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Cradle to Cradle® Design for 3D Printing

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The traditional 3Rs - “Reduce, Reuse, and Recycle” provide an effective measure to reduce consumption rates of natural resources. This process is however considered as “down-cycling”. The quality of recycled materials degrades over time with waste accumulation. To minimize or even eliminate waste accumulation, a Cradle to Cradle® design framework for 3D-printed products interconnecting five elements – plastic recycling, pre-treatment, extrusion to filaments, 3D printing and users, is hereby proposed. The ultimate goal is to essentially prevent any generation of wastes via healthy, regenerative and cost-effective manufacturing cycles that consider materials as assets. A distributed recycling platform for 3D printed products with an international recycling code system is recommended to help the recirculation of regenerated materials. Utilisation of renewable energy and water stewardship are also suggested to reduce both carbon and water footprints. Finally, a standard certification system for 3D printing filaments is also crucial to improve extrusion and 3D printing processes using shredded recycled plastics.

1. Introduction

The 3D printing market is growing highly at a compound annual growth rate of 14.37 % and is expected to reach 8.43 billion USD with a materials market size of 1,432 million USD by 2020 (Marketsandmarkets.Com, 2014). In terms of material volumes, the global demand for 3D printing materials reached to approximately 2 million tons in 2013 (Marketsandmarkets.Com, 2014). There are two major variations in 3D printing techniques – fused filament fabrication (FFF), whereby plastic filaments are deposited on top of the same material to produce objects via adhesion or heat, and stereolithography (SLA)/selective laser sintering (SLS), whereby layers of powders or liquids are deposited with the use of photopolymer and UV laser (Hausman, 2014). The former has been widely adopted in the community due to safe operation and high customisation flexibility. Hence only FFF 3D printing is discussed in this article.
Unfortunately, the rapid growth of FFF 3D printing has resulted in a great amount of equivalent plastic waste. Land use and resource conservation issues make it unacceptable to simply throw away these waste materials, and therefore recycle options have been explored. There are four major plastic waste recycling methods: energy recovery (incineration), feedstock recycling (pyrolysis, hydrogenation, and gasification), chemical (de-polymerisation), and material recycling. Based on the life cycle analysis of these methods for plastic packaging (Wollny et al., 2001) and apparels (Bartl and Haner, 2009), material recycling is identified to be the most preferable method to deal with the waste deposition problem. However, the quality of polymer regularly degrades after each reprocessing step, resulting in poor mechanical properties, and limits the applications of the recycled products. The efficiency of recycling also depends on regional regulations. According to local statistics, plastic waste recycling percentage ranges from about 5 % in Malaysia (Lai, 2012) to 59 % in Europe (Plasticseurope, 2015). For 3D printing to be more environmentally friendly and sustainable, the major consideration is to reclaim and regenerate the wastes into raw materials. This paper will first provide a review on 3D printing, followed by proposing and discussing on a “Cradle to Cradle®” reclamation and reuse framework of plastic wastes as the raw materials for 3D printing.

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2. Printing Filaments

Table 1 compares the properties of commonly-used thermoplastic 3D printing materials. Among commercially available materials, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) are the two most-commonly-used ones, evidenced by their low cost and widespread availability. ABS has a rather high glass transition temperature (the temperature at which the thermoplastic changes from its solid state to a pliable state thus losing its original shape) of around 103 °C, and is relatively strong with slight flexibility. Thus, it is suitable for printing spare parts or parts exposed to high-temperature environments, such as sunlight and hot water. ABS, however, requires a heating plate to reduce its warping problem, and an open space or adequate ventilation to evade the mild odour produced during extrusion. On the other hand, PLA offers a green option, as it is produced from corn starch or sugar cane and is biodegradable. It does not necessarily require a heating plate as it is less prone to warping. However, due to its relatively low glass transition temperature of around 60 ^{o}C, it is susceptible to heat, and thus is not ideal for long-term outdoor use. It also requires a small fan at the extruder to prevent re-melting. It is fairly brittle and usually used to print rain-collectors, pipe fittings and decorative objects.

