engineering terminology, when an object stretches or bends under stress and then returns to its original shape when released, we call this elastic deformation.

When an object is stretched or bent, but stays in its new shape when that force is removed, then we call this plastic deformation.

Ductile materials such as metals display a significant measure of both, for example a structural steel will stretch or bend elastically up to its *yield strength*, after which any more force will cause permanent damage. This is often visible in bent rods and dented panels. The large amount of impact energy absorbed by this process is what makes steel such a safe building material.

Brittle materials such as glasses and concrete only deform elastically before they break suddenly, with little warning.

Plastic materials are called so because of the extreme plastic deformation they will go through without breaking, when at the right temperature.
This allows them to be stretched from a small block of material into a large thin-walled container, many times the original piece's size.

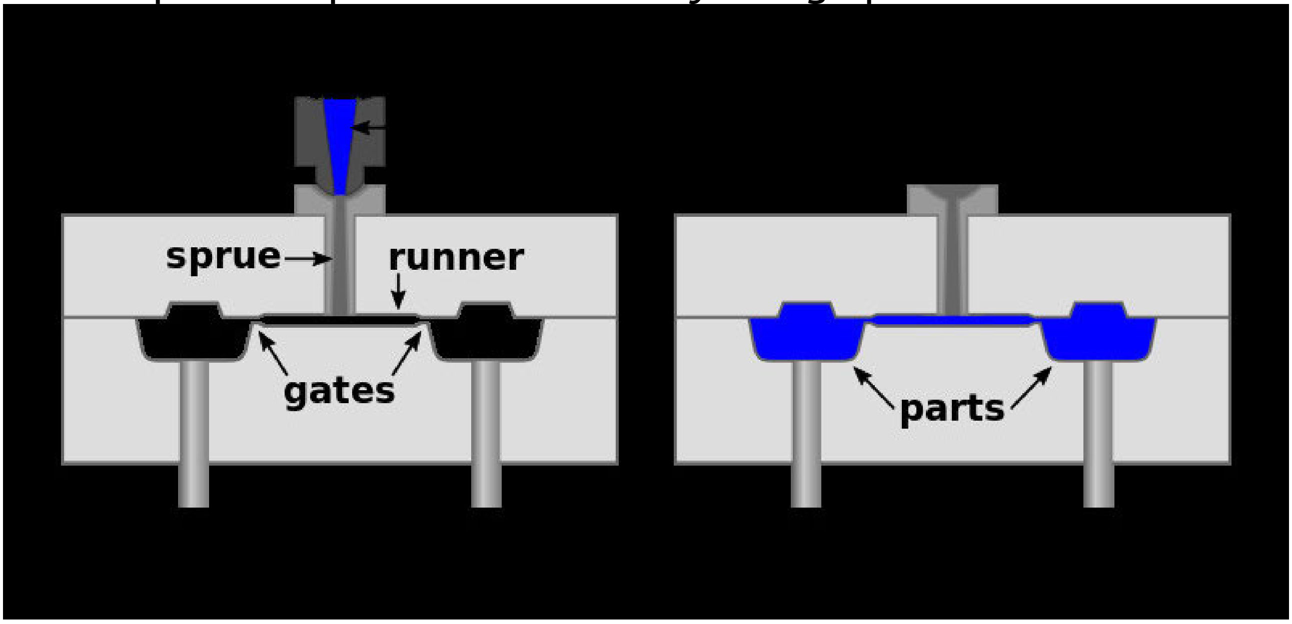
Most polymers exhibit two different states while still solid: a glassy state at lower temperatures, where they are more rigid and relatively brittle, and a plastic state at higher temperatures, where they show the easy workability described above, and significantly lower stiffness.

The temperature at which a polymer goes through this change is known as its glass transition temperature, and is crucial to knowing its practical applications, for instance, the ability to hold a hot drink.

All text by Andrew Drummond, all images via Wikimedia Commons:
PolyAcetylene ball-and-stick model – Ben Mills and Jynto.
Acetylene ball-and-stick model – MarinaVladivostok.
Springs - Jorge Stolfi. James Randi's Fork - Jud McCranie. PET bottle – Nicole Gordine.
Fractured reinforced concrete column – Polyparadigm. Deformed PLA cup – Ginbot86.

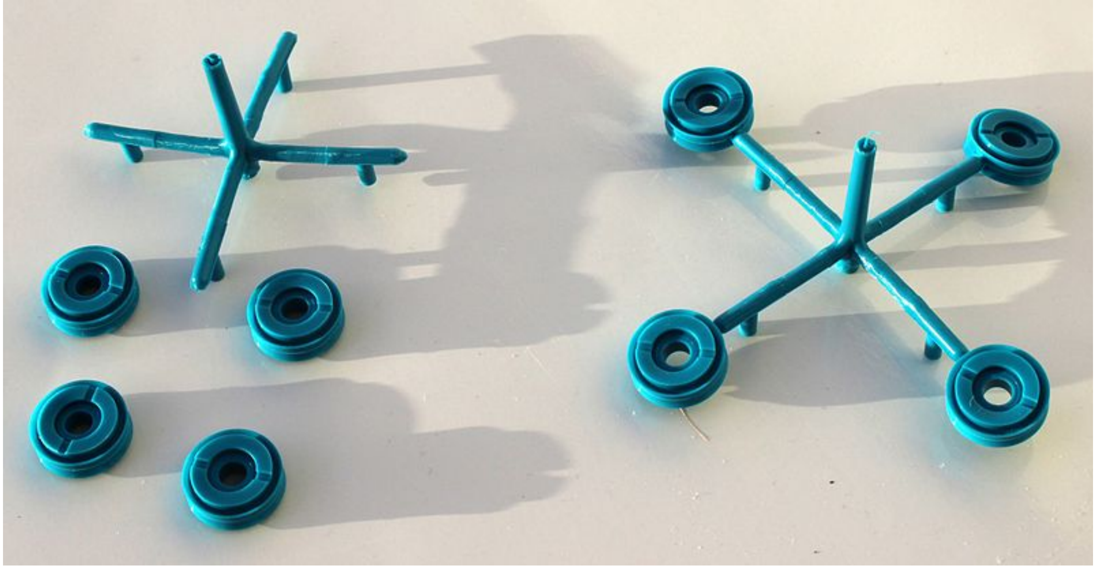
Injection Moulding

Molten plastic is pushed into a cavity at high pressure.



Features:

- High start-up cost due to moulding platen production.
- Process can be reused many (millions of) times.
- Very low unit cost when repeated with automation.
- Typically used in centralised production for globalised trade.
- Shape is limited by what you can remove from a mould.
- Industrial plastic injection machines are heavy and expensive.
- Some waste plastic in runners to cut off and recycle.

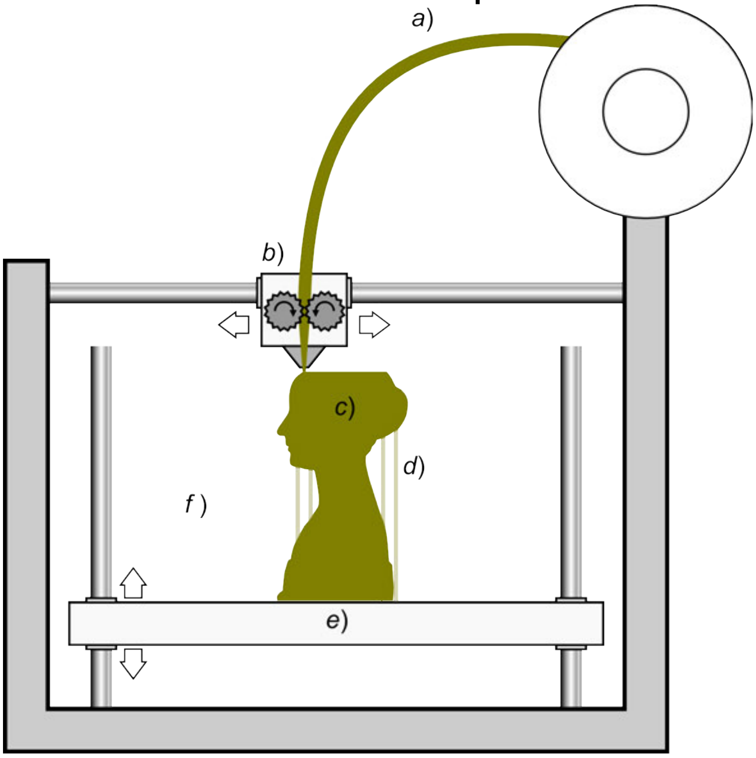


Text by Andrew Drummond; diagram by Ariel Cornejo and photo by Gmhofmann on Wikimedia Commons.

(Filament) 3D Printing

Technical term: Fused Deposition Modelling

A polymer filament is pushed through a fine heated nozzle, moved around by motors to draw cross-sections of a product design. Molten plastic laid down bonds to the previous solidified layer.



Key: (a)filament, (b)extruder with heated nozzle, (c)printed pattern, (d)removable support structures, (e)build platform.

Historically used for Rapid Prototyping.

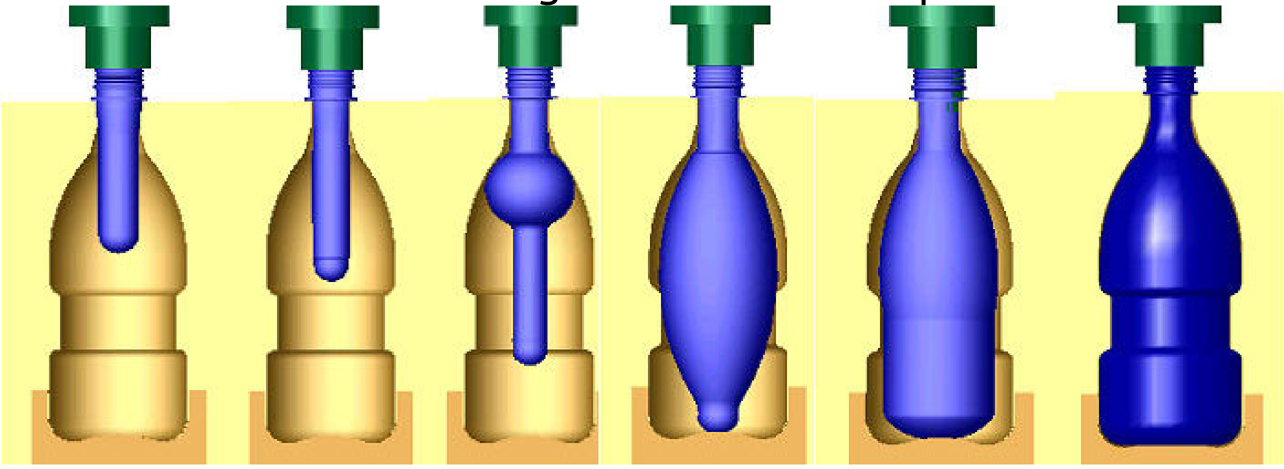
Features:

- Modest cost for production of a unique or small-run product.
- Products are relatively fragile to stress in directions that peel layers apart, compared to a moulded product.
- Almost no plastic is wasted in production.
- Some plastic materials shrink too much when they solidify, causing products to warp out of the desired shape.
- Can produce shapes with inner features impossible to reach by moulding processes, such as pre-placed slots for fasteners.
- Difficult to print overhangs under gravity without supports.
- Can be used to provide moulds for much stronger parts created through metal casting.

Text by Andrew Drummond, diagram by Paolo Cignoni on Wikimedia Commons.

Blow Moulding

A pre-formed blank is stretched into a larger mould by pressurised hot air above the material's glass transition temperature.



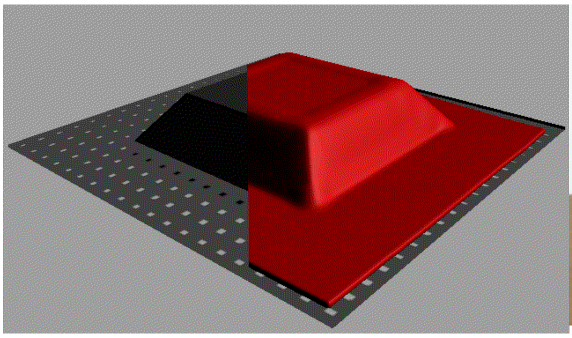
After the material cools while kept under pressure, it retains this shape in its glassy state until heated again.

Features:

- Very lightweight large products such as drinks bottles can be formed, using very little material.
- Products may suddenly deform if exposed to heat.

