



## Full length article

## Tightening the loop on the circular economy: Coupled distributed recycling and manufacturing with recyclebot and RepRap 3-D printing

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## ARTICLE INFO

## Keywords:

Circular economy  
Distributed recycling  
Distributed manufacturing  
Energy conservation  
Polymer recycling  
Sustainable development

## ABSTRACT

A promising method of enhancing the circular economy is distributed plastic recycling. In this study plastic waste is upcycled into 3-D printing filament with a recyclebot, which is an open source waste plastic extruder. The recyclebot is combined with an open source self-replicating rapid prototyper (RepRap) 3-D printer, to enable post-consumer ABS plastic filament from computer waste to be further upcycled into valuable consumer products pre-designed in the digital commons. The total electrical energy consumption for the combined process is monitored and an economic evaluation is completed. The coupled distributed recycling and manufacturing method for complex products reduces embodied energy by half, while reducing the cost of consumer products to pennies. This economic benefit provides an incentive for consumers to both home recycle and home manufacture, which tightens the loop on the circular economy by eliminating waste associated from transportation and retail. It is clear from the results that waste plastic can be significantly upcycled at the individual level using this commons-based approach. This tightening of the loop of the circular economy benefits the environment and sustainability as well as the economic stability of consumers/prosumers.

## 1. Introduction

Over the last 50 years plastics have been used increasingly in a large range of products due to their versatility, low cost and durability (Gu and Ozbakkaloglu, 2016; Passamonti and Sedran, 2012). The global plastic production was 322 million tons in 2015, is growing 3.86% per annum, and is expected to increase to 850 million tons per year by 2050 (Shen et al., 2009; Plastics Europe, 2016). This aggressive plastic production growth aggravates the pressure for waste plastic disposal and generates many well-established environmental issues. Landfill, incineration and recycling are the three main methods to treat post-consumer plastics according to the principle of waste hierarchy in increasing order of environmental responsibility (Gertsakis and Lewis, 2003; Webb et al., 2012). Incineration of plastic has the capability for energy recovery in the form of heat (Sinha et al., 2010), but large quantities of harmful compounds and greenhouse gases are emitted into the atmosphere during incineration (Zhang et al., 2004; Astrup et al., 2009). Plastics usually need more than 20 years to degrade in landfill conditions (Tansel and Yildiz, 2011) and plastic debris in landfill is also a source of secondary environmental pollutants (Zhang et al., 2004).

Incineration and landfill methods generate severe environmental

issues, and this linear model of resource consumption that follows a “take-make-dispose” pattern has increasingly notable economic limits. High demand for resources leads to higher resource prices and supply disruptions, which exposes companies that follow the linear system to risks during heightened competition (MacArthur, 2013). To reduce risk, the concept of circular economy was first proposed by a Chinese scholar in 1998 with the aim to mitigate the contradiction between rapid economic growth and the shortage of raw materials and energy (Zhu, 1998). This fundamentally new model of circular economy is required to separate economic growth from resource consumption growth (Preston, 2012). A circular economy uses material symbiosis between different companies and production processes (Jacobsen 2006). The core of the circular economy is the circular flow of materials and the use of resources and energy through multiple phases (Yuan et al., 2006). The circular economy is beneficial to society and economy as a whole by reducing the use of the natural environment as a sink for waste and reducing the use of virgin materials for economic activities (Andersen, 2007).

Recycling, therefore, is the established best solution to treat post-consumer plastics following the goals of a circular economy (Bicket et al., 2014). However, traditional recycling can have a significant

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environmental impact as it demands the collection and transportation of relatively low-density waste plastics to collection centers and reclamation facilities for separation and reconstruction (Barton et al., 1996). In centralized recycling systems the transportation usually consumes large quantities of energy with the concomitant emissions and environmental detriment (Craighill and Powell, 1996) and needs considerable labor to classify those post-consumer plastics (Themelis et al., 2011). In developing regions this labor is provided by waste pickers, which collect post-consumer plastic in landfills far below poverty-level wages (Hayami et al., 2006; Wilson et al., 2006; Schenck and Blaauw, 2011; Feeley et al., 2014).

Compared to the traditional recycling, distributed recycling (where consumers directly recycle their own waste) has the potential to reduce energy consumption because it can save the energy for transportation needed in conventional recycling (Arena et al., 2003; Ross and Evans, 2003). A new promising method of such distributed plastic recycling is to upcycle plastic waste into 3-D printing filament with a recyclebot, which is an open source waste plastic extruder (Baechler et al., 2013). Waste plastic shards, powder or pellets are fed into the recyclebot through a hopper, and transported to the heating pipe by an auger (replacing the custom machined screw in traditional extrusion systems), which is driven by a motor. The plastic is compressed and melted in this heating pipe and can be extruded through the nozzle to form filament for fused filament fabrication (FFF)-based 3-D printing. In general, plastic recycled for 3-D printing filament is of the same type, and the process is simplified if recycling codes are granular enough to identify different kinds of plastics (Hunt et al., 2015). After classifying the plastic, it is cleaned and shredded into small pieces to improve the filament's quality by maintaining the consistency of the feed rate. The recyclebot makes filament from post-consumer plastics instead of raw materials, which can decrease by a factor of ten the embodied energy of the filament from the mining, processing of natural resources and synthesizing compared to traditional manufacturing method (Kreiger et al., 2013; Kreiger et al., 2014). In addition, the recyclebot provides the potential to recycle plastics at any location so that consumers in their own homes can save money by offsetting purchased filament as well as reducing embodied energy for transportation (Kreiger et al., 2013; Kreiger et al., 2014). In addition, professional waste pickers can sell filament for a substantial high value per kg than they earn for only sorted plastic to increase their personal income (Feeley et al., 2014).