Table 1: Properties comparison of the common 3D printing filaments

Thermo-plastics, USD/kg	Printing T (^{o}C)	Pros	Cons	Others
PLA, From 19.19	175-200	Eco-friendly, biodegradable, good adhesion at high printing speeds, especially good at producing sharp corners, less prone to warping	Fan required at the extruder, fairly brittle, susceptible to heat thus not ideal for long-term outdoor use, limited gluing	Dissolve in Sodium Hydroxide
ABS, From 18.96	220-240	Resistance to high-temperature environments like sunlight or hot water, good adhesion at high printing speeds, slightly flexible, smooth extrusion, easy sanding, easy gluing	Mild chemical odour during extrusion, expands and shrinks in heating and cooling, thus heated plate required. Imperfect bonding between layers, will bubble when exposed to moisture	Dissolve in acetone
Nylon, From 39.95	230-270	Excellent layer adhesion great bridging capabilities and durability, tear resistance, dyeing filaments before print provides a tie-die effect, odourless	More prone to curling thus a heated build platform required, potentially emits cyanide at high temperatures (fine at printing temperatures)	Resistant to acetone, opaque to transparent, can be dyed to different colours
PC, From 49.99	260 or higher	High resistance to scratches and impact, high strength and durability	Hygroscopic, can undergo a change in state when exposed to UV, more opaque and brittle over time, can release toxic fumes	-
PET, From 79.95	212-235	Fairly stiff and very lightweight, strong and impact-resistant, Taulman T-Glase is FDA approved polymer for food contact, 100 % reclaimable	Hygroscopic, more brittle than PLA	-
HIPS, From 25.49	210-230	Easy to paint and glue, great for printing lightweight parts	Still at experimental stage to be used as a soluble support	Dissolve in limonene solvent
PVA, From 35.95	160-205	Biodegradable, recyclable, eco-friendly, high bonding power, good barrier properties	Very hygroscopic, not suitable in slight humid conditions	Dissolve in water

Nylon (polyamides) offers several advantages over ABS and PLA due to its high flexibility and strength, such as excellent layer adhesion, tear resistance, and colour combination. However it is much trickier to print than PLA and more prone to curling thus a heated bed is required. Due to its mechanical strength, it is often used to print mechanical parts. It can also print water-tight objects when using acetone as the solvent and ABS as the soluble support. Other materials, for example, Polycarbonate (PC) offers high resistance to scratches and impact, but susceptible to UV as it becomes more opaque and brittle over time. Polyethylene Terephthalate (PET) is fairly stiff and very lightweight, strong and impact-resistant, and the brand Taulman T-Glase is FDA-approved polymer for food contact. High-impact Polystyrene (HIPS) and Polyvinyl Alcohol (PVA) are also commonly used as soluble support for other thermoplastic materials. For decorative purposes, there are also filaments with special effects, such as glow-in-the-dark, photochromatic, sparky, temperature sensitive and sandstone-like in the market.

3. 3D printers for home users

A comprehensive 3D Printer Guide provided by 3D Hubs (2015), which was based on 2,279 verified 3D printer owners with their collective years of 3D printing experience coupled with 317,000 prints completed on 235 different 3D printer models, has classified 3D printers into five categories – Budget, Kit/DIY, Plug ‘n’ Play, Enthusiast and Resin. The first four categories are listed in Table 2, in terms of user rating and selling price. With less than $ 1,000, the Budget 3D printers listed in Table 2 emphasize value for money as well as reliability. Backup by active open source community support, the Kit/DIY Printers offer good print quality and are especially suitable for tinkerers for adding upgrades or modifications. Plug ‘n’ Play 3D printers, which can be used straight out of the box, offer reliability with the limitation of smaller print volume, best for beginners who want the most straightforward model for their printing projects. From rough models at 350-micron resolution to extremely fine prints at just 20 microns, Enthusiast 3D printers offer great and consistent print quality, and provide enthusiasts flexibility for upgrades and modifications.