Vacuum Forming

A sheet is drawn over a shape on a grille by vacuum pressure.



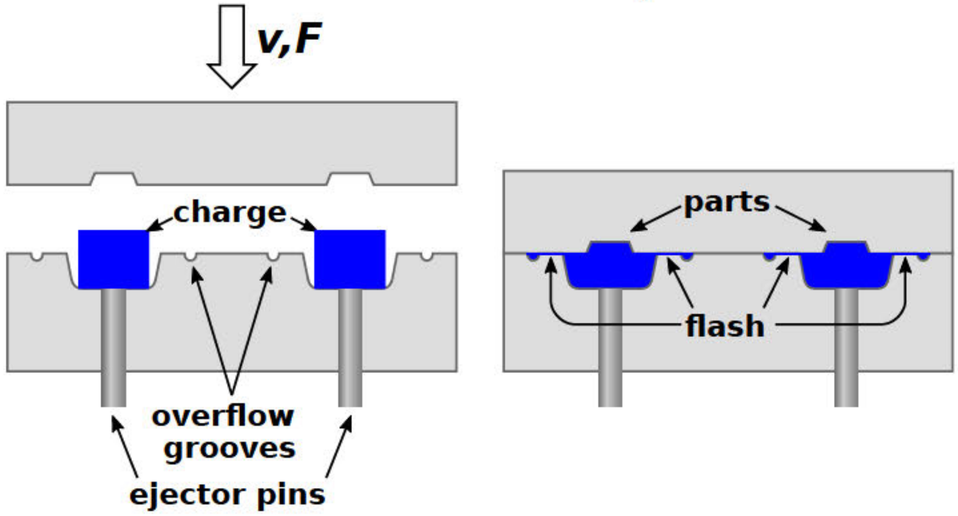
Features:

- Cheap and easy to set up – can be as simple as a drilled-out box connected to a vacuum cleaner, heated by a hair dryer.
- Produces a large amount of waste to be recycled.

Text by Andrew Drummond, blow moulding diagram by Ottmar Brandau, vacuform visualisation by Colagor, and vacuum forming mould & product photo by Pizza1512, via Wikimedia Commons.

Compression Moulding

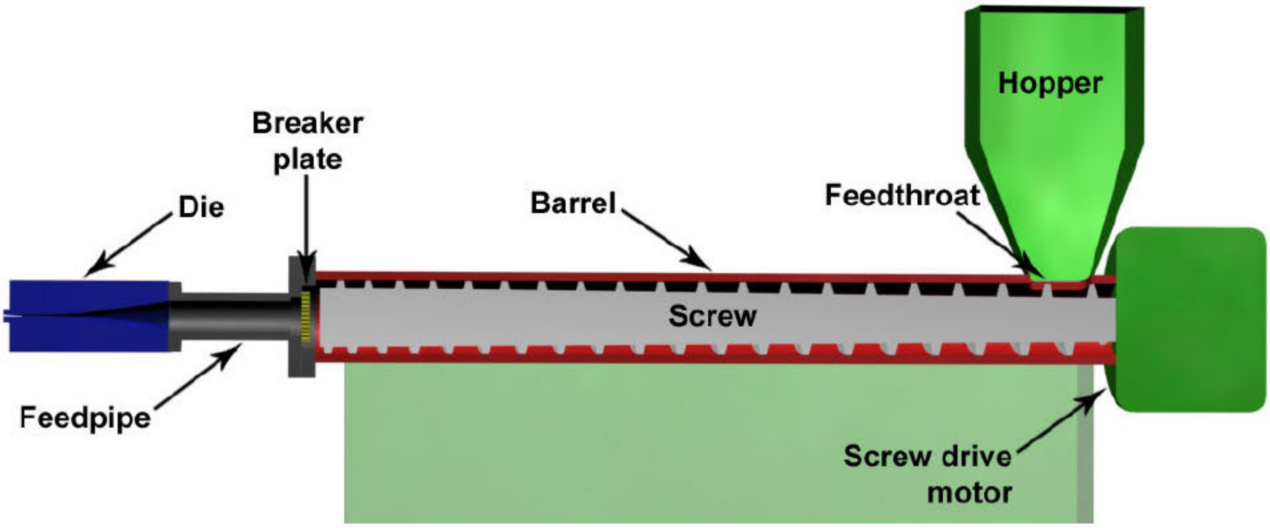
A pre-formed blank is squashed into another shape by heated mould plates.



Features:

- Enables much larger part sizes than injection moulding.
- Repeatable many times.
- Leaves significant flashes (thin waste material between mould plate contact surfaces) to be cut off and recycled.

Plastic Extrusion:



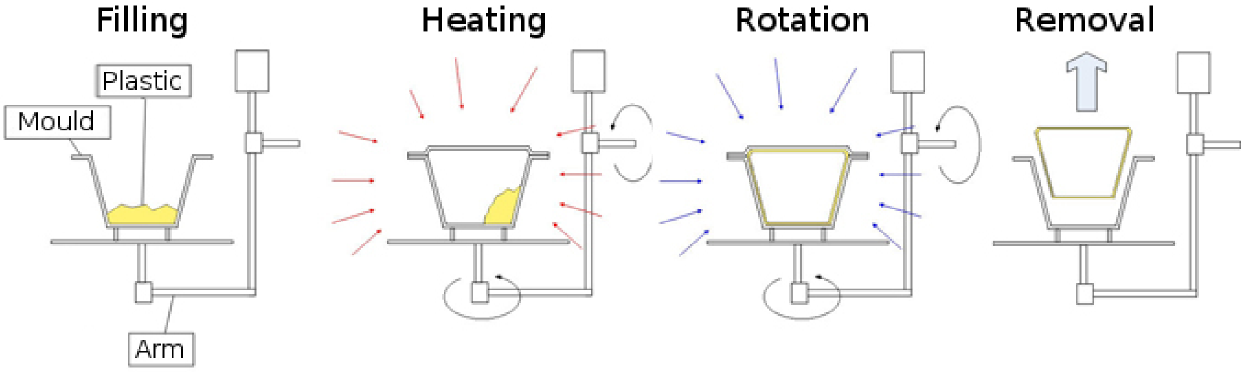
Features:

- Is used to produce very long sections, such as pipes, door/window frames and weather seals.
- Can also produce filament for 3D printing via this method.

Text by Andrew Drummond, diagram by ariel cornejo, photo of compression-moulded rubber boots by Rotor DB, and section diagram of plastic extruder by Mikeeg555, via Wikimedia Commons.

Rotational Moulding

Plastic pellets are poured into a mould chamber, which is then heated and rotated rapidly to spread them across the inside walls.



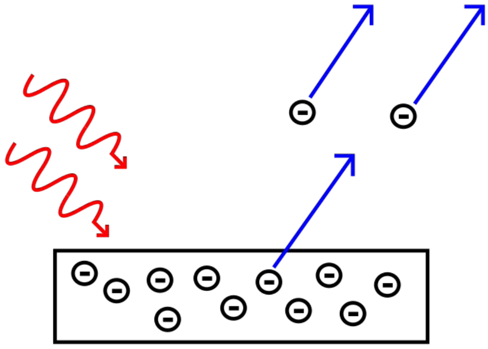
Features:

- Allows very large thin-walled objects to be made, and with much thicker and stronger walls than with blow moulding.
- Used to create products such as kayaks, water tanks and illuminated pedestrian crossing bollards.
- Appropriate for smaller production runs than with blow-moulding.

Text by Andrew Drummond, roto-moulding diagram by Marc Sommer, and photo of rowing boat by Row5000, via Wikimedia Commons.

Ultra-Violet/Environmental/Photo-Degradation

Some plastics take considerable damage from exposure to ultraviolet light.
Because of the high energy of this frequency of solar radiation, individual photons of UV light can cause electrons in the material that they hit to leave the molecule that they were orbiting, creating an electrical charge on an atomic scale.



This process is called ionisation, which is why UV is referred to as ‘ionising radiation’, and is the same process by which UV-C can cause damage to skin cell DNA.
Ionised sections of polymer chains then react with oxygen in the air in random ways, causing some chains to break, with a physical-scale result of weakening the material, visible as discolouration.

In some materials, rainwater also speeds up this process.
Some polymers have less resistance to this effect than others, and this is often combated by adding pigments such as carbon black to absorb the light, UV-reflective paints, or anti-oxidant additives to prevent damaging reactions.

Bio-Degradation:

Some polymers have been deliberately produced from monomers for which there are already widespread microbes to break them down completely, in order to keep them within the circular economy provided by nature.
Some microbes have also evolved to break down other polymers, but this is typically still a slow process.

Text by Andrew Drummond, diagram of the photoelectric effect by Wolfmankurd, and photo of degraded polypropene rope by Peterlewis, via Wikimedia Commons.

04
PE-LD

Polythene (LDPE and HDPE)

Standard chemical name Poly(Ethene).
Spelled “polyethylene” in North America.

02
PE-HD

Features:

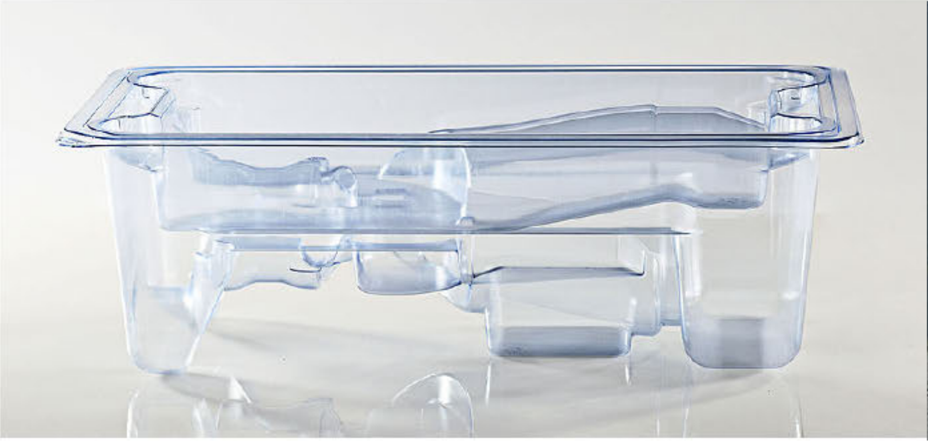
- A relatively soft polymer, categorised by its density.
- Low-Density PE has shorter chains, producing a weaker and more flexible plastic material;
  - Often used in packaging such as plastic bags, bubble wrap, and flexible foam blocks.
- High-Density PE has longer chains, for a stronger and more rigid material;
  - Often used in milk bottles and their tops, hard hats, and some water or waste pipes.
- Has a low glass transition temperature of -110°C, giving its soft and resilient plastic qualities at room temperature.
- However, it also has a low melting temperature of 115-135°C, such that it becomes very soft around boiling water.
- Its inertness can be both good – as it is non-toxic, and bad – as it takes a long time to break down if dumped.

Text by Andrew Drummond, photo of LDPE foam by Tpdwkouaa, photo of HDPE pipe welding by GordonJ86, via Wikimedia Commons.

01
PET

Polythene-Terephthalate (PET or PETE)

A very common bottle plastic.



Features:

- Stiff and can be stretched to very thin-walled containers.
- Excellent optical clarity and fair resistance to UV light.
- Can be recycled straight back into new food packaging, or is sometimes used to produce a strong polyester cloth.
- By processing the plastic in different ways, PET can be made heat-resistant enough to stand up to oven temperatures.
- Some types of PET can also be used in 3D printing.
- Its inertness can be both good – as it is non-toxic, and bad – as it takes a long time to break down if dumped.

Text by Andrew Drummond, photo of blister pack by Plastic Ingenuity, photo of polyester dinghy sailcloth by Dubaj, via Wikimedia Commons.

05
PP

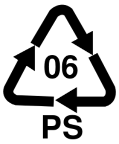
PolyPropene (PP)

Often used for dairy tubs and pots of sauce.

