The Environmental Impact of Desktop 3D Printing in a Distributed Manufacturing Model: Analyzing Spare Plastic Parts Fabricated by Home Users

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The Environmental Impact of Desktop 3D Printing in a Distributed Manufacturing Model: Analyzing Spare Plastic Parts Fabricated by Home Users

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Abstract

Three-dimensional (3D) printing technologies are challenging the existing industrial paradigms and creating expectations that the relationship between manufacturing and the environment can also be different. One of these expectations is that greenhouse gas emissions may be reduced when people fabricate their own products at home because product transportation that is required by the conventional manufacturing model is avoided. Although avoiding product transportation can be beneficial for the environment, the effects of 3D printing in a distributed manufacturing model are essentially unknown. Data on environmental impact from spare plastic parts were obtained from conventional and distributed manufacturing processes by a Life Cycle Assessment (LCA) software, the Ecoinvent-3 database and electricity consumption measurements. The LCA was conducted to compare the environmental impact of spare plastic parts fabricated by two main models: 3D printing in distributed manufacturing and injection molding in conventional manufacturing. This assessment considered that spare plastic parts were manufactured overseas in conventional manufacturing, while in distributed manufacturing, parts were fabricated by users at home using a desktop 3D printer. Therefore, the aim of this study is to answer the following question: is the environmental impact of ABS-made spare plastic parts fabricated at home by a desktop 3D printer lower than that of similar ABS parts made by conventional manufacturing? The findings show that the environmental impact caused by energy consumption used by a desktop 3D printer is significantly higher than any benefit obtained from removing the

need to transport products overseas in the conventional manufacturing model. In fact, TRACI mid-point results demonstrate that global warming of distributed manufacturing is 11 times higher than that of conventional manufacturing. These findings not only highlight the environmental impact of desktop 3D printing in a distributed manufacturing model, but also justify the importance of using quantitative methods for environmental assessments of new technologies.

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Definition of Terms

3D printing: “the fabrication of objects through the deposition of a material using a print head, nozzle, or another technology. Term often used synonymously with additive manufacturing; in particular associated with machines that are low end in price and/or overall capacity”. However, this term was also used to describe the specific technology patented by Sachs et al. in 1993 as 3DP. (ASTM, 2012).

Additive manufacturing: “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2012).

Computer-Aided Design (CAD): “the use of computers for the design of real or virtual objects” (ASTM, 2012).

Conventional Manufacturing: the current manufacturing model where production is concentrated in few manufacturing locations in order to offer cost advantages due to efficiency generated by high volume and standardized production.

Distributed Manufacturing: the manufacturing model where production is distributed in several manufacturing locations. Manufacturing locations definition can vary, but for this study objective, manufacturing locations are the desktop 3D printer users’ homes.

Fused deposition modeling (FDM®): the “material extrusion process used to make thermoplastic parts through heated extrusion and deposition of materials layer by layer; term denotes machines built by Stratasys, Inc.”(ASTM, 2012).

Life Cycle Assessment (LCA): the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO, 1997).

Material extrusion: “an additive manufacturing process in which droplets of build material are selectively dispensed through nozzle or orifice” (ASTM, 2012)

Product system: “collection of materially and energetically connected unit processes which performs one or more defined functions” (ISO, 1997).

STL: ”the file format for 3D model data used by machines to build physical parts; STL is the de facto standard interface for additive manufacturing systems” (ASTM, 2012).

System boundary: an “interface between a product system and the environment or other product systems” (ISO, 1997).

Tooling: “a mold, die, or other device used in various manufacturing and fabricating processes such as plastic injection molding, thermoforming, blow molding, vacuum casting, die casting, sheet metal stamping, hydroforming, forging, composite lay-up tools, machining and assembly fixtures, etc.” (ASTM, 2012).

Thermoplastic: a kind of plastic that is moldable when heated to a specific temperature.

Unit process: the “smallest portion of a product system for which data are collected when performing a life cycle assessment” (ISO, 1997).

Chapter I

Introduction

Desktop three-dimensional (3D) printers enable users to fabricate physical objects from digital computer files in their homes. With the evolution of 3D printing technology applications and the reduction of operational costs, products tend to be manufactured close to the point of consumption, and ultimately in customers' homes (D'Aveni, 2013). Considering that it is economically and technically feasible to build products at home using desktop 3D printers, in the near future, 3D printing users may decide to stop buying products from retailers and fabricate their own products at home. Production will no longer be concentrated in few conventional manufacturing locations but will be distributed among numerous users fabricating their own products at home through desktop 3D printers.

Distributed manufacturing requires no product transportation from conventional manufacturers to users, thereby possibly reducing the environmental impact of overseas transportation. Conventional manufacturing usually relies on mass production and a centralized manufacturing model in locations such as China, where labor and material costs are reduced. Consumer products fabricated in China are then transported from manufacturers to retailers in the United States (U.S.) using ocean ships which consume fossil fuels and emit carbon dioxide—increasing greenhouse gas concentrations in the atmosphere. Conversely, distributed manufacturing tends to avoid greenhouse gas emissions because manufacturing production is distributed among local users, making overseas transportation unnecessary.

Research Significance and Objectives

Although one may intuitively suggest that desktop 3D printing associated with distributed manufacturing is beneficial for the environment because it reduces greenhouse gases, the problem is that there is little evidence to support this broad declaration. There is a common belief that 3D printing can reduce the need for product transportation and then reduce the energy required to move products from centralized manufacturing locations to retailers, reconfiguring the entire supply chain; consequently, reducing the impact on the environment (Gibson, Rosen & Stucker, 2009; Lipson & Kurman, 2013; Despeisse & Ford, 2015). Nevertheless, these authors fail to deliver objective evidences to support their conclusion; moreover, they transmit a misleading message that 3D printing by itself is beneficial for the environment.

The environmental impact of desktop 3D printing in a distributed manufacturing model needs to be evaluated considering Fused Deposition Modeling (FDM) because this is the most common technology used on desktop 3D printers by home users. Wittbrodt et al. (2013) demonstrate that there are economic benefits when users fabricate their own products at home using desktop 3D printers with FDM technology, showing that it is feasible to do so. From an environmental perspective, Kreiger and Pearce (2013) make a comprehensive Life Cycle Assessment (LCA) using an FDM desktop 3D printer and conclude that “distributed manufacturing using open-source 3D printers has the potential to have a lower environmental impact than conventional manufacturing for a variety of products."

However, Kreiger and Pearce (2013) make at least three general assumptions that misrepresent the environmental impact resulting from desktop 3D printing. First, products selected in their study do not represent a specific product category that desktop 3D printer users are willing to fabricate at home instead of buying from manufacturers. It is incorrect to draw a broader conclusion about the environmental impact of 3D printing based on a set of products that may not have a significant effect on conventional manufacturing. Second, the study does not consider transportation of raw material used by desktop 3D printers in the life cycle inventory. Desktop 3D printer users require raw material, which usually comes from overseas, to fabricate their products; for this reason, it is necessary to ship the raw material to users' homes. Third, conventional and distributed manufacturing comparison uses different thermoplastic materials. In Kreiger and Pearce's study, Acrylonitrile Butadiene Styrene (ABS) was used in conventional manufacturing while Polylactic Acid (PLA) was used in distributed manufacturing. ABS and PLA are both thermoplastics used to manufacture plastic parts, but parts produced with ABS require more energy than similar parts produced with PLA.

Therefore, this thesis proposes to use LCA to compare the environmental impact of spare plastic parts fabricated at home by a desktop 3D printer, considering raw material coming from overseas, and using only ABS to compare conventional and distributed manufacturing models. Spare plastic parts represent a true product category that can generate users' interest in fabricating objects at home instead of buying from manufacturers, as well as manufacturers' interest in sharing their product designs with users as digital files instead of managing a complex supply chain of spare parts. From a raw material perspective, assessing the environmental impact of raw material production and transportation is relevant to the overall environmental impact of the distributed manufacturing model. Desktop 3D printer users need plastic filament to fabricate their parts and this raw material usually comes from overseas manufacturers; consequently, it is important to consider the filament process as part of a distributed manufacturing system. Finally, the assessment needs to make clear that distributed and conventional manufacturing are compared using the same plastic material. Comparing different materials within the same study may result in a misleading message since the energy required to process ABS is significantly different compared to that required to process PLA.