Table 2: 3D FFF printer categories, adapted from 3D Hubs (2015)

Category	Printer name (USD, user rating out of 10)
Budget	Printrbot Simple Metal ($ 599, 8.6), Sharebot KIWI ($ 860, 8.6), Solidoodle 4 ($ 599, 8.5), FlashForge Creator ($977, 8.4), UP mini ($ 599.99, 8.3), Da Vinci 1.0 ($ 499.99, 7.5), Da Vinci 2.0 ($ 649, -)
KIT/DIY	Rostock MAX ($ 999, 9), Mendel90 ($ 785, 8.9), Kossel ($ 650, 8.8), Ultimaker Original+ ($ 1,225, 8.8), Bukobot 8 V2 Duo ($ 1,299, 8.6), RepRap Prusa i3 ($ 490, 8.4), Printrbot Simple ($ 349, -)
Beginners	Zortrax M200 ($ 1,990, 8.9), BEETHEFIRST ($ 1,699, 8.9), UP Plus 2 ($ 1,299, 8.8), Afinia H480 ($ 1,299, 8.7), Makerbot Replicator Mini ($ 1,375, 8.6), Flashforge Dreamer ($1,099, 83), Cubify Cube 2 ($ 650, 7.2), Makerbot Replicator 5th Gen ($ 2,799, 6.3)
Enthusiast	Makergear M2 ($ 1,475, 9), FlashForge Creator Pro ($ 1,349, 8.7), Ultimaker 2 ($ 2,500, 8.6), Witbox ($ 1,699, 8.6), Type A Series 1 ($ 2,749, 8.5), Lulzbot TAZ 4 ($ 2,195, 8.5), Felix 3.0 ($ 1,855, 8.1), Airwolf AW3D HDX ($ 2,995, 8.1), Makerbot Replicator 2X ($ 2,499, 7.5), Leapfrog Creatr ($ 1,860, 7.0), Cubify Cube X (-, 6.2)

4. Open-source community repositories

There are a number of community repositories on the internet which support open-source designs and shared licensing models. These community repositories, coupled to the “Maker Movement’, encourage the creation of versatile, low-cost and open-source 3D printers to accelerate technology innovation and diffusion into the society. The most notable open-source 3D Printer projects are the RepRap (Reprap, 2015) and Fab@Home (Fab@Home, 2010) – the first two open-source DIY 3D Printers.

RepRap stands for Replicating Rapid-prototyper, capable of self-replicating by making a kit of itself. It was the first of the low-cost 3D printers invented by Adrian Bowyer and first appeared online in February 2004. RepRap uses FFF to lay down material in layers. It can print with PLA, ABS, Nylon, HDPE and similar thermoplastics. All of these designs are released under a free software license, the GNU General Public License (Bowyer, 2006). Jones et al. (2011) provides a reasonable literature review on RepRap, outlining the background, process selection, designs of key parts, and estimation of the reproductive success.

Fab@Home stands for Fabrication device at Home, the first multi-material 3D printer available to the public. The project was led by Hod Lipson and Evan Malone, students at Cornell University’s department of Mechanical & Aerospace Engineering in 2006 and was closed in 2012. Unlike RepRap and other 3D home printers which uses FFF, Fab@Home is a syringe-based deposition system in which multiple syringes can be independently controlled to deposit material through syringe tips. It can print with a broad range of materials that could be squeezed through the tip, such as liquid, paste, gel and slurry, covering from hard materials, elastomers, biological materials, food materials, to engineering (Fab@Home, 2010).

Other open-source 3D printers are mostly from the variations of the RepRap and Fab@Home, such as MakerBot, Lutzbot, Ultimaker, PrintrBot, Rostock and Repman, each of which consists of active community repositories. For instance, the Thingiverse open-source design repository (Makerbot, 2015) created by the co-founders of MakerBot is the most popular website for sharing creative common 3D files for home 3D printing. Michel and Yves (2015) has provided an updated list of online 3D model repositories.

5. The proposed Cradle to Cradle® framework for 3D printed products

Gebler et al. (2014) developed the first sustainability-based study with both qualitative and quantitative assessment of 3D printing. It was predicted that 3D printing is beneficial to manufacturing high-value, low-volume and customized products in five key markets – aerospace, medical component, tooling, automotive and consumer products, and it has the potential to reduce capital costs of 70-593 billion USD, total energy supply of 2.54-9.3 EJ, and CO_2 emissions of 130.5-525.5 Mt by the year of 2025 (Gebler et al., 2014).
To go beyond sustainability, a new conception of design was developed. It was known as Cradle to Cradle® (C2C®), which was popularized by William McDonough and Michael Braungart in 2002 (Cradle to Cradle Products Innovation Institute, 2014). Similar to the nature eco system, the Cradle to Cradle® model involves closed-loop cycles, i.e. all material inputs and outputs contribute as either "biological" or "technical" nutrients, with essentially "zero waste" produced. Technical nutrients can be recycled or reused in continuous cycles without losing their quality, and biological nutrients are organic materials that can be composted or consumed.