Features:

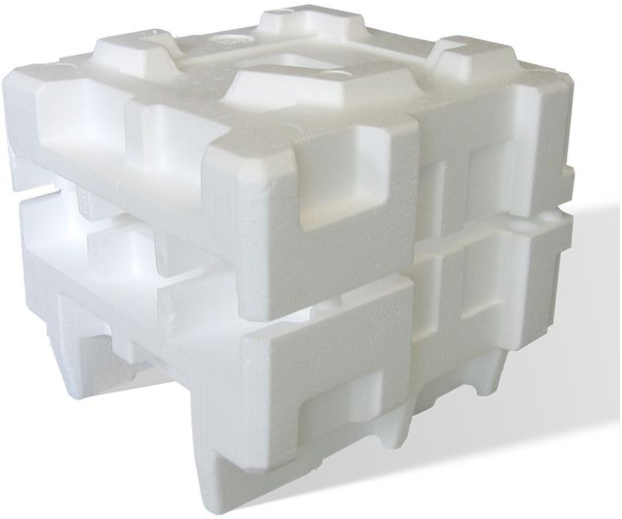
- Slightly harder and more heat resistant than PE, so it is often found in ready-meal containers.
- Very weakened by UltraViolet light when left in sunlight – it will even crack and crumble up if old white food containers are used as plant pots.
- Often one of the last plastics to be collected by councils.
- Has been used as fibre in ropes, tarpaulins, fishing nets, heavy-duty sacks and sweat-wicking clothing.

Text by Andrew Drummond, photo of 2ton PP sacks by Cjp24, and photo of PP tub by Gmhofmann, via Wikimedia Commons.



PolyStyrene (PS)

Often used for yoghurt pots and as packaging foam.



Features:

- A brittle polymer, stiffer than PP, well-known for its crumbly expanded form, less-known for its use in AirFix models.
- PS is sometimes reacted with tougher polymers such as the polybutadiene, to produce High Impact PolyStyrene, used in some appliance casings.
- Often one of the last plastics to be collected by councils.
- The monomer styrene is toxic, so its use in food packaging is carefully controlled to make sure that all of it has reacted, and it tends not to be recycled into more food packaging.
- While the great volume of EPS entering landfills and floating around the earth has been causing problems, recent research found that the gut microbes of some mealworms have adapted to digest it as a source of energy.

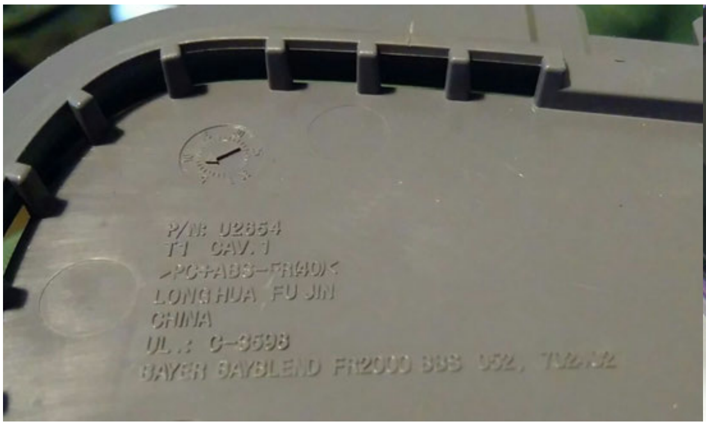
Text by Andrew Drummond, photo of EPS packaging by Acdx via Wikimedia Commons

Acrylonitrile-Butadiene-Styrene (ABS)

Commonly used in electronics casings,
ABS is a copolymer – a mix of different monomer units
combined in the same polymer chains.

Features:

- Good toughness due to rubbery parts. Used in Lego bricks.
  - Those plasticisers tend to degrade when re-heated, making recycling difficult.
- Working with molten ABS can produce toxic fumes.
- Very flammable, so often mixed with flame retardants.
- Poor UV resistance, so often mixed with pigments.
- Can be used in 3D printing where heat resistance is needed.



PolyCarbonate (PC)

Uncommon material in electronic casings and bottles

Features:

- Polycarbonate is known for its great toughness, often laminated with glass to produce ‘bulletproof’ glass.
- Sometimes alloyed (mixed while molten) with ABS to improve its strength further, as PC resists heating better.
- Its use in baby bottles was restricted on the precautionary principle, based on hormonal effects of Bisphenol A (BPA), one of the precursor chemicals used to make polycarbonate.

Text and photo of casing recycling code by Andrew Drummond, photo of gameboy by Vaughan Weather via Wikimedia Commons.

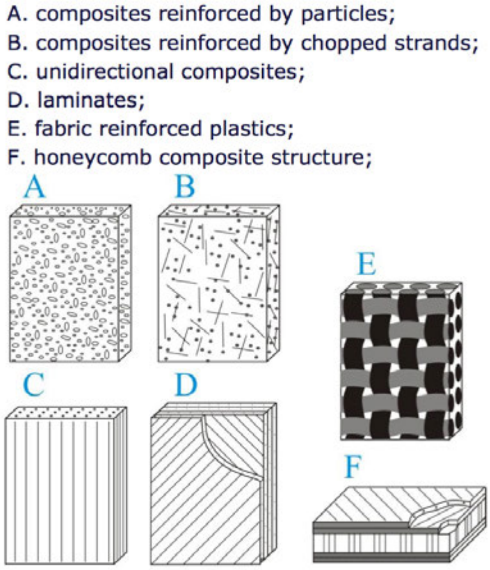
Thermosetting Resins

Most of the materials described here are called thermoplastics, which can be re-melted after use as a solid object. Thermoset resins by contrast do not melt after they have cured, but degrade when heat is applied. Common examples include Epoxy, PolyUrethane, Polyester Resin, and vulcanised natural rubber. These are often used as paints or coatings, and are not recyclable.

(Glass) Fibre Reinforced Plastic

(Fibreglass, GFRP, CFRP, PP%+GF%…)

FRP is a composite material made by soaking sheets of woven glass fibres (or carbon fibre, aramid, etc.) in a thermoset resin (or by injecting a mix of shredded fibres with a thermoplastic).



Features:

- The combination of the fibre’s stiffness and the toughness of the plastic matrix that it rests in, creates a material that is stronger than steel, per weight of material.
- These are often used for the hulls of light aircraft and boats, by laying sheets of fibreglass over a pre-formed shape and then coating it with resin.

Text by Andrew Drummond, composite materials diagram by Kokcharov, and fibreglass boat photo by Jean-Pierre Bazard via Wikimedia Commons.

07
O

Poly(Lactic Acid) / PolyLactide (PLA)

A compostable polymer:
Made from the same acid that occurs in your bloodstream during strenuous exercise, there are already naturally-occurring enzymes to take it apart.

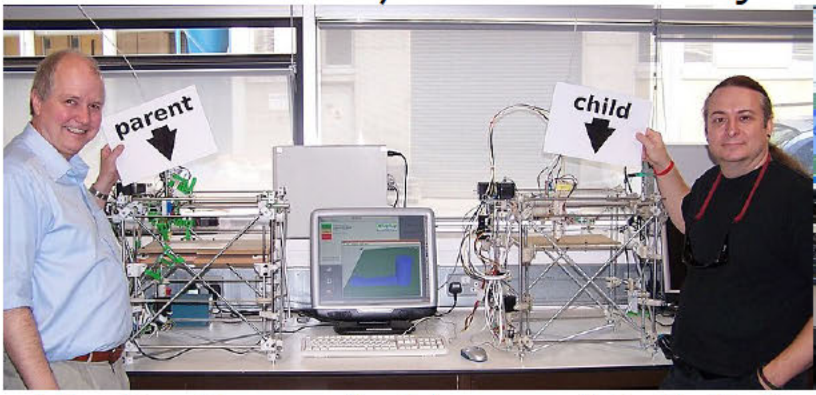
Features:

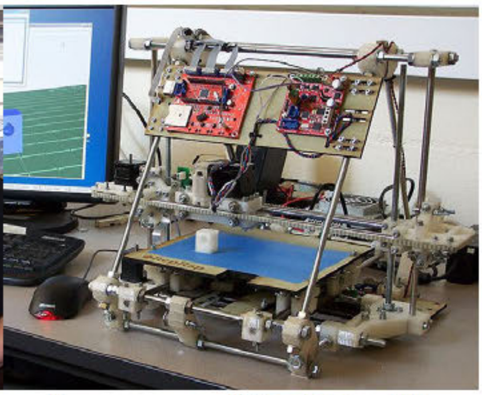
- Low shrinkage when cooling after being melted makes it highly suitable to 3D printing.
  - Its biodegradability also makes it more appealing for rapid prototyping, as failed models can be disposed of cleanly.
- A quite rigid polymer similar to PET at room temperature.
- However, its low glass transition temperature of 60-65°C means that it can’t be used for high-temperature applications (hot water makes it floppy).
- Being compostable makes it suitable for garden aids.
- Without being surrounded by the biological activity of a compost heap, it may still take many years to break down just under sun and rain.
  - Ignoring this can lend it to misleading greenwashing as a truly ‘disposable’ plastic.
- If made from sugar, this can put unwanted pressure on existing agricultural land needed to feed humanity.
- However, it has been used in ‘dissolving sutures’, enabling relatively minor injuries to be stitched up without needing a patient to return to have them removed.

Text by Andrew Drummond, photo of PLA cups by Ildar Sagdejev via Wikimedia Commons, and photo of modular mounting system by yyh1002 on Thingiverse.

The Replicating Rapid-Prototyper (RepRap) Project

In response to patent restrictions on the rapid prototyping industry, and a will to make advanced manufacturing more accessible, the RepRap project was born with an aim to make 3D printers capable of producing their own parts (except for common nuts & bolts) so as to drastically decrease their cost.



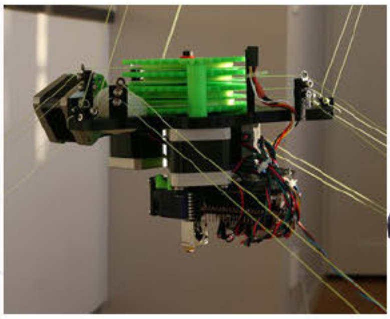


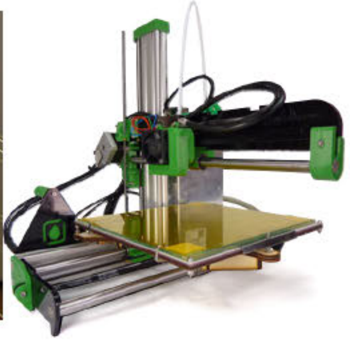
The RepRap project began at Bath University around 2005 with Professor Adrian Bowyer and his students. Their first design was named Darwin; the second, Mendel.

They succeeded in bringing the cost of desktop 3D printers down 100-fold, from tens-of-thousands of pounds to hundreds of pounds, and by sharing their designs freely online as open-source hardware, they enabled a rapid evolution in the machines.

Since then, hundreds of varieties have been invented by enthusiasts to suit different applications.

For more information, visit reprap.org





Text by Andrew Drummond; Photos: Darwin's first replication and Reprap Mendel by the RepRap project. Bottom row: Prusa i3 by Josef Průša, Hangprinter by Torbjørn Ludvigsen, Ormerod 2 and Fisher by SallyRepRap. All via Wikimedia Commons.

The Precious Plastic Project

Started to address the slow uptake of recycling due to the high investment cost of shredding and moulding machines.

Hot on the heels of hobbyist research within the RepRap Project aiming to recycle plastic back into filament for use in 3D printers, with grant funding to develop open-source designs, Dave Hakkens assembled a team in the Netherlands to work on this problem.

Shredder Extruder Injection Moulder Compression Moulder

Precious Plastic brought the cost of shredding and moulding machinery from thousands or tens-of-thousands of pounds down to hundreds of pounds in much simplified forms.

However, designs are still a bit rough around the edges for compliance with industrial standards and are under active development, so they only tend to be used by grass-roots projects.

For more information, visit preciousplastic.com

Text by Andrew Drummond, image via Precious Plastic.