The environmental impact comparison in this study used the LCA methodology to assess both conventional and distributed manufacturing through the Ecoinvent-3 database and TRACI mid-points. As the main benefit, the results of this LCA will show desktop 3D printer users the environmental impact of fabricating their own plastic parts at home and, eventually, influence their behavior regarding the conscious use of 3D printing resources. It is also hoped that this research will bring awareness to LCA practitioners regarding the importance of studying more realistic scenarios in order to extrapolate the environmental impact for a specific product category. Furthermore, this study may also assist future researchers in quantifying the ways in which spare plastic parts, fabricated by desktop 3D printing, can contribute to extending the life of obsolete products and promote environmental benefits through product re-use.

Background

Although prior work has been conducted in the field, the Stereolithography apparatus (SLA) patented by Charles W. Hull is generally recognized as the first major milestone in commercial 3D printing technology (Gibson, Rosen, & Stucker, 2009). The SLA printing process starts with a Computer Aided Design (CAD) file that is converted or translated into a file type named STL, a file type format develop by the 3D Systems Company, which commercializes the SLA 3D printers (Gibson, Rosen, & Stucker, 2009). An STL file slices the CAD file into layers and then the 3D printer has the information required to print each layer. Next, the STL file is sent to the 3D printer where a low-power laser beam traces a cross-section layer in a liquid photopolymer resin, solidifying this layer through photopolymerization. Finally, a new liquid layer is replenished over the previously solidified layer and then the process is repeated until a 3D object is built (Swift & Booker, 2013).

Many other commercial 3D printing technologies have emerged following Stereolithography and they typically differ in their way of fabricating cross-section layers. Their technologies often use different materials and fabrication processes but they all build 3D objects layer upon layer. ASTM International (2012) provides a set of terms to structure the most common fabrication processes of 3D printing technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. In the Manufacturing Process Selection Handbook, Swift and Booker (2013) detail the manufacturing process differences among five of these main 3D printing technologies, and also describe the advantages and disadvantages of using them for various applications. Similar to SLA, behind every 3D printing technology, there is one original patent that initiated a different technology and enabled the creation of a new 3D printing company (Table 1).

Table 1. Summary of 3D printing technologies listed by Swift and Booker (2013).

3D Technology	Main Process	Company
Stereolithography Apparatus, SLA (U.S. Patent No. 4,575,330, 1986)	Photopolymer resin solidified by light.	3D Systems
Laminated Object Manufacturing, LOM (U.S. Patent No. 4,752,352, 1988)	Laminate thin sheets of paper, plastic or metal.	Helisys
Selective Laser Sintering, SLS (U.S. Patent No. 4,863,538, 1989)	Powder material fused by laser.	DTM
Fused Deposition Modeling, FDM (U.S. Patent No. 5,121,32, 1992)	Thermoplastic extrusion.	Stratasys
3-Dimensional Printing, 3DP (U.S. Patent No. 5,204,055, 1993)	Powder material fused by UV cure.	ZCorp and others.

Adapted from (Gibson et al., 2009; Bechthold et al., 2015).

Fused Deposition Modeling

While patents protected Stratasys, Inc.'s intellectual property for a limited time, their gradual expiration has given rise to new 3D printing companies. In 1989, S. Scott Crump filed the first FDM technology patent and founded Stratasys, Inc. (U.S. Patent No. 5,121,329, 1992). This original patent was the key to the success of Stratasys, Inc. because it protected Stratasys, Inc. and allowed it to explore this new technology and develop the 3D printing market with fewer competitors. In 2009, the original FDM patent expired and then an open source project called RepRap made use of FDM 3D printing technology and became commercially available (Manyika et al., 2013). In order to build a

3D printer from the RepRap open source project, a significant amount of technical skills are required, which may frustrate less skilled users. With the objective of facilitating the access of 3D printing to the general public, Bre Pettis, Zack ‘Hoeken’ Smith, and Adam Mayer founded MakerBot in 2009; similarly, RepRap early adopters Erik de Bruijn, Martijn Elserman, and Siert Wijnia founded Ultimaker in 2011 (Frauenfelder, 2013).

The adoption of desktop 3D printers by home users has grown with an increase in companies competing in the 3D printing market, resulting in lower desktop printer prices, and increased investment in more competitive FDM technologies. With the original FDM patent expiration, the market competition of new emerging 3D printing companies has reduced desktop 3D printer prices to an affordable level and promoted the adoption of 3D printing by home users (Horn & Harrysson, 2012; Brooks, Kinsley, & Owens, 2014; Walls, Corney, & Vasantha, 2014). In four years, Makerbot sold 22,000 desktop printers and the market growth opportunities called the attention of Stratasys, Inc., which acquired Makerbot in a 604 million-dollar deal (Clay, 2013). Comprehensive market share information about 3D printers is not publicly available; however, the 3D printing communities make use of internet website portals to share their printer models and what they are fabricating. The 3D Hubs (2015) website portal provides public market research based on its users’ records. A trend report from September 2015, based on a survey of more than 20,000 printers around the globe, shows that Ultimaker 2, RepRap Prusa i3, and Makerbot Replicator 2 and 2x represent 25% of the desktop 3D printer market (Figure 1).

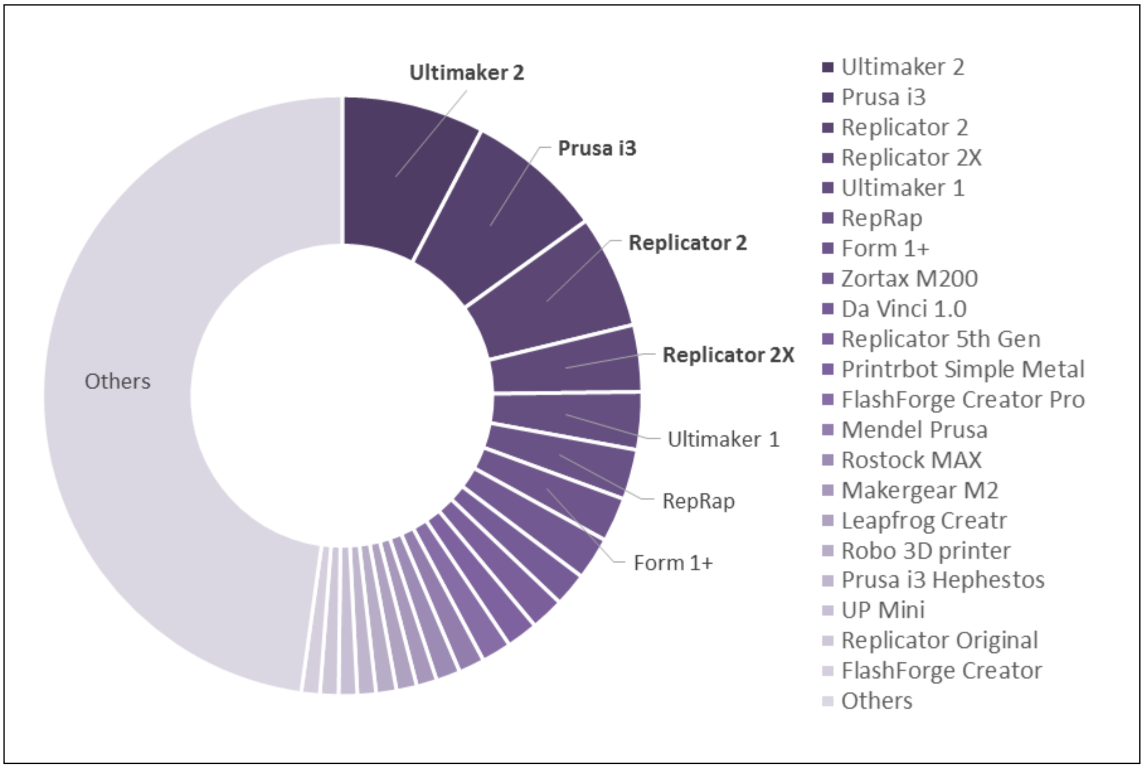


Figure 1. Distribution of 3D printer models. Adapted from (3D Hubs, 2015).