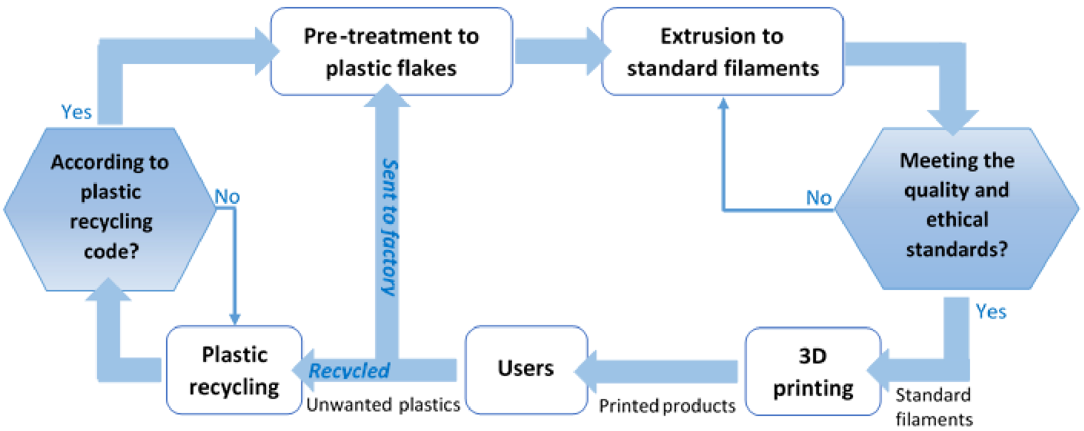

Figure 1: The proposed Cradle to Cradle® framework for 3D printed products

With "zero waste" as the ultimate goal, a C2C® design concept for 3D-printed products consisting of five elements is hereby proposed. As shown in Figure 1, recycled plastic materials sorted according to the resin code are washed and cut into flakes. The flakes are used as the raw materials for filament extruders. The filaments produced will go through verification steps to guarantee their compliances with the quality and ethical standards. These standard filaments can then be sold or reused in 3D printers. The unwanted 3D-printed items are then recycled or brought back to factory, thereby creating a closed-loop waste-free cycle. Each step is elucidated as follows.
(1) Plastics recycling: plastic wastes are recycled and sorted according to their resin identification codes. The recycled plastics can be HDPE, LDPE, PET, and PLA. However, with the growing demand of 3D printing, there is a need of expanding recycling codes for the 3D printed objects. Hunt et al. (2015) raised the issue of increasing amount of waste plastics generated from the 3D printing industry in the future which will make recycling a difficult task especially when dealing with complex printing materials. They therefore proposed and demonstrated with OpenSCAD scripts a voluntary recycled code model based on the resin identification codes in China (Hunt et al., 2015).
(2) Pre-treatment: Sorted plastics are subject to pre-treatment including washing and cutting into flakes.
(3) Extrusion to standard printing filaments: Plastic flakes are then fed into filament extruders, such as Lyman/Mulier filament extruder, Strooder, Filastruder, Ewe, Filabot Wee, ExtrusionBot, Noztek Pro, STRUdittle, RecycleBot/BottleBot, FilaMaker, and Photocycler. Current efforts are mostly on producing 3D printing filaments from recycled plastics (Bastian, 2012) and improving the device (Braanker et al., 2010). Developments are still ongoing for improved filament qualities comparable to virgin ones (Kreiger et al., 2014). In order to minimize the heating history of plastics, development of extruders using plastic flakes as the raw materials are essential. For waste-derived printing filaments to align with societal and environmental outcomes, at the same time with economic incentives for cooperation, the filament