If the recyclebot is combined with an open source self-replicating rapid prototyper (RepRap) 3-D printer (Sells et al., 2010; Jones et al., 2011), then the post-consumer plastics can be turned into useful and more valuable products (Wittbrodt et al., 2013; Redlich and Moritz, 2016). Compared to the traditional plastic manufacturing methods, like plastic injection molding, additive manufacturing with a 3-D printer has two advantages. First, a 3-D printer allows for accurate fabrication and scale models as it can directly produce complex parts by building a component in layers from 3-D digital designs with essentially no material waste (Crane et al., 2011; Gebhardt et al., 2010). Secondly, the 3-D printer can control the fill density of a product. By reducing the fill density of parts to the minimum necessary for mechanical functionality (Baich et al., 2015), 3-D print-based manufacture can save materials, reduce energy consumption and decrease greenhouse gas emissions all which contribute to sustainability (Kreiger and Pearce, 2013a; Kreiger and Pearce, 2013b; Ford and Despeisse, 2016). In addition, as 3-D printing can be accomplished locally (even in the homes of consumers) the transportation related energy can also be reduced (Birchneil et al., 2013). There is thus considerable research that has shown distributed manufacturing with 3-D printing can benefit the circular economy (Charter and Keiller, 2014; Mohr and Khan, 2015; Van Wijk and van Wijk, 2015; Stahel, 2016; Despeisse et al., 2017). The open source nature of the RepRap 3-D printer has resulted in rapid technical evolution and reductions in the cost; currently a basic polymer printing RepRap 3-D printer can be constructed for less than \$500 in parts (Anzalone et al., 2015). Reducing the cost of 3-D printers has greatly

expanded its popularity and enabled wide applicability for distributed manufacturing throughout the world for a wide range of products (Pearce et al., 2010; Mota, 2011; Richardson and Haylock, 2012; Gwamuri et al., 2016; Kietzmann et al., 2015; Pearce, 2015; Wittbrodt et al., 2015; Wittbrodt and Pearce, 2015; Petersen and Pearce, 2017).

In order to analyze the impact of combining these two trends, this paper for the first time combines the distributed recycling method using a vertical recyclebot to make filament with distributed manufacturing using a delta RepRap to print useful products from post-consumer waste. Specifically, this study analyzes the recycling of acrylonitrile butadiene styrene (ABS) from computer waste (approximately 20 wt percent of end of life electronics (MOEA, 2001)), for the first time in such systems, into useful and valuable products. The total electrical energy consumption for the combined process is monitored and an economic evaluation is completed. These results are compared to the combination of traditional recycling and traditional manufacturing, and discussed in the context of improving the circular economy, energy conservation, greenhouse gas emission mitigation and economic benefit.

## 2. Devices and methods

### 2.1. Material and energy measurements

This project presents a distributed method to completely recycle thermoplastic into valuable consumer goods at the consumers' residence. Post-consumer ABS,  $(-C_8H_8C_4H_6C_3H_3N-)_n$ , which is a versatile plastic used for a variety of durable goods, was chosen to test this method. ABS is good choice of plastic for recycling into filament because its glass transition temperature is not changed and the decomposition temperature increases slightly by 3 °C after recycling due to the decreasing of volatile monomers (Kim and Kang, 1995). The increased decomposition temperature provides a broader temperature range during the recycling process and after recycling, although its impact resistance decreases slightly, the tensile strength, elongation and hardness of ABS are constant (Kim and Kang, 1995).

Further all open source hardware-based equipment (Ackerman, 2008; Gibb, 2014) was used in all steps of the processing including an open source granulator (Appropedia, 2016a), a vertical recyclebot ac4.0 (Appropedia, 2016b), and delta-style RepRap (Appropedia, 2016c). Post-consumer ABS stabilizing feet (92.36 g/foot) for a 5G tower or smart UPS as seen in Fig. 1 was shredded by the granulator. The crushed plastic was used to make 3-D printing filament and then three case study consumer goods were manufactured including a camera tripod, an SD card holder and a camera hood. In order to compare this method with the combination of traditional recycling and traditional manufacture in energy consumption, the electricity consumed at each step was recorded by a multimeter (+/- 0.01 kWh). To account for mass loss at each processing step, at each stage of processing the plastic was massed with a digital balance (+/- 0.01 g).

### 2.2. Small-scale shredding of post-consumer plastic waste

Mechanical cleaning of the post-consumer plastic waste is necessary before the shredding step. Impurities not only degrade overall filament consistency, but also increase the clogging frequency in the nozzle of



Fig. 1. Post-consumer stabilizing foot made of ABS.

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