Appendix C – Transcript codes:

	Codes
1.	Meta
2.	Introduction, Culture Café, Findhorn Bay Arts, Meta,
3.	Introduction, Culture Café, Findhorn Bay Arts, Meta,
4.	Introduction, Meta,
5.	Introduction, Consent, Meta,
6.	Product,
7.	Third sector, municipal services,
8.	Gaps, municipal services,
9.	Contamination
10.	Responsibility, contamination,
11.	Logistics, sorting
12.	Logistics, transparency,
13.	Landfill,
14.	Logistics, responsibility, international, trade, waste,
15.	Municipal services, investment,
16.	Municipal services, international, sorting, automation,
17.	Downcycling,
18.	Municipal services, consultation, supply seeking a demand,
19.	Investment,
20.	Funding, waste-to-energy,
21.	Separation,
22.	Landfill mining,
23.	International, county scale, waste-to-energy,
24.	Toxins, sequestration,
25.	Pollution, microplastic,
26.	Waste-to-energy, international, pollution,
27.	Separation, pollution,
28.	Incineration, landfill, size reduction, international,
29.	Pollution, making visible,
30.	Incineration, efficiency, international,
31.	International, landfill, pollution, drinking water,
32.	Toolchain,
33.	Gardening, product, degradation,
34.	Product, furniture,
35.	Gardening,
36.	Town scale, logistics, marginal cost,
37.	Meta

38. Meta, rural replication,
39. Degradation, beach wash-up, marine plastic, fishing, waste,
40. Rural scale, localism,
41. Funding, rural replication,
42. Precious Plastic,
43. Product,
44. Machinery, start-up effort,
45. Meta,
46. Surplus, waste, opportunity,
47. Craft, ropes, weaving,
48. Feedstock supply,
49. Marine plastic,
50. Waste, backlog, marine plastic, disposable paradigm,
51. Survey, marine plastic, pollution,
52. Beach cleans, labour-intensive, case-study,
53. Contamination, marine plastic,
54. Degradation, UV filters,
55. Waste sources, marine plastic, repair offcuts,
56. Making visible, environmental impact,
57. Beach cleans,
58. Polymer persistence, local pollution, marine plastic,
59. Marine plastic, aquaculture, industrial pollution,
60. Corporate responsibility,
61. Corporate PR,
62. Environmental regulation,
63. Organisation legal status, social enterprise, start-up support, transferability,
64. Tourist souvenirs,
65. Compression moulding, materials testing,
66. Financial sustainability,
67. Art installation,
68. Introduction,
69. Marketing,
70. Marketing, rural scale, web commerce,
71. Start-up effort, commissioning,
72. Project prerequisites,
73. Energy cost, shredding,
74. Floor space, investment,
75. Marine plastic, toxins, bioaccumulation, nurdles,
76. Nurdles, marine plastic
77. Logistics, economy of scale,

78. Marketing,
79. Marketing,
80. Meta, consent,
81. Floating islands, pollution,
82. Toxin adsorption,
83. Pollution, food-safety,
84. Floating islands, ecology,
85. Toxins, denial/taboo,
86. Media attention, toxins, denial/taboo,
87. Awareness, responsibility,
88. Disposable paradigm, comfort, packaging,
89. Environmental regulation, marine plastic,
90. -
91. Activism, festivals, waste
92. Sequestration, making visible,
93. Current state of industry,
94. Blended polymers,
95. Aesthetic, product,
96. Tabletop figurines, downcycling, materials selection,
97. Bioaccumulation, toxins,
98. Biodegradable polymers, degradable bags,
99. -
100. Meta, goodbyes,
101. Weaving, trip,
102. Meta, craft classes,
103. Mapping,
104. Meta, goodbyes,
105. Pyrolysis, oil,
106. Separation,
107. Pyrolysis, oil market,
108. Meta,
109. Oil supply, pollution, fossil fuels, energy cost,
110. Pyrolysis, oil supply, pollution, fossil fuels, fungibility,
111. Resource conservation, greed,
112. Resource conservation, oil supply,
113. Pollution, responsibility,
114. Pollution, responsibility,
115. Greenwashing, pollution,
116. Environmental regulation, pollution,
117. Fossil fuels, pollution,

118. Packaging, responsibility, activism,
119. Biomaterials, materials selection, cleaning products,
120. Degradation, sequestration,
121. Paving, microplastic,
122. Despair, choice, individualism,
123. Encouraging behaviour, making visible,
124. Carbon footprint, making visible,
125. Local needs, housing,
126. Local needs, housing, product,
127. Product, artefact story,
128. Relatability, humanising problems,
129. Grass-roots action, inspiration, stories,
130. -
131. Activism, sports,
132. Tool versus trinket, practicality,
133. Cyclical consumption, disposable paradigm, design for longevity,
134. Upcycling, product,
135. Product, process design,
136. Toxins, education,
137. Degradation, industrial practice, UV filters,
138. Ingredient opacity, toxins,
139. Alternative materials, biomaterials,
140. Awareness in use, disposable paradigm,
141. Special occasion/infrequent use,
142. Planned obsolescence
143. Waste, re-use, access vs ownership, municipal services,
144. Furniture, waste,
145. Re-use, furniture,
146. Re-use, informal sharing economy,
147. Hoarding, furniture,
148. Frugality, charity shopping,
149. Art festival, awareness,
150. Art festival, responsibility, cleanup,
151. Environmental regulation, responsibility, packaging, logistics, international,
152. Environmental regulation, municipal services, international,
153. Municipal bins, recycled containers, consistency, using recycled material to recycle like materials,
154. Waste transition (adjusting scale),
155. Material story,
156. Green lifestyle options,

157. Ropes, re-use, kite rigs,
158. Degradation, downcycling,
159. Responsibility,
160. -
161. Materials selection, standardisation, biomaterials, cradle-to-cradle design,
162. Toxins, making accessible,
163. Meta
164. Sequestration, using material to contain polymers,
165. Toxicity, education,
166. Making visible,
167. Green lifestyle options,
168. Shopping bags,
169. Despair, overwhelming task, inspiration, making visible,
170. Comparison to CFC transition,
171. Disposable paradigm, materials selection, biomaterials, teabags,
172. Inspiring, overwhelming task, despair, making visible,
173. Litter, schools, youth,
174. Making visible, interactive sculpture, waste collection,
175. Different motivational needs, incentives, legislation, making visible,
176. Curriculum, schools, making visible,
177. Gatekeeping, schools,
178. Different motivational needs, despair, overwhelming task, disconnection,
179. Overwhelming task, dissociation,
180. Gatekeeping, schools, entrepreneurship.
181. Using upcycled material to recycle like materials, boatbuilding, schools,
182. Schools, curriculum,
183. -
184. Awareness, youth,
185. Conformity, hedonism, philanthropy,
186. Popular media, corporate PR, exposure,
187. Microplastic, clothes washing, cora ball,
188. Concentrated detergents,
189. Cora ball,
190. Soap nuts,
191. Cleaning practices, convenience,
192. Cleaning products, COSHH,
193. Product, shopping bags, crates, reusability,
194. Reusability, crates,
195. Corporate social responsibility, incentive,
196. Standardisation,

197. Greenwashing,
198. Re-use, container washing, glass economy, dairy,
199. Bulk savings,
200. -
201. Economy of scale, packaging reduction,
202. Glass economy, logistics, standardisation,
203. Reusability, clothes washing, nappies,
204. Energy cost, material cost, nappies, clothes washing,
205. Automation, clothes washing, ubiquity of machines,
206. Regional culture, opportunity, community receptiveness,
207. Addressing biggest differences first, funding,
208. High-quality material, waste washing, opportunity,
209. Meta, conversation dynamics,
210. Activism,
211. Municipal services, off-loading on other councils,
212. Community size, different motivational needs, necessity,
213. Plastic-free areas, certification,
214. Plastic-free areas, tourism,
215. HHGTTG, material flow management,
216. Sci-fi,
217. Material flow management,
218. In-house recycling,
219. Downcycling, degradation,
220. HHGTTG, Babelfish,
221. Meta,

Tally of Codes, sorted by frequency and order of mention:

Code	Occurrences	Mentioned
Pollution	17	31st
Meta (housekeeping, etc)	16	1st
Making Visible	11	35th
Marine plastic	11	46th
Product	10	6th
Responsibility	9	11th
International	9	16th
Toxins	9	29th
Municipal Services	7	8th
Logistics	7	12th
Waste (avoidable)	7	18th
Degradation	7	40th
Schools	6	180th
Introduction	5	2nd
Separation	5	13th
Disposable paradigm	5	59th
Environmental regulation	5	74th
Re-use	5	155th
Downcycling	4	21st
Sequestration	4	30th
Furniture	4	41st
Marketing	4	84th
Activism	4	103rd
Materials selection	4	109th
Biomaterials	4	125th
Despair	4	128th
Overwhelming task	4	176th
Clothes washing	4	199th
Contamination	3	10th
Landfilling	3	15th
Investment	3	19th
Funding	3	25th
Waste-to-Energy	3	26th
Microplastic	3	32nd
Energy cost	3	88th
Awareness	3	100th
Packaging	3	102nd
Pyrolysis	3	116th
Oil supply	3	119th
Fossil fuels	3	120th
Inspiration	3	139th
Different motivational needs	3	184th
Reusability	3	207th
Culture Café	2	3rd
Findhorn Bay Arts	2	4th
Consent	2	5th
Automation	2	20th
Incineration	2	33rd
Toolchain	2	38th
Gardening	2	39th
Rural replication	2	44th
Rural scale	2	48th

Start-up effort	2	51st
Opportunity	2	53rd
Ropes	2	55th
Weaving	2	56th
Beach cleans	2	61st
UV filters	2	64th
Corporate PR	2	73rd
Bioaccumulation	2	91st
Nurdles	2	92nd
Economy of scale	2	93rd
Floating islands	2	94th
Denial/taboo	2	98th
Goodbyes	2	112th
Resource conservation	2	122nd
Greenwashing	2	124th
Cleaning products	2	126th
Local needs	2	133rd
Housing	2	134th
Education	2	148th
Art festival	2	161st
Green lifestyle options	2	169th
Standardisation	2	171st
Shopping bags	2	175th
Youth	2	181st
Incentives	2	185th
Curriculum	2	187th
Gatekeeping	2	188th
Cora ball	2	200th
Crates	2	206th
Glass economy	2	210th
Nappies	2	214th
Plastic-free areas	2	226th
HHGTTG	2	229th
Material flow management	2	230th
Third Sector	1	7th
Gaps	1	9th
Transparency	1	14th
Trade	1	17th
Municipal Services	1	22nd
Consultation	1	23rd
Supply seeking a demand	1	24th
Landfill mining	1	27th
County-scale	1	28th
Size reduction	1	34th
Efficiency	1	36th
Drinking water	1	37th
Town-scale	1	42nd
Marginal cost	1	43rd
Beach wash-up	1	45th
Fishing	1	47th
Localism	1	49th
Precious Plastic Project	1	50th
Surplus	1	52nd
Craft	1	54th
Feedstock supply	1	57th
Backlog	1	58th

Survey	1	60th
Labour-intensive	1	62nd
Case-study	1	63rd
Waste sources	1	65th
Repair offcuts	1	66th
Environmental impact	1	67th
Polymer persistence	1	68th
Local pollution	1	69th
Aquaculture	1	70th
Industrial pollution	1	71st
Corporate responsibility	1	72nd
Organisation legal status	1	75th
Social enterprise	1	76th
Start-up support	1	77th
Transferability	1	78th
Tourist souvenirs	1	79th
Compression moulding	1	80th
Materials testing	1	81st
Financial sustainability	1	82nd
Art installation	1	83rd
Web commerce	1	85th
Commissioning	1	86th
Project prerequisites	1	87th
Shredding	1	89th
Floor space	1	90th
Toxin adsorption	1	95th
Food safety	1	96th
Ecology	1	97th
Media attention	1	99th
Comfort	1	101st
Festivals	1	104th
Current state of industry	1	105th
Blended polymers	1	106th
Aesthetic	1	107th
Tabletop figurines	1	108th
Biodegradable polymers	1	110th
Degradable bags	1	111th
Group trip	1	113th
Craft classes	1	114th
Mapping	1	115th
Oil	1	117th
Oil market	1	118th
Fungibility	1	121st
Greed	1	123rd
Paving	1	127th
Choice	1	129th
Individualism	1	130th
Encouraging behaviour	1	131st
Carbon footprint	1	132nd
Artefact story	1	135th
Relatability	1	136th
Humanising problems	1	137th
Grass-roots action	1	138th
Stories	1	140th
Sports	1	141st
Tool versus trinket	1	142nd

Practicality	1	143rd
Cyclical consumption	1	144th
Design for longevity	1	145th
Upcycling	1	146th
Process design	1	147th
Industrial practice	1	149th
Ingredient opacity	1	150th
Alternative materials	1	151st
Awareness-in-use	1	152nd
Special occasion / infrequent use	1	153rd
Planned obsolescence	1	154th
Access vs ownership	1	156th
Informal sharing economy	1	157th
Hoarding	1	158th
Frugality	1	159th
Charity shopping	1	160th
Cleanup	1	162nd
Municipal bins	1	163rd
Recycled containers	1	164th
Consistency	1	165th
Using recycled material to recycle like materials	1	166th
Waste transition (adjusting scale)	1	167th
Material story	1	168th
Kite rigs	1	170th
Cradle-to-cradle design	1	172nd
Making accessible	1	173rd
Using material to contain polymers	1	174th
Comparison to CFC transition,	1	177th
Teabags	1	178th
Litter	1	179th
Interactive sculpture	1	182nd
Waste collection	1	183rd
Legislation	1	186th
Disconnection	1	189th
Dissociation	1	190th
Entrepreneurship	1	191st
Using upcycled material to recycle like materials	1	192nd
Boatbuilding	1	193rd
Conformity	1	194th
Hedonism	1	195th
Philanthropy	1	196th
Popular media	1	197th
Exposure	1	198th
Concentrated detergents	1	201st
Soap nuts	1	202nd
Cleaning practices	1	203rd
Convenience	1	204th
COSHH	1	205th
Corporate social responsibility	1	208th
Container washing	1	209th
Dairy	1	211th
Bulk savings	1	212th
Packaging reduction	1	213th
Material cost	1	215th
Ubiquity of machines	1	216th
Regional culture	1	217th

Community receptiveness	1	218th
Addressing biggest differences first	1	219th
High-quality material	1	220th
Waste washing	1	221st
Conversation dynamics	1	222nd
Off-loading on other councils	1	223rd
Community size	1	224th
Necessity	1	225th
Certification	1	227th
Tourism	1	228th
Sci-fi	1	231st
In-house recycling	1	232nd
Babelfish	1	233rd

Appendix D – Account of my visit to the Plastic@Bay workshop:

Plastic at Bay had so far tried moulding coasters / slates from chopped rope. The top surface of this tile has texture to it due to one side of the mould being left cold before the press was closed. The reverse is smooth. If all parts of the mould are pre-heated then both sides should be smooth.