The benefit of having relatively simple technology and inexpensive raw materials has helped FDM become popular among home users, but there are also disadvantages such as fabrication speed when compared to conventional manufacturing. Similar to the SLA process, printing starts with a compatible STL file that is sent to the printer. Inside the printer, a filament of a thermoplastic (i.e., a plastic filament) is pushed into a heated nozzle where the plastic is heated to its transition temperature, melted, and extruded. Then, the print nozzle moves and deposits the molten plastic over a heated plate to create a hardened layer of material. Next, the process is repeated and more material is deposited over the previous layer and then a 3D object is built layer upon layer (Swift & Booker, 2013). The printing velocity is restricted by the capability of a printer to melt, extrude, and deposit thermoplastic material without compromising the resolution and quality required by the user.

In general, print speed and layer resolution are the main printing parameters that affect fabrication velocity. The print speed is directly related to the capability of a 3D printer to supply the plastic filament into the heated nozzle. After the plastic filament, which typically has a diameter ranging from 1.75 to 3.00 mm, is heated, the molten material is extruded through the nozzle, which has a diameter smaller than the filament. Thus, one important parameter is the velocity at which the printer can fill the heated nozzle with plastic filament. For example, the Ultimaker 2 model uses 2.85 mm plastic filament and has a 0.4 mm nozzle, and its print speed can range from 30 to 300 mm/s according to specifications (Ultimaker, 2015). Another important printing parameter is the layer resolution, which defines the layer height of extruded material. The distance that a printed object can reach in z direction—moving the print nozzle or the base plate—defines the layer resolution. For instance, the Ultimaker 2 can move its base plate into z direction and obtain a layer resolution of between 0.04 and 0.20 mm (Ultimaker, 2015).

In contrast, mass production manufacturing processes have faster building speeds and are more suitable to deal with high production volumes. The injection molding process is a common mass production manufacturing process designed to produce plastic parts. In this process, the heated thermoplastic material is forced into a steel mold tooling cavity, where it is cooled and formed. While one single plastic part may take hours to be fabricated by a desktop 3D printer, hundreds of parts can be produced per hour using injection molding process. On the other hand, contrary to 3D printing, injection molding requires upfront investments to design and fabricate steel mold tooling (Anderson, 2012; Lipson, & Kurman, 2013).

3D printing may not be suitable to substitute mass production but it can be feasible for smaller production lots since it requires significantly fewer pre-production steps to fabricate a plastic part. “It may be hard to imagine that this technology [3D printing] will displace today’s standard ways of making things in large quantities” (D’Aveni, 2015b). However, in order to operate 3D printing it is only requires a 3D printer, raw material (e.g., plastic filament, resin powder, etc.) and electricity, making 3D printing presumably suitable for low production challenges. For instance, one specific study using SLS technology finds the break-even point of 87,000 units produced, where 3D printing technology has an advantage over injection molding (Atzeni, Iuliano, Minetola, & Salmi, 2010). The break-even point will certainly change depending on the 3D printing technology and product, but Atzeni et al. (2010) demonstrate that it is reasonable to affirm that 3D printing is feasible for lower production volumes, as opposed to large volumes, where injection molding process is more suitable.

Environmental Impact

The feasibility of 3D printing for low production volumes has not only produced substantial economic growth by promoting the rise of the 3D printing industry, but it has also created some expectations about its contribution to the environmental field. Because it is economically feasible to produce parts for low production volumes, in the future, 3D printer users may be able to fabricate their own products at home instead of buying these products from manufacturers (D’Aveni, 2013). This new manufacturing paradigm enables a community of users to work collectively on the design of new products, taking advantage of digital files that can easily be shared across the internet. Unlike the conventional manufacturing model, which is based on mass production, distributed manufacturing merges the designer, manufacturer, and consumer contribution into a single role in a collective community of makers, thus, eliminating the need for product transportation. Distributed manufacturing brings, among other things, the concept of on-demand manufacturing, which in its variations can develop different consequences in the productivity of the manufacturing system but also for the environment (Chen et al., 2015). According to this rationale, in the future, conventional manufacturers may no longer ship products to users because users may fabricate their own products at home; then, less consumption of fossil fuels will be required for product transportation and, consequently, greenhouse gas emissions will be reduced.

Consensus exists that 3D printing has the potential to reduce product transportation and, consequently, to lower the environmental impact through distributed manufacturing. Gibson, Rosen, and Stucker (2009) assert that 3D printing has the potential to generate distributed employment that is environmentally friendly since "it involves much lower energy consumption than the established concentration of product development, production and distribution." Similarly, Lipson and Kurman (2013) also argue that 3D printing can reduce the need for product transportation and storage, which leave huge carbon footprints due to their fuel and electricity consumption. A complementary perspective is proposed by Despeisse and Ford (2015), who state that 3D printing can promote a "reconfiguration of the supply chain," enabling the fabrication of products with fewer components and assemblies that may require fewer participants and interactions, potentially leading to a reduction in the environmental impact of logistics.

Additionally, another study emphasizes that the benefits for the environment are uncertain unless the scenario considers a narrow scope of 3D printing applications. Gleber, Schoot-Uiterkamp, and Visser (2014) suggest that there is a potential reduction of carbon dioxide emissions for aerospace fuel demands, aerospace production, and medical production due to "reduced handling, shorter supply chains, and reduced material demands;" however, the environmental benefits for consumer products are not significant according to their study. The study suggests that consumer products require technical and economic conditions that 3D printing still cannot fulfill, thereby reducing the potential environmental contribution of 3D printing in the consumer market.

The comparison presented by Gleber et al. (2014) highlights the importance of assessing 3D printing's environmental impact in terms of technical and economic feasibility for consumer products. From an economic perspective, researchers fabricated 20 different 3D objects using a desktop 3D printer based on FDM technology and showed that it is economically feasible for an average U.S. household to fabricate commercial products at home instead of buying those products from conventional manufacturing (Wittbrodt, Glover, Laureto, Anzalone, Oppliger, Irwin, & Pearce, 2013). They also concluded that electricity consumption was a key element in determining the economic feasibility of fabricating products with desktop 3D printing. However, even 3D printing enthusiasts are still careful about declaring the environmental benefits of this new technology. For instance, although Lipson and Kurman (2013) believe in the potential of 3D printing for the economy and society, they also warn their readers about the importance of using a lifecycle approach: specifically, considering that 3D printing consumes up to 10 times more energy than a mass production manufacturing process such as injection molding does. A study comparing products fabricated by FDM and milling machines elucidates the importance of selecting a restricted scenario and using LCA to understand the environmental impact of 3D printing (Faludi, Bayley, Bhogal, & Iribarne, 2015). This study did not focus on distribution manufacturing but on rapid prototyping; nonetheless, the study compared products fabricated by different manufacturing processes and showed, using LCA results, that energy consumption is a key contributor to the environmental impact of 3D printing.

While potential sustainability benefits have been reported by previous studies, quantitative studies that focus on FDM technology are needed in order to specifically answer whether the environmental impact of distributed manufacturing is lower than that of conventional manufacturing. Moving toward sustainable manufacturing requires scientific data to assess the environmental impact of new forms of manufacturing. For this reason, the use of a standardized framework and methodology based on the Life Cycle Inventory is required "to truly understand and appreciate the environmental impact beyond just postulations and suggestions based on statically insignificant data" (Mani, Lyons, & Gupta, 2014). Among previous research approaches (Table 2), one particular study underscores the importance of using LCA as a quantitative environmental impact analysis of the FDM technology.

Table 2. Environmental impact of 3D printing research matrix.