production must be of high quality and ethical, with compliances to various standards. The Cradle to Cradle Product Innovation Institute (C2CPII) founded by William and Michael in 2010, guides designers and manufacturers and provides certification to make products in a systemic approach which turns product innovation and development into a positive force for society and the environment. In addition, the Ethical Filament Foundation, founded by UK Charity techfortrade in 2013, in partnership with Dreambox Emergence is working to develop an ethical filament production standard and certification process to guarantee the quality and ethical value of any certified filament in terms of minimum pricing, fair trade premium (Feeley et al., 2014), labour standards, environmental and technical standards, health and safety standards, and social standards. Other organisation such as the Plastic Bank and the Perpetual Plastics Project are also dedicated to waste plastic recycling for the production of 3D printing filaments.
(4) 3D printing: The standard printing filaments are then sold and used on 3D printers. Developments are ongoing for improved print quality, which contains interrelated aspects including dimensional accuracy, surface finish, overhand capabilities, deposition control, motion mechanics, motion control, material properties, and slicing algorithms (Bastian, 2014). In the annual guide to 3D printing provided by Make: (2015), a methodical, quantitative framework for evaluating and improving print quality is introduced. With this framework, changes to software, mechanics, and materials can now be correlated with changes in a specific quality performance quality (Make:, 2015).
(5) Users: Users can print any 3D objects of interest, either by generating or scanning the model, or using the open-source repositories. The unwanted 3D-printed objects can then be recycled to a local recycling point to be regenerated into new products.

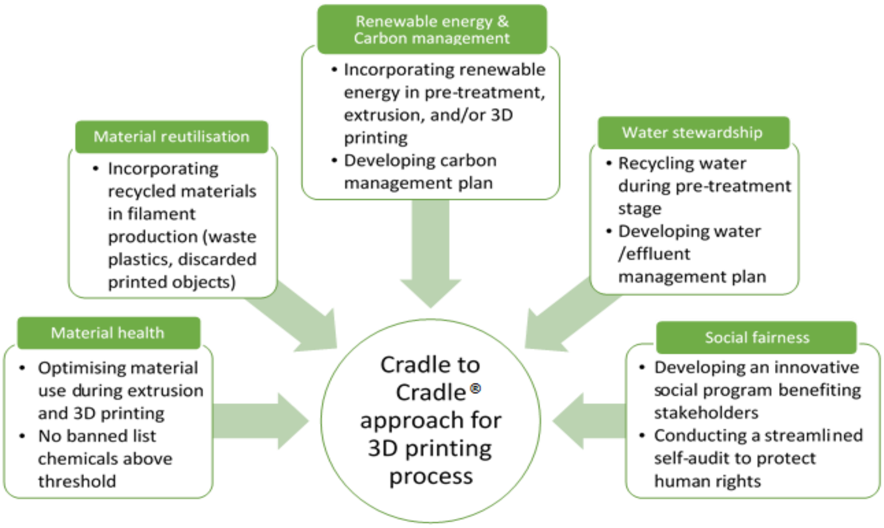

Figure 2: The Cradle to Cradle® approach for 3D printing process based upon C2CPII's certification criteria in Cradle to Cradle Products Innovation Institute (2014)

Towards achieving healthy, regenerative and cost-effective manufacturing cycles, a C2C® approach based upon C2CPII's certification criteria is outlined in Figure 2, which includes five perspectives: (1) optimising material use in the extrusion and 3D printing processes, (2) incorporating recycled materials in filament production, (3) incorporating renewable energy in pre-treatment, extrusion and 3D printing, and developing carbon management plan, (4) advancing water stewardship through recycling and effluent management, and (4) achieving social fairness via sustainable operations benefiting stakeholders.

6. Conclusions

The paper serves as a reference for 3D printing processes, covering the reviews on 3D printing filaments, 3D printers, online community repositories and sustainability-related research. A Cradle to Cradle® design framework and approach for 3D-printed products were proposed to reach the goal of zero waste production. A distributed recycling platform for 3D printed products with an international recycling code system is recommended to help the recirculation of regenerated materials. Utilisation of renewable energy and water stewardship are suggested to reduce both carbon and water footprints. Finally, a standard certification system for 3D printing filaments is also crucial to improve extrusion and 3D printing processes using shredded recycled plastics. The proposed framework not only provides new guidelines for material recycling process, but also helps to shape a better and greener 3D printing industry.

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