Their shop featured a mix of educational displays, the few things that they had moulded so far, and a couple of third-party green products.

A half-built bench-top injection moulding machine also sat in the corner there (bottom-right), waiting to be finished and tested.

They had some dies for adding recycling symbols to products, which don't seem to be used by the vast majority of groups on the Precious Plastic 'Bazar' web-shop.
It seems that these were supplied by somebody in the project, and there is no easy way to mount them in moulds (a rectangular plate with mounting holes would be better), so they would need to be pressed onto parts after fabrication, possibly with a soldering iron, pyrography tool or similar.

On the right, see our granulated ABS casings compared to their granulate of a blue PE barrel found on the beach:

When I arrived, Joan & Julien had just received a new extruder built to the Precious Plastic open source design, which Julien had tested for half an hour before it stopped working.
Below, see one piece made at the end of the test extrusion, by wrapping the plastic around a mould as it came out:

The machine (bottom-left) was constructed by a workshop in Catalonia, and Julien reported that they spoke highly of themselves on the PPP forum, but the build quality was actually poor, with unclear wiring (it all used the same blue insulated wires, and some temperature sensors were incorrectly wired), and something having stopped working on the machine, which Julien thought might be the controller. He had already removed a cover from one end of the motor that held a cooling fan, as the fan was visibly broken from the outside when it arrived, and complained to his supplier.

The compression moulder (left of photo on right) was welded together for them by a blacksmith in Lairg, who Julien said was more of an artistic blacksmith than an engineering fabricator, clear by the *very* rough measurements used in construction.

A plate at the top of the oven is used to press against the back of any mould placed in the oven. This plate should be parallel, but is about 10 degrees off! Unfortunately this was welded in place in such a way that it would be very difficult if not impossible to cut it out and correct the angle without taking the entire assembly apart.

Julien was fixing electronics on the temperature controller too, as a spade connector had come loose due to using poor quality connectors with a short crimping area holding the wire:

On day 2, after Julien got the oven running and warming up, he sanded down the mould plates with a 400 then 1000-grit pad (palpably smooth, used for polishing) to remove any previous residue and prevent the new polymer from sticking. He typically also used a fine coat of mould-release wax.

While waiting for the oven to preheat, Julien showed me their granulator, a smaller model with similar single-axis operation to the one that MRO got, but this one fits on a pallet:

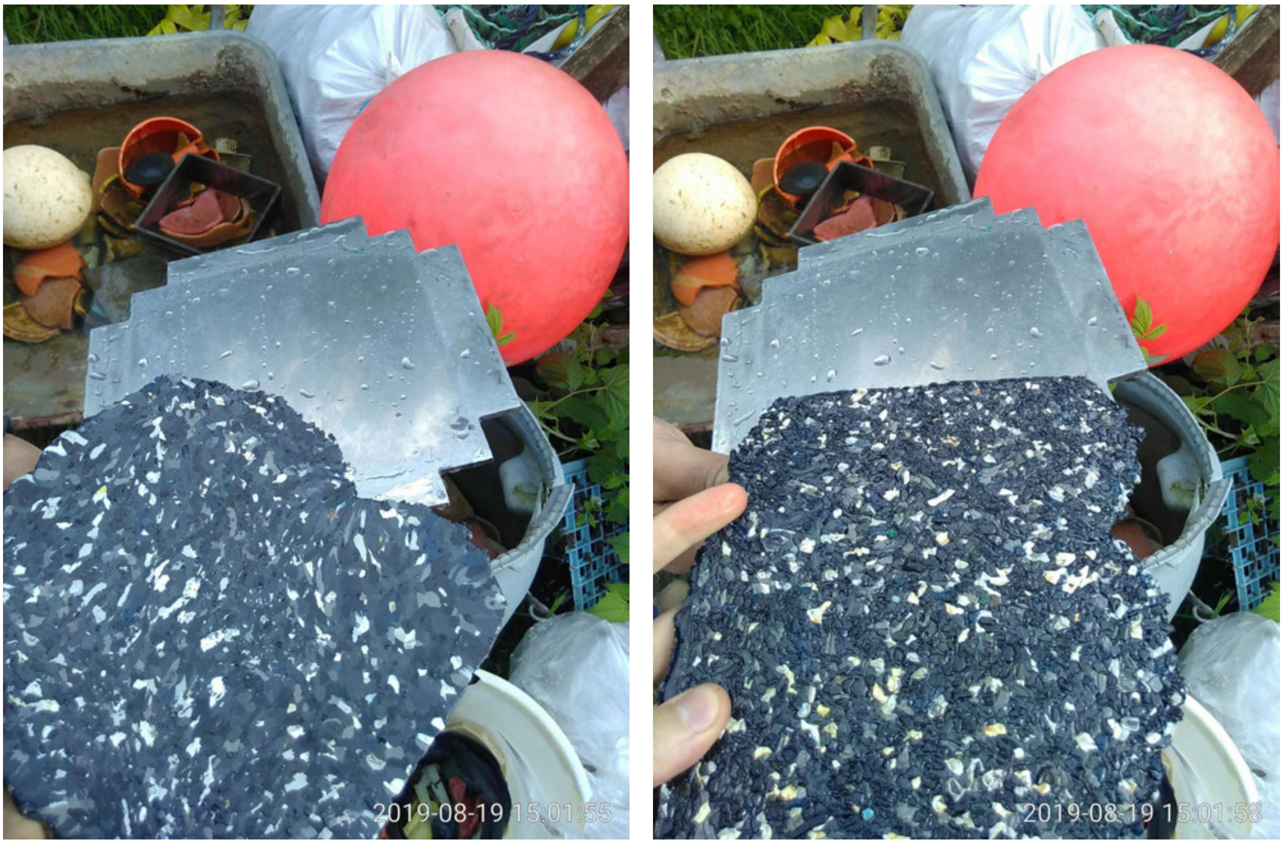
We poured most of my sample of ABS into a mould and allowed that to warm up in the oven, increasing the target temperature incrementally after Julien gave the granules a poke with a spatula to test whether they stuck together at all yet. They did not seem to clump at all until around 165°C.

(ABS has a glass transition temp. around 105C and a melting temp around 205°C, with most injection moulding and 3D printing taking place from 210-230°C.)

On approaching 190°C, it could be flipped like a pancake, so we set the final target temp to 195°C.

As it approached 195°C, Julien placed an unheated top plate into the mould and jacked up the mould inside until resistance was felt as it reached the top of the oven and plastic flowed.

The entire mould was then taken outside to be quenched in water (effective but energy-wasteful).



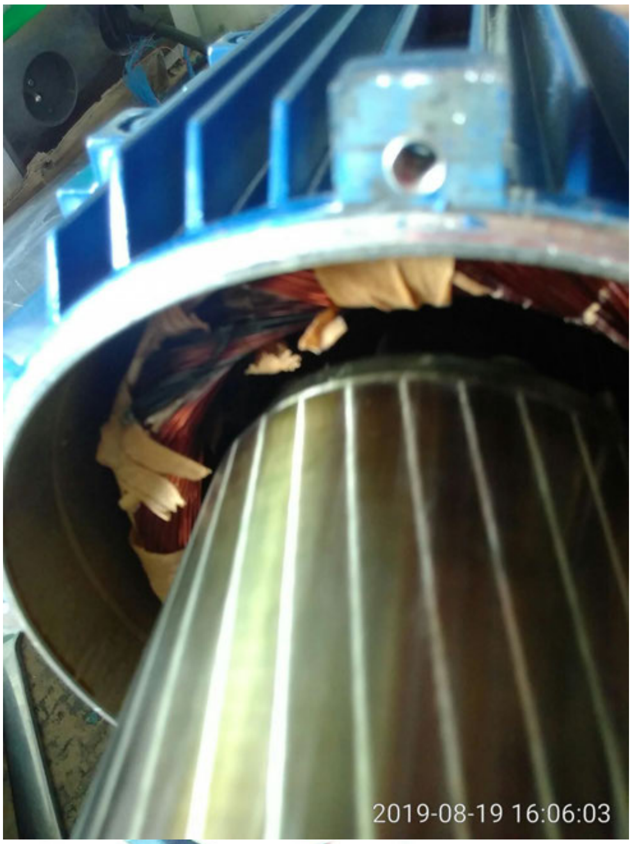
The final product had an appearance of a polished granite work-surface on the hot side, and tarmac on the cold side, interesting features to consider in product design.

Also worth noting was some visible contamination in the granulated cases – in the centre of the tile in the second photo, a piece of a rubber (probably the foot of a device) did not melt and easily picked off the outside of the mould. This could have possibly added to the toxic fumes generated. There were also several tiny flakes of foil stickers visible.
Although not evenly pressed, the ABS did not stick to the clean metal at all.
The plate produced was far more rigid than the other tiles they had moulded out of PE.

After testing the extruder's 3-phase inverter thoroughly, finding nothing wrong with it, while the machine continued to blow fuses, I suggested opening up the motor itself, because we heard a whining noise like an electrical arc, to see whether there had been any internal damage.

Was there ever! Some parts at one end of the coils appeared to have collided and torn away at other internals, resulting in some short-circuit arcing and burning.
Julien looked up the motor and found it to be a Chinese counterfeit of an Italian brand, available on Alibaba, and contacted the machine seller who said the motor was brand new as far as they know.

He is now trying to get it replaced. Who can say where this story will go…



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PARTICIPANT INFORMATION SHEET

Title of study
Closing Gaps in Plastic Recycling

Invitation Paragraph
Thank you for expressing interest in this study. By taking part you could help to both improve the recycling systems of Moray and help me to improve my skills as a researcher.

What is the purpose of the study?
To find ways for plastic materials that are typically not recycled to be reused in local creative industries.
The study aims to inform public bodies, third-sector organisations and grass-roots associations in effective ways of addressing the problems of small-scale plastic recycling.

Why have I been invited to take part?
Your input is sought due to your local expertise and experience as a creative practitioner.

Do I have to take part?
There is no obligation to take part in this study, and you may discontinue involvement at any time after beginning.

What will happen to me if I take part?
You may be invited to take part in a collaborative design workshop, or an interview. These may recur over 2019/2020 as research progresses.

Incentives (where relevant)
There will not be any monetary compensation for participating in this study.
However, artefacts or materials produced during the course of the study may be donated to the participants, you may receive a copy of the final thesis, and/or volunteer time may be given by the researcher as thanks for your help.
This depends upon your preference and the researcher’s discretion.

What are the possible benefits and risks of taking part?
As a piece of action research, the study could result in a local service being created to make scrap materials easily available to individuals for creative pursuits, or even help some local creative practitioners to start small enterprises using these resources.
There is a risk that the study could fail in its aims, and just as many usable materials may continue to go to landfill. There may be some minimal health and safety risk to participating in workshops if we get to actually make some plastic products.

Will my taking part be kept confidential?
Yes, and all of your input will be confidential for the duration of the study.
At the point of publication, any quotation or reference to your input will be kept anonymous as far as is possible, unless you ask to be credited for your input. If doing so, you need to consider any possible positive or negative impact on your reputation from taking part.
Please be aware that in a small community, some context can enable those with local knowledge to identify others within their community, for example if very few people share a particular trade, so anonymity cannot be absolutely guaranteed.