	Qualitative (vision, reasoning, opinion)	Quantitative (cost benefit, LCA)
General (many technologies)	- Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G., & Thiede, S. (2015) - Despeisse & Ford (2015) - Gibson, Rosen, & Stucker (2009) - Lipson & Kurman (2013)	- Gebler, Schoot-Uiterkamp, & Visser (2014)
Specific (FDM technology)		- Faludi, Bayley, Bhogal, & Iribarne (2015) - Kreiger & Pearce (2013) - Wittbrodt, Glover, Laureto, Anzalone, Oppliger, Irwin, & Pearce (2013)

The studies about the environmental impact of 3D printing were categorized as “General” or “Specific” depending on the scope of technology studied and as “Qualitative” or “Quantitative” depending on whether or not conclusions were based on quantitative data.

Finally, Kreiger and Pearce (2013) apply the LCA methodology to three different products and then contrast the environmental impact of producing these products at home using desktop 3D printers with similar products using injection molding at an overseas manufacturer. The LCA results from their study show “that distributed manufacturing with a RepRap 3D printer will have less environmental impact than conventional manufacturing.” Kreiger and Pearce's study is, in fact, the most specific and quantitative work that could assist 3D printer users in determining whether it is sustainable to fabricate objects at home instead of buying those same products from the market. Consensus exists among many authors that there are environmental benefits associated with 3D printing, but Kreiger and Pearce (2013) are some of the few who draw this conclusion based on an LCA approach.

Although Kreiger and Pearce (2013) based their conclusion on reasonable assumptions and LCA results, they do not consider three important elements to make their broader statement sound. First, it is not realistic to assume that low-end products selected in their study (e.g., a spout, a juicer, and a toy) are feasible in a distributed manufacturing model. The products chosen in their study do not represent a realistic product category that 3D printer users are willing to fabricate at home and, consequently, do not promote distributed manufacturing. Second, their study's boundary and system conditions do not take into consideration that raw material transportation from suppliers to desktop 3D printer users will occur, and that injection molding and 3D printing use different raw materials. It is reasonable to investigate whether including the raw material supply chain into life cycle inventory and LCA calculation can offset any environmental gain from avoiding the product transportation in conventional manufacturing. Third, the authors' comparison consider the possibility of fabricating products through 3D printing using PLA instead of ABS. If comparison between conventional and distributed manufacturing uses different materials, it is possible that results are biased toward the systems that use PLA because processing PLA requires less energy than processing ABS does.

Spare Plastic Parts

Neil Gershenfeld, professor at the Massachusetts Institute of Technology (MIT) and the head of MIT's Center for Bits and Atoms, is an enthusiast of digital fabrication, which includes 3D printing as one of its technologies. However, he is cautious about the potential of the application of 3D printing technology in the future. At the same time that he believes that 3D printing will allow users to “design and produce tangible objects on demand, wherever and whenever they need them,” he also considers that 3D printing is too slow and may not be suitable to fabricate whatever a user needs (Gershenfeld, 2012). In his view, today’s interest in 3D printers resembles the 1950s enthusiasm for microwave ovens. At that time, many foresaw that microwave ovens would have a great impact on cooking, but, in fact, even today the microwave oven has not replaced the conventional oven. Professor Gershenfeld has great hopes for 3D printing: he believes that 3D printing will follow the same steps as personal computing, which started as hobbyists’ equipment and has become ubiquitous in one’s daily activities. However, this particular observation—that today’s 3D printers resemble yesterday’s microwave ovens—clearly drives one to think about where, specifically, 3D printing fits into its actual context of technical development and about the most likely purpose that 3D printers may serve in avoiding conventional manufacturing.

Therefore, the present study proposes to select spare plastic parts as a realistic product category with which to measure the environmental impact of desktop 3D printers. Spare plastic parts are usually fabricated in a mass production model and then stocked until they are required to substitute a broken part from a product. Because products have a significant quantity of individual parts, storing and making spare parts available to users is a complex and expensive operation for manufacturers. According to Despeisse and Ford (2015), the environmental benefits are expected to be higher for modular and upgradable components since products can be kept in operation using 3D printed parts and can thus have their lifespan expanded. Distributed manufacturing can eliminate resources that do not add value to centralized manufacturing, such as injection molding tools, energy consumption arising from the transportation of products, and stocking spare parts (Gibson, Rosen, & Stucker, 2009). From an economic perspective, fabricating spare plastic parts at home is a win-win situation because users can save money and time fabricating these parts at home while manufacturers can get rid of managing non-added value operations on their side.

The economic feasibility offered by a desktop 3D printer is not the same for all spare plastic parts fabricated. For instance, maintenance spare parts such as nuts and bolts can be easily found at retail stores because they are manufactured under a mass production model. In contrast, there are original parts that are not supposed to be replaced before a product's end of life; these spare plastic parts are usually expensive and difficult to find at retail stores. In this case, their production volume is smaller and parts are more expensive when injection molding is used, creating a potential cost advantage for desktop 3D printer users to fabricate them at home using FDM technology (Figure 2).

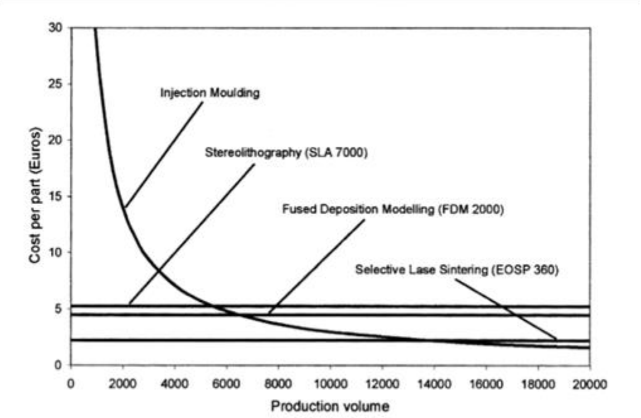


Figure 2. Cost per part variation according to production volume. Adapted from (Hopkinson & Dickens, 2003).

Spare plastic parts are necessary to substitute an original broken part from a product that requires this part to operate properly. Spare parts that are required for preventive maintenance fall outside the scope of this work because they are already part of the established mass production model. Product designers can foresee that some parts will need to be replaced before the end of life of a product. For example, fuel filters used by regular cars are spare parts typically replaced before the car's end of life. These parts are produced together with original parts and are directed to maintenance locations instead of manufacturers' assembly lines. Consequently, they already take advantage of conventional manufacturing savings and their supply chain is not necessarily independent from that of regular conventional manufacturing.

However, when an original plastic part that is not supposed to break during a product's lifetime needs replacement, manufacturers need to manage a non-standardized supply chain management to supply the repair centers with this specific part and, eventually, to replace the whole product. This alternate supply chain model is not the core business of manufacturers. Therefore, in order to comply with regulations and customers' requirements, manufacturers are required to produce non-optimized small lots of production to supply the market with spare parts.

Understanding why original plastic parts break before products' end of life is crucial for determining the characteristics of spare plastic parts. Assuming that manufacturers have made the correct material, design, and manufacturing process choices, the original plastic part should last the entire product's lifetime, unless the product was inappropriately used or overextended its expected lifetime. The inappropriate use of a product may put the original plastic part under a situation where its mechanical, thermal, environmental, electrical, and chemical properties will not assure its functionality. Conversely, if the product is used within the manufacturer's specifications, the product will last beyond the expected end of life and, eventually, fail due to its overextended lifetime. This present study will assume that users make the correct use of the product and spare plastic parts are used to replace original plastic parts broken due to overextending the product's expected lifetime.