How is the project being funded?
Tuition fees for this Master of Research degree are being covered by the Creative Futures Partnership with Highlands and Islands Enterprise.
The researcher has worked part-time in order to cover the costs of studying.

PARTICIPANT INFORMATION SHEET

What will happen to the results of the study?

Any thesis or portfolio produced as a result of this study will be published in physical and digital format via the Glasgow School of Art library.
If the study becomes part of a doctoral thesis then that will also be published digitally by the British Library E-Theses Online Service.

Who should I contact for further information?

If you have any questions or require more information about this study, please contact me using the following contact details:
Andrew Drummond, ReBOOT (Moray Computer Recycling), [redacted]
[redacted]. [redacted]

What if I have further questions, or if something goes wrong?

If this study has harmed you in any way or if you wish to make a complaint about the conduct of the study you can contact my project supervisor at GSA using the details below for further advice and information:
Dr. Paul Smith, Glasgow School of Art Highlands & Islands Campus, [redacted]
[redacted] [redacted]

Thank you for reading this information sheet and for considering taking part in this research. Please keep this sheet for future reference

GSofA

Research Consent Form

Research Project Title: Closing Gaps in Plastic Recycling

Lead Researcher: Andrew Drummond

Contact Details: [redacted]

Please initial boxes

1. I confirm that I have read and understand the participant information sheet for the above study; ☐
2. I have had an opportunity to consider the information, ask questions and have had these answered satisfactorily; ☐
3. I agree to being photographed / audio recorded as part of the research and understand that these will be kept anonymous; ☐
4. I agree to photographs being made publicly available in publications, presentations, reports or examinable format (dissertation or thesis) for the purposes of research and teaching – I understand that these will remain anonymous; ☐
5. I agree to the results being used for *future* research or teaching purposes; ☐
6. I agree to take part in the above study. ☐

Name of participant	Date	Signature
Name of person taking consent (if different from researcher)	Date	Signature
Researcher	Date	Signature

Complaints about the conduct of this research should be raised with: Dr. Paul Smith, Glasgow School of Art Highlands & Islands Campus, [redacted]

Appendix G – Material Explorations, technical report prepared for the ROAR project

Water sample testing report from Heriot Watt University.

MRO sent a granulated PET sample to Clean Tech in November 2018 and received vague feedback saying that it had discoloured brown in their oven and was not usable. There seemed to be a miscommunication or assumption that the granulate had been washed, later noted because it was cleaner than loose plastic that they would typically receive.
Once the project's development workers started 3 months later, the opinion received from the technical manager responsible for the test at CT after he returned from holiday was that there were too many variables to consider for a short conversation, and so two of CT's staff came to visit MRO in May 2019 in order to see the operation and discuss a possible business relationship.
Out of this meeting came recommendations around how to treat PET in a wash cycle so as to prevent it from degrading under the acidic conditions that it was being stored after exposure to soft drinks, and a verbal agreement that CT would be more than happy to buy MRO's granulated PET once they produced a volume suitable to ship.

Flakes of granulated pet bottles were washed to remove residues of sugary drinks and dirt from collection and make them more suitable for extrusion. Because an industrial hot washing machine was outside the budget scale of this project, this was done with a domestic washing machine on a hot cycle, with granulate held in various cloth bags purpose-made by MRO crafts, based on advice from the Precious Plastic Project.
Being aware that there may be micro-particles chipped off by our granulator that could slip through any mesh we put the granulate in, we attempted to filter these particles out of the waste-water with a variety of filters improvised from scrap.

There were also macroscopic particles (whole granulated flakes) in some of the waste captured by our filters when experimental wash bags had failed to seal properly.

We then sent samples of the post-filtration water to the marine biotechnology department at Heriot-Watt University, Edinburgh, in order to find out how much plastic was remaining. After these samples were blinded by the team, there was again a misunderstanding of what was expected, and test results were sent back with attempts to identify rather than quantify what was in the water.

However, although the improvised filters could not be compared quantitatively, the results were useful in demonstrating that there was not enough material present to analyse in water samples where the waste-water had been allowed to settle in large containers for days before taking a sample of it, showing that at least with PET, its heavier-than-water nature makes a settling tank a cheap and effective initial step in waste-water treatment, at very least for the macroscopic particle fraction.

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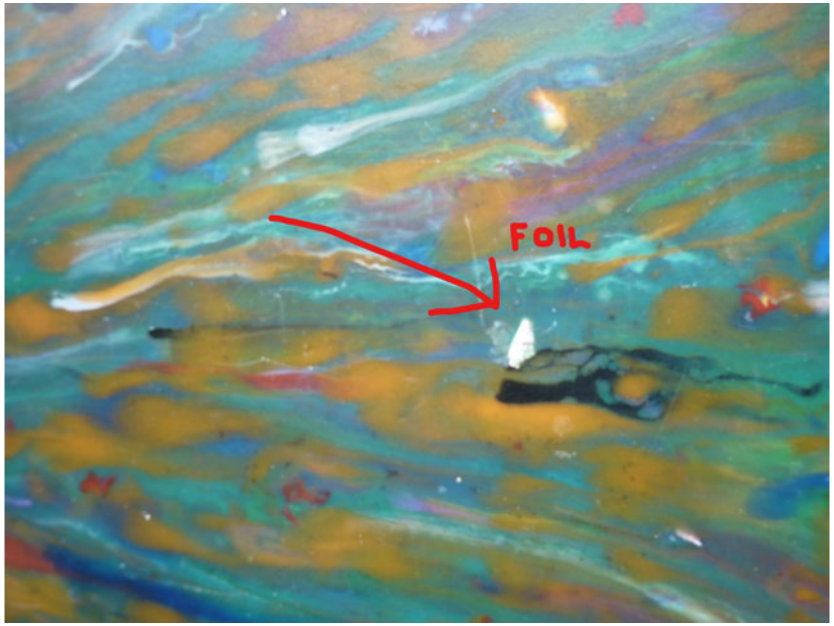
Contamination in HDPE granulate.



Dehydration.

Due to the hygroscopic nature of some polymers (attracting water to their surface), and to improve the quality of our extruded and pressed stock material, we purchased a cheap Electriq EDFD04 digital electronic food dehydrator in order to remove moisture that may otherwise form trapped bubbles as it evaporates while granules melt.

It works by simply passing warm air, typically around 60 or 70°C, over the contents of a stack of trays, with controls for temperature and time.

Whatever held granules needed to resist moderately hot air and remain rigid, while having enough ventilation for air to pass over the nurdles/pellets or granulated materials without them dropping through.

One drawback of this system is that the trays normally used to hold food items have gaps that are far too wide to hold granules up, and so secondary trays or containers had to be improvised to contain the granules while they are dried.

For example, perforated metal dishes from an oil filter and a speaker, cardboard packaging with pinholes added, a cotton sock, and lids of 5kg tubs that were being used for clean granule storage. The best-fitting solution found was a 28cm frying pan splatter guard, but this came with an issue of fine particles falling through to the dehydrator base, even after trying to sieve the granulate beforehand. Cloth socks are the tidiest for the machine, but may catch on sharp edges of granulate and introduce fibre contamination, and by restricting airflow to the material it may slow drying times.

Although the dehydrator can hold up to 6 tiers of trays, the recommended time to run the machine on wet material is for several hours - the default being 10 hours for food items. However, because it runs at relatively low temperatures, the energy consumption is low. Also, bags of silica desiccant granules can be placed in the first layer and used to maintain low humidity in sealed bags of material after the cycle has finished.

This can also be used to improve 3D print quality to very high levels, by putting an entire reel of filament into the dehydrator before using it, and/or placing desiccant packets next to the printer inside a sealed box. As the glass transition temperature of PLA starts at about 60°C, it should not be heated above this, in order to prevent the filament from sagging and becoming tangled.

Granulate processed in the ***Rotajet* JST 250-300** granulating machine.

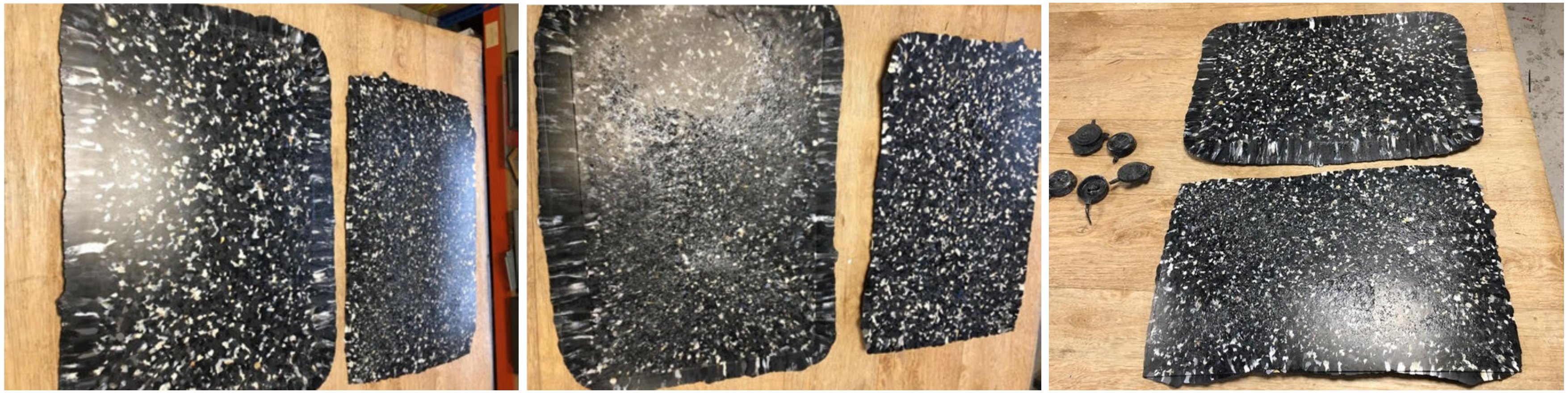
From left to right: Mixed HDPE bottle caps, green drum HDPE, clear and blue bottle PET, and ABS from electronics casings.

CR Clarke using ROAR ABS granulate : sheet press and injection moulding

After we sent a sample of our granulated ABS casings to CR Clarke Ltd, they tested some of it in one of their sheet presses and returned the samples to us.

With a sheet pressed at 180°C, they found that a sheet produced from this material had many small bubbles and pock marks where water evaporated and tried to escape, due to moisture content of some of the ABS from damp storage.

When they dehydrated this granulate and tried the test again at 190°, results were much improved.



Experimentation on the CR clarke press.

After considering several options for various types of compression moulding machines, we settled on the R30 Sheet Press from CR Clarke, an off-the-shelf solution that was very easy to set up, has a maximum temperature of 200°C, and clearance for a mould up to 60x40x4.5cm in size:

The press was supplied with a 19"x11" sheet mould with a non-stick surface and a 6"x6" tile mould required coating with release wax.

Set-up with either mould takes several minutes, as granules must be spread out evenly in the sheet mould, and the tile mould cleaned and wiped with wax between press cycles.

Pressed sheets have significant flashes (leaked excess material) around the edges that are easily trimmed off with a knife or paper guillotine.
The tiles by comparison can be more difficult to extract, where HDPE tends to stick to the steel mould cavity if the wax coating is not perfect, while ABS that doesn't stick as much or shrink as much can be tricky to pull out as it fits the cavity snugly.

Thin Sheet initial assessment:
This sheet measures 482x278x1.1mm, weighs about 150g, and has many possibilities:

- Raw material for vacuum forming - one of these sheets cuts into two standard ones, as used by the Formbox vacuum former at GSA's highland campus in Forres, so we could supply stock material to them. These sell at £1/sheet in packs of 30.
- The sheet is flexible enough to wrap around one's head with no risk of breaking, so could be cut into strips for production of face shield headbands. If we could do the same with PET or PC, that would make an ideal reusable visor material. However, the machine is unable to reach the 250C+ temperatures required to melt those.
- It is also flexible enough that it could be used to make a colourful lampshade by simply binding the short edges together, or cut up and incorporated into parts of a costume.
- It may be fastened to a surface, e.g. tacked to a shed, as a waterproof layer.

More applications will be explored, but we at least have a usable product straight away.
The main issue to solve at the moment is removal of contaminants, as this was produced from unwashed bottle caps, there are some flakes of foil from lid seals in the mix, among other dirt.