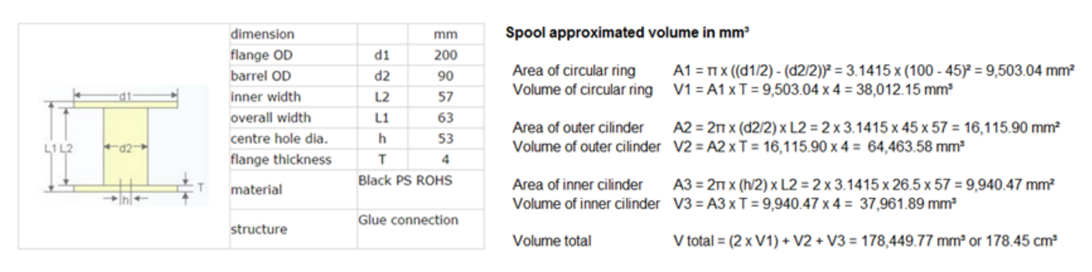
Due to the popularity of 3D software modeling, part design information is no longer restricted to manufacturing facilities. Collaborative websites, like Thingiverse, are dedicated to 3D printing communities and share the 3D design for several parts intended to replace a broken part. Usually, 3D printer users are familiar with mechanical design and desktop 3D printer capabilities, so whenever their own household products break, they are inclined to resolve the problem by disassembling and fixing the product by substituting the broken part with a 3D printed part. In the household category of the Thingiverse website, there is a sub-category named Replacement Parts that presents a significant number of examples of the ways in which users can fix their household products using 3D printed parts.

However, not all products listed in this category are suitable for this study. Again, if a part produced by a 3D printer does not avoid the manufacturing of a new part by conventional manufacturing, it does not reduce the need for production and product transportation from overseas; consequently, it is out of the scope of this study. For instance, some parts that may complement the use of a product, such as holders, may assist users with domestic challenges but they do not fix a broken part. Instead, they simply make the product more functional. Furthermore, some parts are experiments to prove 3D printing capabilities but there are clearly more suitable substitutes available on the market. Some nuts, bolts, washers, and brackets are examples of parts produced by users with this intent. On the other hand, some parts are clearly designed to replace a broken part from a product that users may feel compelled to fabricate it instead of waiting for an original replacement part.

Raw Material Transportation

Fabricating products at home may avoid product transportation from conventional manufacturers to customers but it also introduces the necessity to transport raw material from suppliers directly to 3D printer users. While thermoplastic material used in the injection molding process comes in pellet form, desktop 3D printers use the thermoplastic material in filament form. Like injection molding, plastic filament production uses the thermoplastic material in pellet form. The thermoplastic pellets are fed into an extruder to produce a plastic filament. Next, similar to the electric wire package process, the plastic filament is rolled into plastic spools. Then, filament spools containing a plastic filament are vacuum packaged into a polyethylene bag to protect the filament from humidity (Torwell Macromolecule Material Limited, 2015).

It should be noted that packaged plastic filament contains the plastic spool, which is not directly used in the fabrication of an object but may have an impact on the LCA. Plastic spools can vary in format and material, but according to one plastic spools manufacturer, spools are manufactured using an injection molding process and are made from Polystyrene (PS) or Polypropylene (PP) plastic that has a regular density of 1.05 g/cm^3 (Dongguan Changhong Bobbin Co., Ltd, 2015). In order to transport one kilogram of ABS filament, 187.37g of PS is also required by injection molding to manufacture one spool—assuming that PS density is 1.05 g/cm³ (Figure 3).



dimension		mm
flange OD	d1	200
barrel OD	d2	90
inner width	L2	57
overall width	L1	63
centre hole dia.	h	53
flange thickness	T	4
material	Black PS ROHS	
structure	Glue connection	

Spool approximated volume in mm³

Area of circular ring $A1 = \pi \times ((d1/2) - (d2/2))^2 = 3.1415 \times (100 - 45)^2 = 9{,}503.04\ mm^2$
Volume of circular ring $V1 = A1 \times T = 9{,}503.04 \times 4 = 38{,}012.15\ mm^3$

Area of outer cilinder $A2 = 2\pi \times (d2/2) \times L2 = 2 \times 3.1415 \times 45 \times 57 = 16{,}115.90\ mm^2$
Volume of outer cilinder $V2 = A2 \times T = 16{,}115.90 \times 4 = 64{,}463.58\ mm^3$

Area of inner cilinder $A3 = 2\pi \times (h/2) \times L2 = 2 \times 3.1415 \times 26.5 \times 57 = 9{,}940.47\ mm^2$
Volume of inner cilinder $V3 = A3 \times T = 9{,}940.47 \times 4 = 37{,}961.89\ mm^3$

Volume total $V\ total = (2 \times V1) + V2 + V3 = 178{,}449.77\ mm^3$ or $178.45\ cm^3$

Figure 3. Plastic spool dimensions and estimated volume. Adapted from (Dongguan Changhong Bobbin Co., Ltd, 2015)

Raw material package density from conventional manufacturing is different when compared to raw material density for 3D printing processes. Conventional manufacturing uses the thermoplastic material in pellet form for its injection molding process. Raw material comes in ABS pellets, which yield an estimated package approximated density of 1.05 g/cm³—similar to ABS density itself. Distributed manufacturing, on the other hand, uses plastic filament as raw material for the 3D printing process. Assuming that one carton of 8 x 8 x 3 inches contains 1kg (2.2 pounds) of 3.0mm ABS filament and has a total package weight of 3.0 pounds, one may estimate a density of 0.4325g/cm³ for a plastic filament package. Thus, considering a fixed volume of transportation in a truck, about 2.4 times more trucks are required to transport the same amount of raw material to distributed manufacturing when compared to conventional manufacturing.

Research Questions and Hypotheses

This study tests the hypothesis that fabricating products at home using desktop 3D printers has less environmental impact than buying products from manufacturers. The dominant argument is that because users fabricate products at home there is no reason to transport products from manufacturers to users' homes; consequently, fossil fuel consumption and greenhouse gas emissions are diminished (Gibson, Rosen & Stucker, 2009; Lipson & Kurman, 2013; Despeisse & Ford, 2015).

To test this hypothesis, this study must assess a product category that users have more interest in fabricating at home than in buying from a conventional manufacturer. Therefore, the aim of this study is to answer the following question: is the environmental impact of ABS-made spare plastic parts fabricated at home by a desktop 3D printer lower than that of similar ABS parts made by conventional manufacturing?

In order to answer this question, a LCA compared the environmental impact of spare plastic parts fabricated by these two main models: 3D printing in distributed manufacturing and injection molding in conventional manufacturing. As a result, this study's findings will assist desktop 3D printer users to understand the environmental impact of fabricating their own plastic parts at home and, hopefully, will influence their behavior regarding the conscious use of 3D printing resources.

Chapter II

Methods

LCA methodology was used to compare the environmental impact of distributed manufacturing versus conventional manufacturing. The International Organization for Standardization (ISO) 14040:1997(E) standard “provides principles and framework and provides some methodological requirements for conducting LCA studies,” and details each phase of this framework. According to the ISO, the phases of LCA are goal and scope definition, inventory analysis, impact assessment, and interpretation. LCA methodology is not linear. Although it starts with goal and scope definition, the remaining phases do not come one after the other; instead, they are all interconnected in an LCA framework. Thus, the LCA methodology is iterative and not linear; consequently, the LCA practitioner might eventually be encouraged to interpret and review any phase of LCA at any time because the more data is collected, the more is learned about the system (ISO, 1997; Bauman and Tillman, 2004).

It is desirable to establish a main regular flow from goal and scope definition to the final interpretation of results, although LCA is iterative and activities may freely go back and forth along the assessment. A straightforward approach assists LCA practitioners in objectively approaching each LCA phase and in performing key activities or reaching milestones that need to be accomplished to assure the completion of an LCA study. In addition, this approach does not prevent the iterative nature of LCA to start a new activity every time a new finding detours the regular flow of actions expected by the straightforward LCA approach. Therefore, a flow was designed to describe high-level research steps to be accomplished, establishing a pragmatic methodology process and offering a cadence for this research study (Figure 4).

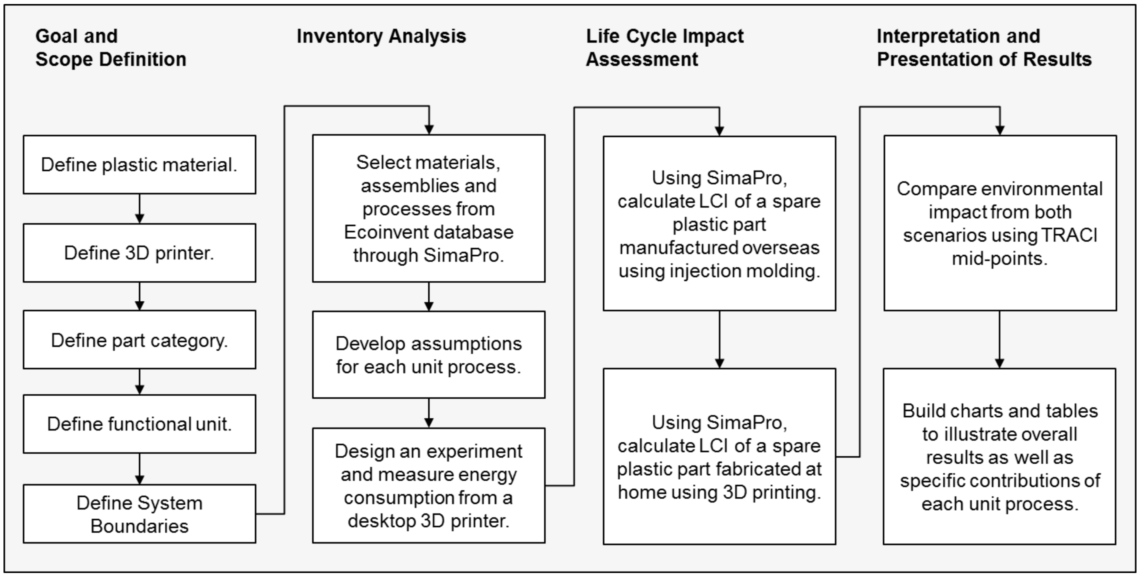


Figure 4. High-level research methodology steps based on life cycle assessment.

Goal and Scope Definition

The goal of this study was to compare the environmental impact of a plastic part fabricated by a desktop 3D printer in a distributed manufacturing model with a similar plastic part fabricated by injection molding in a conventional manufacturing model. For this reason, the first step was to select the plastic material to be used in the experiment. The second step was to select the desktop 3D printer model based on the most common technology used in desktop 3D printers, the plastic material choice, and the printer models available for purchase. Next, a part category was defined by considering a scenario where a specific part category is currently produced by conventional manufacturing and potentially feasible to be fabricated by desktop 3D printer users. Then, a functional unit was designed in order to compare conventional with distributed manufacturing on a similar basis. Lastly, system boundaries were delimited in order to capture only production stages that are distinctive between conventional and distributed manufacturing systems; moreover, the analysis was simplified and focused only on the core stages of both systems.

Plastic Material

The material selection of an original and spare plastic part must be compatible to its use because material choice is critical for defining plastic properties. PLA is a material commonly used in desktop 3D printers, but not in conventional manufacturing. Instead, products such as plastic toys, electronic equipment, and household appliances are usually made of many individual ABS parts. ABS is commonly used in conventional manufacturing due to its resistance to chemicals, heat, and impact.

One may consider comparing conventional manufacturing using ABS with distributed manufacturing using PLA, but this is not a fair comparison. Kreiger and Pearce (2013) consider PLA a better environmental choice than ABS with regard to energy consumption during desktop 3D printing fabrication. However, comparing PLA with ABS is not appropriate for an LCA study because PLA properties are not completely suitable for ABS applications; otherwise, conventional manufacturers would be using PLA instead of ABS in production.

3D Printer

There are several 3D printer models available for desktop users. The criteria used in this study was to choose a specific 3D printer model that represented a significant segment of the market share of 3D desktop printers. According to a 3D Hubs (2015) report, the main 3D printers are the Ultimaker 2, the RepRap Prusa i3, and the models Replicator 2 and 2x from MakerBot. Different desktop 3D printers may use different plastic materials. For instance, the Replicator 2 uses only PLA as a raw material, while the remaining top listed printers (e.g., Ultimaker 2, Prusa i3, and Replicator 2x) use PLA and ABS. Although all of these desktop 3D printer models use FDM technology and fabricate plastic parts with similar characteristics, their differences regarding raw material use must be considered from an environmental assessment standpoint. Thus, the Replicator 2 could not be used in this study because it only uses PLA as raw material

Therefore, the printer selected for this study was the Ultimaker 2. The choice was based on its popularity among users, the similarity of its power specifications when compared to other 3D printers, and availability for testing. The Ultimaker 2 is the most popular printer according to the 3D Hub survey, which made it the strongest candidate for the study (3D Hubs, 2015). In addition, the Ultimaker 2 has similar power consumption specifications to those of the Prusa i3 and the Replicator 2x (Table 3). Finally, this printer model was available for testing in a nearby university. The convenience of executing a test in the controlled environment of a university, the similarity of power consumption and the popularity index provided by 3D Hubs drove the choice of the Ultimaker 2 printer model.

Table 3. 3D printer model main characteristics.

3D Printer Model	Price (US$)	Build Envelope (cm)	Plastic Material	Nozzle (mm)	Filament (mm)	Power (watts)
Ultimaker 2	2,500	22.3 x 22.3 x 20.5	ABS, PLA	0.4	2.85	221W
Prusa i3	300-1,000	20.0 x 20.0 x 20.0	ABS, PLA	0.4	1.75 or 2.85	n.a.
Replicator 2X	2,500	24.6 x 16.3 x 15.5	ABS, PLA	0.4	1.75	221W

Adapted from (Makerbot, 2015; RepRap, 2015; Ultimaker, 2015).

Part Category

This study focused on parts that fit inside a desktop 3D printer's build envelope. Spare plastic parts need to be small enough to fit inside a desktop 3D printer build envelope in order to be produced at home. For instance, the Ultimaker 2 can produce plastic parts that fit inside a build envelope of 22.3cm x 22.3cm x 20.5cm. For this reason, large ABS parts that cannot fit inside the building envelope were out of the scope of this study. The parts needed to replace ABS parts from toys, electronic equipment, and household appliances are generally small enough to fit inside the building envelope; hence, they were suitable for this study.

Research was conducted on the Thingiverse website in order to determine which spare part category was most suitable for the scope of this study. Thingiverse has thousands of parts listed in the Household Replacement Parts category; therefore, in order to avoid any research bias, the first 10 parts uploaded by users every month from January to May 2015 were sampled. Then, only parts made to replace an original broken part were categorized. Next, since Thingiverse users can express their enthusiasm regarding any part design by voting in a similar fashion to the Facebook "like" button, parts were categorized according to the quantity of “likes” and ranked into a descending order to determine the most liked category. Finally, parts were also categorized into broader categories in order to assess which kind of part was most recurrently designed by users. Overall, this selection methodology provided a 3D printer user perspective regarding which spare plastic part made more sense to be evaluated.

Functional Unit

The functional unit of this study was defined as “the volume of ABS spare parts required by one individual to make self-repair of household appliances along an extended product’s lifetime.” The functional unit is a key element to enable the comparison between two distinctive systems: “it is a measure of the performance that the systems under study have in common” (Bauman & Tillman, 2004). Once the spare part fits into a specific three-dimensional slot in a product and makes it functional again, the repair is complete. Thus, although it is tempting to define a functional unit based on plastic weight, in fact, the first key characteristic of a spare plastic part is its volume.

Injection molding and 3D printing processes may produce plastic parts with different weight. While a 3D printer can produce solid or hollow plastic parts that still occupy the volume required to make a part functional inside a product assembly, an injection molding design can also produce parts with less material than a completely solid object. Despite the quantity of material used, all characteristics must be preserved in both cases to make a plastic part functional. In order to compare injection molding and 3D printing parts, the functional unit may consider whether other important mechanical properties are preserved independently from the weight variation of the plastic part.

Probably, the most important mechanical property of a spare plastic part is its durability. One may assume that mechanical, thermal, environmental, electrical, and chemical part characteristics are preserved when using the same ABS material for both conventional and distributed manufacturing scenarios. However, this is not entirely correct because a 3D printer fabricates anisotropic parts: the mechanical parts vary according to the direction in which they are fabricated (Ahn, Montero, Odell, Roundy, & Wright, 2002). Ahn et al. (2012) demonstrate that “the compressive strengths of FDM specimens ranged from 80 to 90 percent of those for injection molded ABS,” and measured tensile strengths of FDM specimens “were between 65 and 72 percent of the measured strength of injection molded FDM ABS.” In summary, 3D printed parts seem to be less resistant than injection molding parts are.