Removing these contaminants may be crucial for this to be used in vacuum forming, and while it will probably never be food-safe, other applications will appreciate a cleaner sheet material.
Another flaw to work out is the presence of bubbles within the product, which the manufacturer advises are most likely caused by moisture on the granules, which has a hard time escaping from the mould. We will need to dry granules in larger batches than before in order to meet the capacity of this machine.

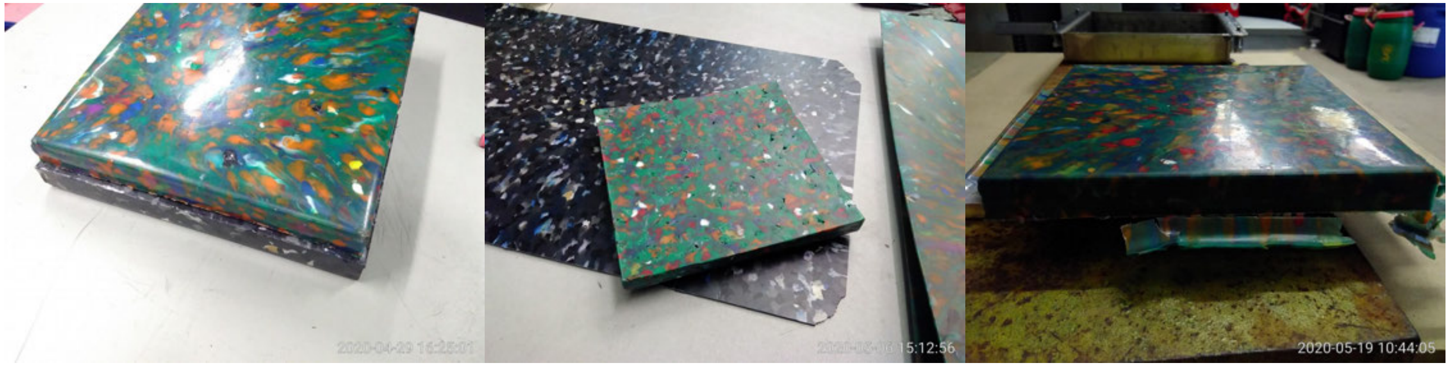
Tile Mould initial assessment:
The tile mould takes a lot more time and effort to fill and empty than the sheet mould, but slightly less time to press, so it is hoped that a more valuable use will be found for the material. The potential uses of these tiles for raw material may be limited by the curvature caused by shrinkage when one side cools faster than the other, and inclusion of gas bubbles when these fail to escape the mould. The shrinkage occurs more with HDPE, and these voids are a serious problem but should be solvable with scaling up our dehydration.

One quick use for these could be as part of protective gear commonly used in cycling, motorcycling, skateboarding and longboarding to protect the joints from impacts on falls and skids.
For longboarding in particular, very simple blocks of plastic called “pucks”, smaller than these tiles, are often used on gloves as a type of brake pad, and sell for several pounds per set.
If a thinner tile can be produced, possibly using a thicker upper plate, and allowed to pop into a deep curve as it cools without pressure, this could make an ideal knee & elbow pad material.

Cooling under compression:

Both the sheet and tile moulds have been left in the press to cool overnight, in order to test the results of maintaining pressure on the product as it cools.

This has visibly improved the final flatness of both the sheets and the tiles, showing the value of a secondary hydraulic press to place a mould into while it cools and reload the heated machine with a different mould.



Extrusion. PET, HDPE and ABS filament for 3D printing.

A Noztek Pro Mk.1 extruder **(Ref: www.noztek.com/product/noztek-pro)** was tested for the production of FDM 3D printer filament, because production of such filament would greatly increase the value of our recycled ABS and PET. Reels of such filament typically sell for £10-£30 per kilogram, and in excess of £40/kg for specialist filaments such as fibre composite materials and elastomers.

When first released, this model was claimed to be the top of its class in how much material could be extruded for a desktop machine.

However, improved models were released by the same manufacturer after the initial funding bid, but at a significantly higher price point.

Several problems were encountered with the design/manufacture/operation of this machine over the course of these tests:

1. The 3mm nozzle that was supplied with the machine was incorrectly drilled with a slot for the thermocouple (temperature sensor probe) not in the right position, and the nozzle outlet hole was only drilled to 2mm.
2. There was no repeatable way provided to secure the thermocouple on the nozzle, where it was held down by tape on delivery, which soon lost its adhesion. The first attempts to improvise a wire tie did not hold the sensor tightly enough, resulting in the machine overheating, a problem which was not resolved until a few test runs later.
3. While the temperature problem was unresolved, the overheated ABS released copious amounts of fumes, likely breakdown products such as butadiene and styrene, and so a simple fume extraction hood was built for the machine, which could not keep up with the gases generated as the door(s) needed to be open most of the time for adjustments to be made to the extruder.
4. The auger had difficulty pulling in pellets of ABS at a steady rate, unless the hopper was topped all the way up, and had great difficulty pulling in our granulated PET steadily, even while full.
5. If there was too much material extruded at the nozzle compared to how fast it was being wound onto a spool, then a section of filament could be too wide and get stuck in one of the guides that it passed through

on its way onto the spool, causing the machine to stop, and a fused coil of solid material to back up in front of the nozzle, which could only be cut off and the machine restarted.

6. The optical sensor used to detect when there was slack in the extruded filament to wind up would create a lot of oscillation in the winding speed, pulling the filament to wildly different diameters, and sometimes fail to detect the filament when it had been pulled too thin, resulting in the filament dropping onto the table and backing up at the nozzle.
7. When this was caught in time and the sensor manually triggered before the filament could back up, the remaining filament would often be too thick again, get caught in the winder's filament guide, back up at the extruder outlet, and/or snap at the previous narrow section.
8. There is an option to manually set a constant winding speed instead of having it automatically start/stop with the sensor, however even after finely tuning this to get a consistent filament for a few metres, some perturbation in the feed of granules through the barrel would be enough to make the diameter too wide again, get caught on the winder's guide and once again grind to a stop.
9. Extruded PET would crystallise on exposure to air cooling and become so brittle as to be completely unusable, requiring a hot water bath immediately at the exit for more gradual cooling.
10. The water bath supplied for later extruder models by Noztek would not fit close enough to our existing extruder for this to work, with its cooling fan in the way, and attempts to improvise a water bath with the extruder tilted at a steeper angle resulted in exacerbating feed-in problems at the hopper.

Conclusions:

Since dedicated industries manage to extrude high-quality printable filament in these materials by the ton, while this machine has so many small mechanical niggles and an over-arching shortage of feedback control, it seems that an easily usable machine may not be practical at this price point right now.

This first model cost £1k, after previous open-source development/hobbyist kits cost a few hundred, while industrial extruders cost in the tens of thousands. The latest model from Noztek consequently costs £8k. **(Ref: www.noztek.com/product/noztek-xcalibur)**

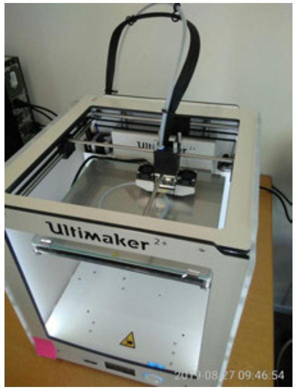
It may be possible yet to get a passable quality filament from this extruder with a lot of time spent adjusting it to some ideal settings, but that goes to show that it lacks attention to detail in design above the preceding development/hobbyist machines.

Producing a consistent high precision filament suitable for high-quality 3D printing will most likely require investment in a more complete set of equipment, and we note that a part of the toolchain produced by Noztek just for adjusting filament diameter to such fine tolerances costs £4k alone.

(Ref: www.noztek.com/product/tolerance-puller)

There may be opportunity for other competitors to beat this system on price while retaining high quality, which will be investigated if this is pursued further.

3D printing



We tested an Ultimaker 2+ 3D printer for its ability to turn prepared coils of our recycled plastic into valuable products at low production scales.

3D printers are typically known as “additive manufacturing” machines, as they only add material to a workpiece, with zero or extremely low waste, instead of cutting shapes out of some stock; and as “rapid prototyping” machines due to their use in producing physical models of a new idea directly from a Computer Aided Design file, without the need to set up conventional production tooling that typically is only cost-effective for runs of thousands or millions of parts.

These machines used to cost tens of thousands of pounds, and were only seen in universities and engineering firms, until the RepRap (self-Replicating Rapid-prototyper) project brought this cost down to hundreds of pounds, as they released open-source designs for 3D printers built out of printed parts and common metal fixings. The printer that we bought was a professional offshoot of that work, constructed with laser-cut polymer sheets.

Material Considerations:

Ideally we wish to print parts with our own recycled plastic, in order to turn a previously worthless waste stream into products that have high value to our community. However, doing so depends on us first creating a filament of high dimensional accuracy using our extruder, and so while we don't have a usable feedstock to print with, we have continued to test our printer for possible saleable products, while up-skilling our existing trainees as they learn about this increasingly relevant technology.

The type of 3D printer which we are using, a Fused Deposition Modelling machine, which works by extruding very thin cross-sectional patterns of molten plastic on top of each other in successive layers, has limits in what polymers it can work with based on their material properties.

When some polymers cool from a molten to a solid state, they shrink enough that the outer edges of a layer can warp upwards slightly, enough to leave cracks in an object or render it unprintable.

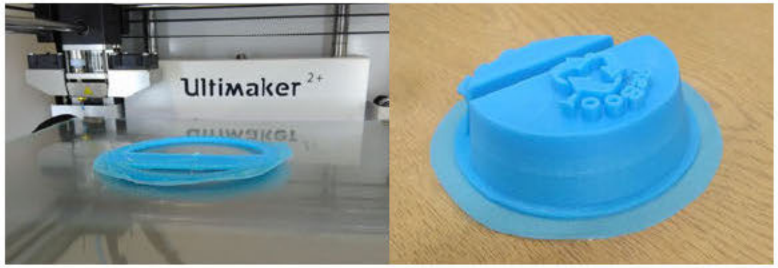
For this reason, the most common material used for this is Poly Lactic Acid, a compostable bio-polymer similar to PET in some of its physical properties, with a very low shrinkage factor and the added bonus of its waste having a safe disposal route.

ABS, which we wish to prepare, is also heavily used for its higher temperature resistance, typically in parts surrounding the 'hot-end' (heated extruding head) of printers that have had their own parts printed from open-source designs in the RepRap project. It

does however suffer from more shrinkage than PLA, but not enough to be unmanageable.
Polycarbonate (PC), which is sometimes used in electronics casings where very high strength and temperature resistance is desired, can also be used but is far more difficult as it also has higher shrinkage. Many others such as HPDE are not suitable at all based on this shrinkage factor.

Our printer worked very well with PLA filament from day 1, able to produce models with a degree of detail under 0.1mm. Although staff and trainees had to learn a few lessons about proper cleaning of the heated build plate, appropriate temperatures to set for each material, and the limits of scaling down a model, this was an all-round success.

On the first attempts with ABS (shown here in blue), due to its shrinkage, parts would fail to stay stuck down to the build platform during printing, or would crack on later layers. The adhesion problem was solved by painting a very thin layer of ABS dissolved in acetone onto the glass build plate, which could be peeled off afterwards.



The temperature required of the build plate and surrounding air to prevent warping and cracking in parts was about at the limit that this printer could manage, especially in fall and winter, when most of this testing occurred. Time had to be allowed for the printer to warm up in the morning - on days when the ambient temperature began in single degrees Celsius, the printer's LCD would even show an error, with its firmware assuming the temperature sensor to be faulty until the room warmed up!
In order to help with this, we placed the printer inside a closed cabinet (shown on right), which maintains a higher air temperature immediately around the printer, improving ABS print quality and keeping most fumes inside until the print is finished.

Conclusions:

Our 3D printer will be very capable of producing a few high-value products at low volume, and prototype products for us to produce in greater volumes with different moulding and forming technologies.

While it is possible to produce small objects in runs of tens or hundreds, this will be very time consuming and is not practical unless the demand is very great.