If lower tensile and compression strength are influenced by anisotropic characteristics of 3D printed parts, it is perhaps reasonable to assume that fatigue stress is also affected and, therefore, influences plastic part lifetime. The fatigue stress properties of FDM 3D plastic parts not only display anisotropic behavior, but are also influenced by the orientation of the layers of molten plastic (Lee and Huang, 2013; Ziemian, Okwara, & Ziemian, 2015). Although 3D printed parts seem to have lower resistance to fatigue stress than injection molded parts, the lack of a study directly comparing fatigue stress properties between a part fabricated by a desktop 3D printer and injection molding prevents including any data in the LCA study.

While it is not conclusive, a comparison of fatigue stress results from different studies can provide an approximate indication of whether 3D printed parts behave differently than injection molded parts do during fatigue stress tests. One common fatigue data chart used for this evaluation was the S-N curve, which plots the magnitude of cyclical stress (S) against the cycles to failure (N) (McKeen, 2009). Various authors provide tensile stress amplitude versus cycles to failure data for 3D printed and for injection molded parts, but no direct comparison was found in existing studies (McKeen, 2009; Lee Huang, 2013; Ziemian et al., 2015). Again, while it is not conclusive, a 3D printed part always breaks with fewer cycles when compared to injection molding at the same stress level when comparing data from 3D printed parts with injection molded parts (Figure 5).

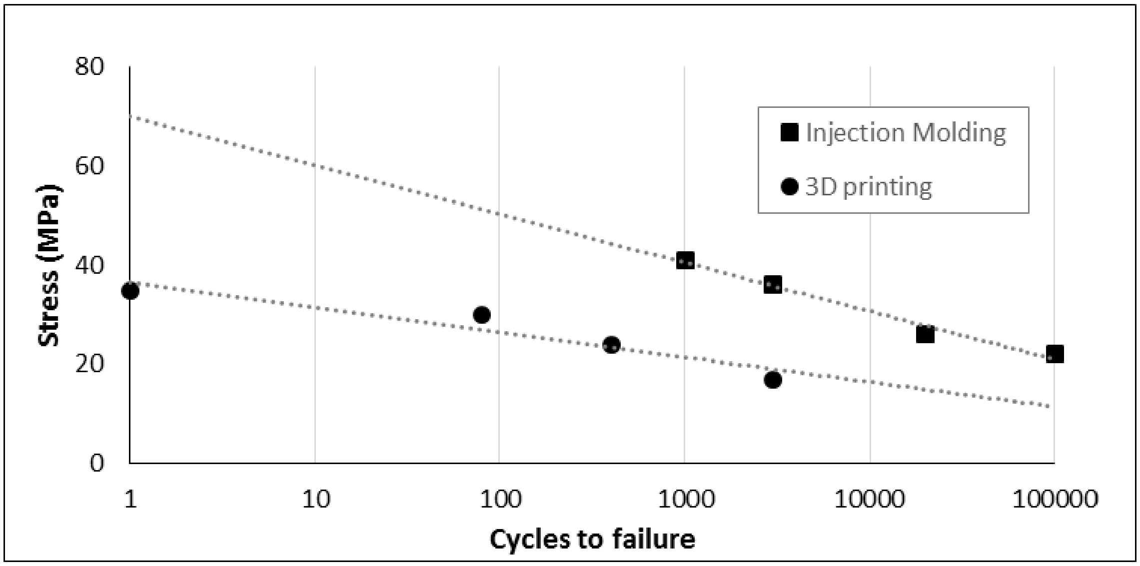


Figure 5. Stress per cycles to failure graph from ABS part produced using injection molding and 3D printing process. Adapted from (McKeen, 2009; Lee & Huang, 2013)

Although it is not possible to assert the exact influence on durability among these two distinctive manufacturing processes, this comparison strengthens this study's assumption that, under similar conditions, 3D printing parts are expected to fail before injection molding parts do. While tension and compression static test differences per se cannot indicate whether durability is affected, this simple data comparison provides a reasonable amount of confidence that 3D printing parts may have lower durability when compared to injection molding parts. Unfortunately, these experiments were not designed to be compared, so it is therefore not safe to conclude that 3D printing and injection molding behave in exactly the same proportion as illustrated in Figure 5; for this reason, this data cannot be safely used in the functional unit definition. All in all, ideally, the functional unit should consider that more 3D printing parts are required to fulfill spare part needs compared to parts produced by injection molding.

Due to a lack of data, in this study the functional unit will not consider the durability disadvantage of 3D parts over injection molding. On one hand, this may become a clear advantage from an environmental assessment perspective toward 3D printing because in the real world it is expected that 3D printed parts submitted to mechanical cycles break more often than injection molding parts do. On the other hand, acknowledging this bias will create extra confidence in the environmental impact results in a situation where injection molding proves to be more environmentally friendly than 3D printing.

System Boundaries

Assumptions about the circumstances and ways in which spare plastic parts are produced, packaged and stocked for a future request, and then shipped to users, are critical to the definition of supply chain scenarios. Considerations about the minimum amount of products that can be stocked and transported will be important to delineate the differences between conventional and distributed manufacturing, and to define the system boundary of the study.

In this study, two main systems were compared: conventional manufacturing and distributed manufacturing. The raw material process is exactly the same for both systems, so, the raw material process is out of system boundaries because the environmental impact of this process is the same for both systems. Similarly, product use and disposal processes also tend to be the same for both systems. Ultimately, both conventional and distributed manufacturing produces a plastic object that will be used and discarded. Because these systems are not supposed to differ in terms of use and disposal, these unit processes were not part of system boundaries. It is more important to compare the manufacturing process of conventional manufacturing with the fabrication process of distributed manufacturing. In fact, the system boundary aims to focus the environmental study on manufacturing stages where differences between injection molding and 3D printing can be seen, and where product transportation occurs (Figure 6).