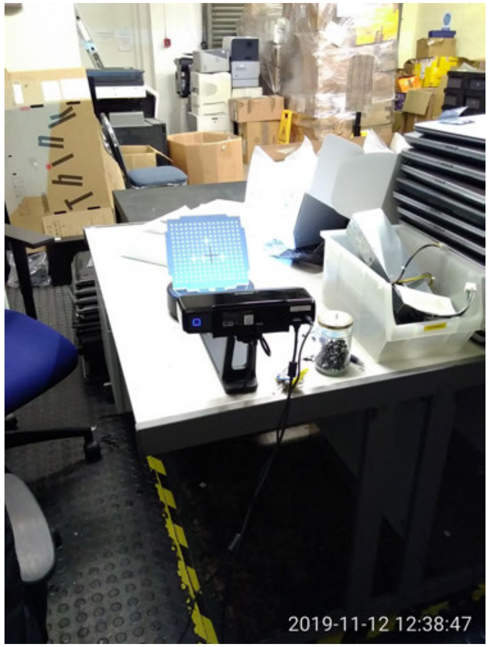
3D Scanning

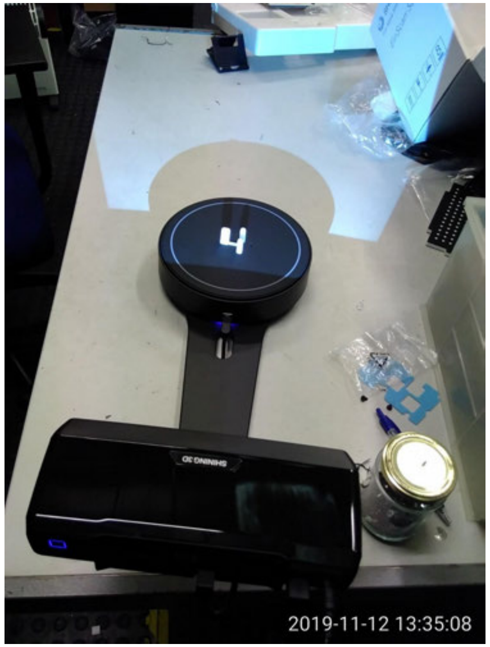
The Shining 3D EinScan-SE is a small desktop 3D scanner using a turntable, stereoscopic cameras and a light projector to shine a grid on rotating objects.

We set the scanner up with its calibration board and then tried scanning a couple of objects around an IT workshop for examples.

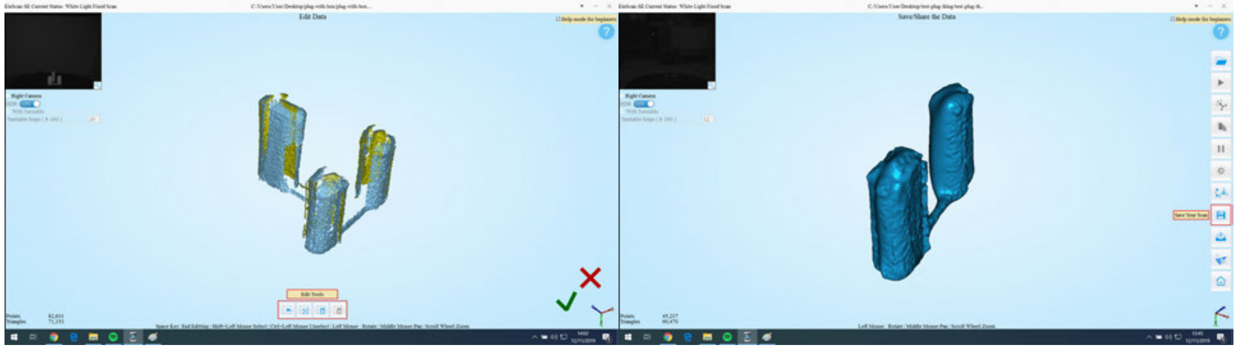
Advice with the use of these machines is that reflective surfaces can make an object more difficult to scan, but a dusting or spray solution of chalk can be enough to solve this.

Placing the scanner inside a box in order to remove reflections from distant objects also helps.

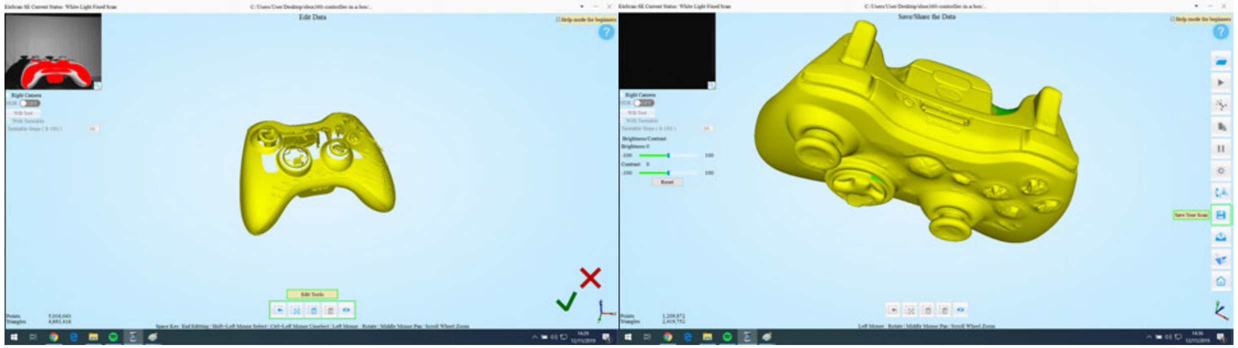




This was confirmed when a plug protector was scanned at first with poor results, being a small object with a somewhat glossy surface.



Next we tried scanning a games controller, which had many small details but a mostly matt surface.By turning the object in smaller steps, we obtained a model in high detail.

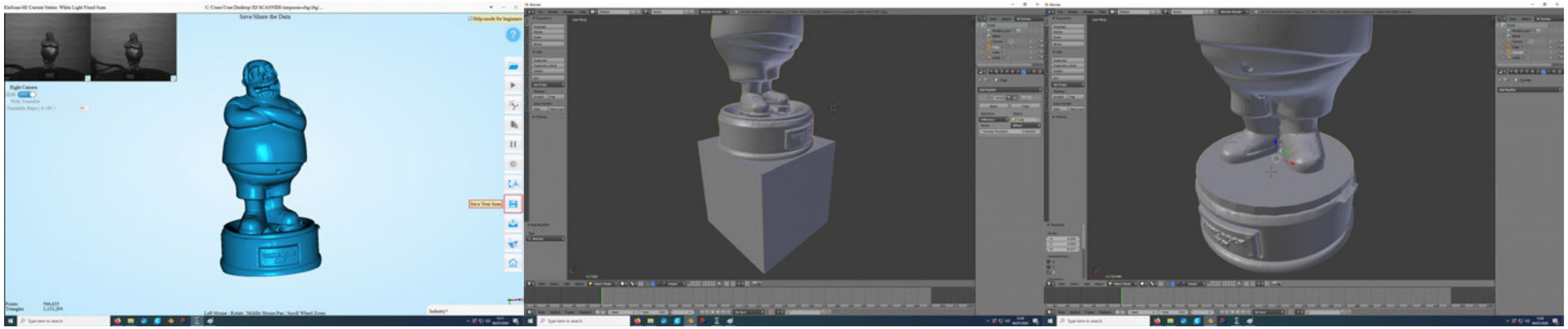


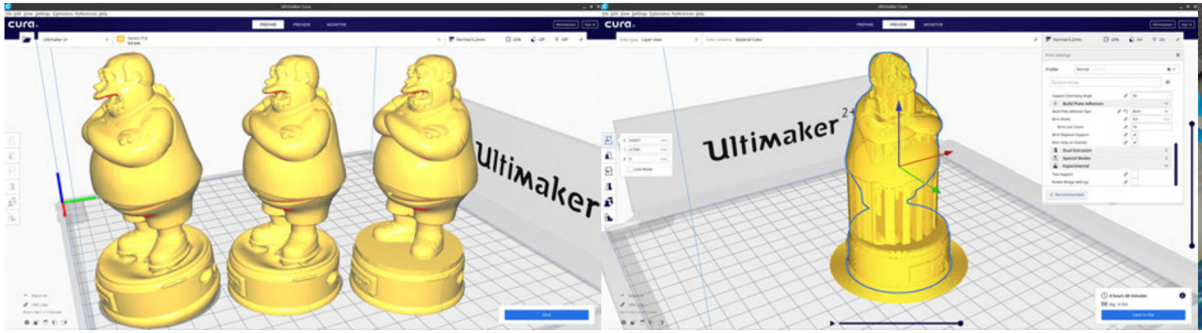
Despite not being able to see some parts of the object in shade of other parts, which shows up as large holes in the model, and the machine being knocked by someone passing through the workshop towards the end, showing up as a few scratch lines, the software is able to repair these holes as shown here.
In the case of such a piece where we wish to scan all sides of it, the object can be scanned twice while laid at two different angles, and the two partial meshes combined into one model in software.

Otherwise, an ideal application for this is an object under 20cm in size with a flat base, such as a small sculpture or miniature statue, i.e. the same conditions that would make such an object easy to 3D-print. This can be used with small museum artifacts in order to produce a replica that the public can handle.

When more time was available later in the project, this was trialled with a Simpsons desktop ornament shown below. A little post-processing was required to flatten the base, where the 3D scanner struggles to make out very dark objects. This was done quite quickly in the free software application Blender.

On objects such as this, with wide overhangs, a support structure needs to be 3D printed around the model, as shown in the print preview screenshot.



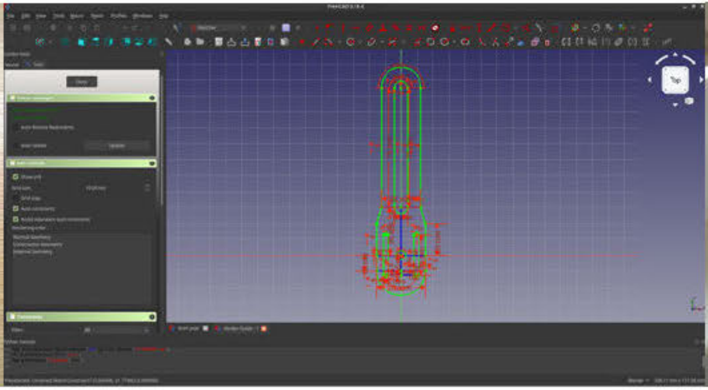


In some cases, where an object has very simple geometry, it can be just as fast and more appropriate to measure a required replacement part and draft it in CAD software.

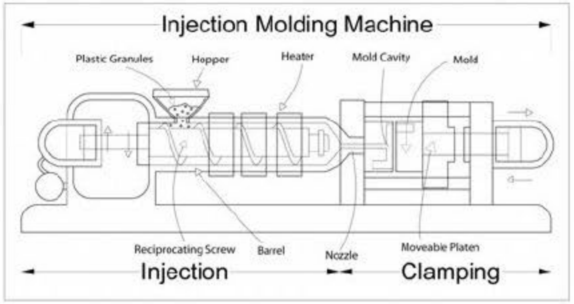
As an example of this, a blender was brought to Forres repair café with a broken toggle on the bottom of its jug, meant for the safety switch on the base. The old part was measured out and replaced with a single printed part, (shown bottom-right), screwed into place with existing parts and a small nail added for structural reinforcement.

Drafting the replacement part in FreeCAD took around an hour of work, 3D printing took 7 minutes at high detail, repeated once with an adjustment to improve fit, and the tiny part worked very well.

In the same way, we were also able to upgrade a filament guide part on our extruder (shown bottom-left) to allow wider filament to be fed onto spools.



Injection moulding.



Injection moulding machines work by forcing molten polymers at high pressure into mould cavities made up of two or more metal platens securely fastened. This process is capable of producing parts with a very high degree of detail thousands or even millions of times depending on the mould quality.

Industrial injection moulding machines typically run on a similar principle to our extruder, using an auger/screw mechanism, but with added valving stages that increase the pressure to high levels, and the tight seals used on the moulds typically produce smaller flashes than with compression moulding. These machines also come with a very high investment cost, with expectations of high production volume to make up for it.

While our extruder could technically be fastened to a mould and fill it with molten plastic, the low pressure would result in significant shrinkage of products.

However, there is a different solution for hobbyist and small business scales. Benchtop injection moulders work on a much simpler principle of forcing material using a piston mounted to a bench press. Investment cost is greatly decreased and labour cost is increased, which is less of an issue for small social enterprises.

Some come as kits that mount into an existing drill/bench press and there is an open design for a standalone machine published by the Precious Plastic project (bottom-left).

CR Clarke offer a high-quality benchtop machine (bottom-centre), so when we sent them a sample of our ABS to test in their sheet press, they also tested this in one of their injection moulders with good results.

The results (bottom-right) are from moulds for castor wheels and spinning-tops. The spinning tops show some flashes on the edges, indicating that higher clamping force and/or temperature than their tests may improve the quality further.

We have not done any injection moulding as part of this project yet, but it remains a possibility for future exploration.