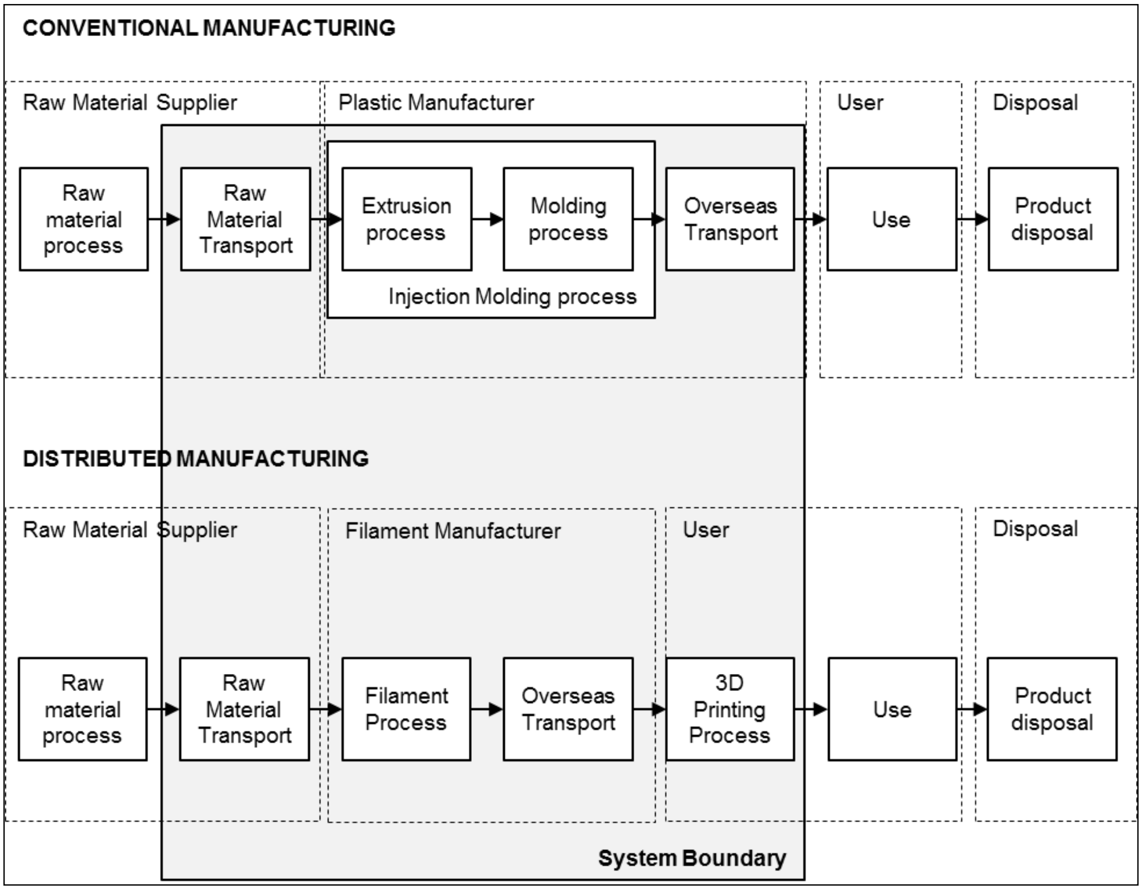


Figure 6. System boundary of conventional and distributed manufacturing scenarios. The system boundary highlighted represents which individual processes will be considered in the LCA study.

Inventory Analysis

A life cycle inventory calculation was performed using SimaPro software and the Ecoinvent-3 database for each unit process from both conventional and distributed manufacturing systems. The unit processes inside the system boundaries were considered in the inventory analysis. Materials, assemblies, and processes were selected and developed using SimaPro and the Ecoinvent-3 database for each unit process, taking into consideration the characteristics of the unit process and its geography of application (Table 4).

Table 4. Materials, assemblies, and processes used in LCA inventory.

Unit processes	Materials, assemblies and processes from the Ecoinvent-3 database
Raw material transport	Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, S
Injection molding process	Injection moulding {ROW}| processing | Alloc Def, S
Filament process	Extrusion, plastic pipes {RoW}| production | Alloc Def, S; Injection moulding {ROW}| processing | Alloc Def, S; Polystyrene, general purpose {GLO}| market for | Alloc Def, S
Overseas transport	Transport, freight, lorry, unspecified {GLO}| market for | Alloc Def, S; Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, S
3D printing process	Electricity, low voltage {WECC, US only}| market for | Alloc Def, S

Raw Material Transport

The first step, or unit process, of both conventional and distributed manufacturing systems is the transport of ABS pellets from the raw material supplier to the injection molding or filament process. ABS pellets are small cylindrical pieces of ABS plastic with a diameter and length of few millimeters. Due to their granular shape, they are transported in different sizes of packages: 25kg and 1-ton bags are commonly used in the industry. Hence, both package standards are suitable for truck transportation from raw material supplier to plastic part or filament manufacturer. The density of the package is estimated to be similar to ABS's density of 1.05 g/cm^3 due to pellets' fine-grained characteristics. In this study, it was assumed that the raw material supplier and plastic part or filament manufacturer were both located in Shenzhen, China, separated by a distance of 100km.

Injection Molding and Filament Processes

In this process, ABS pellets are fed into a hopper just above the injection molding equipment to produce a plastic part. ABS pellets are heated inside a structure called a barrel, then a screw motor drive propels the molten material from the barrel to inside a steel tooling cavity, where the material is cooled and formed. After that, parts are gathered and packaged into cardboard boxes.

Similar to the injection molding process, ABS pellets are the raw material of the filament process. ABS pellets are also fed into a hopper just above the extruding equipment to produce a plastic filament. Again, ABS pellets are heated inside a barrel and then a screw motor drive propels the molten material out of the extruder; however, unlike injection molding, the final product is not molded inside a steel tooling, but is instead cooled in filament form and rolled into polystyrene spools. It should be noted that these spools are made by injection molding and become part of this unit process. Finally, the plastic filament, when ready and packaged, becomes a secondary raw material for the 3D printing process.

Overseas Transport

While in conventional manufacturing, the plastic part is shipped to the end user after the injection molding process, in distributed manufacturing, the filament roll is shipped to the end user as secondary raw material for the 3D printing process after the filament process. In both cases, it was assumed that the plastic part or filament was transported by truck from the manufacturer location to Shenzhen port, an estimated distance of 100km. Because it was assumed that the end users were in Boston, U.S., plastic parts and filament were considered to be transported from Shenzhen to Boston port by ocean. According to data retrieved from the Ports.com website, a ship must travel 12,769 nautical miles, or 23,648.19 km, to go from Shenzhen to Boston, passing through the Suez Canal (Ports.com, 2016). Finally, in Boston, another truck needed to travel an additional 100km to take plastic parts or filament from the Boston port to local retailers.

3D Printing Process

This is the last unit process in the distributed manufacturing system and it occurs in the user's home. In this unit process, the plastic filament is transformed into a physical object through 3D printing technology. In short, the 3D printing process heats the filament plastic to make it malleable to give form to the objects layer by layer. This operation requires the plastic filament as (a secondary) raw material as well as electricity to produce energy to melt the plastic filament. Because the Ecoinvent-3 does not contain the required information to perform the life cycle inventory for the 3D printing process, an assumption was made that the life cycle inventory of the 3D printing process is directly related to its energy consumption in melting a certain mass of plastic.A desktop 3D printer has few printing settings that significantly determine energy consumption. The energy consumption of desktop 3D printers varies depending on the models and especially on certain printing parameters (Walls, Corney, & Vasantha, 2014). According to Walls et al. (2014), more research is needed to assess the influence of filament diameter, layer height and printer speed parameters on energy consumption. Filament diameter is a fixed parameter in this study because the desktop 3D printer Ultimaker 2 uses only the filament size of 2.85 mm. Layer height determines the quality of the fabricated part as well as the printing velocity. If the layer height is low, more layers are necessary to fabricate an object; consequently, the printing time is longer. Finally, printer speed is the velocity at which the filament is pulled into the desktop 3D printer. In summary, filament diameter, layer height, and print speed are printing parameters to be defined before measuring the energy consumption of a desktop 3D printer.

As with any ordinary equipment that relies on electricity, a printer's energy consumption is proportional to its operation time: the longer the printing time, the higher the energy consumption. In desktop 3D printers, electricity is used to power small motors to move a printer nozzle that is kept heated above the transition temperature to extrude ABS plastic; therefore, it is expected that the more the nozzle moves and is kept heated, more energy is consumed. In the desktop 3D printer Ultimaker 2, the plastic filament diameter is fixed at 2.85 mm; thus, print speed and layer height become parameters that significantly influence the time needed to print an object. Layer height is related to the amount of material deposited per layer. When layer height is relatively high, fewer layers are needed to fabricate an object, resulting in a reduced printing time. Conversely, the print speed parameter is the velocity with which the plastic filament is inserted into the 3D printer. It is expected that higher print speeds will make objects faster, thereby reducing energy consumption. Therefore, since this study aimed to measure electricity consumption, layer height and printer speed were the parameters of interest in this experiment.

Printing parameters were chosen based on information provided by the Ultimaker 2 software and laboratory technician expertise. Version 15.04 of Cura (2015), the 3D printing software used to prepare 3D computer files, indicates in its instruction manual that a layer height of 0.1 mm is required to achieve normal quality. Although this desktop 3D printer model can print layers from 0.006 to 0.25 mm, the choice was made to keep product quality at the normal standard to avoid printing rework and to reflect the most likely parameter used by general users. Next, print speed was kept below 80 mm/s under the advice of a laboratory technician who's past experience proved that above this threshold printing becomes less stable. In fact, Version 15.04 of Cura (2015) indicates that the Ultimate 2 printers can reach up to 150 mm/s, but it requires personal experimentation to adjust the optimized settings. Thus, this study relied on the laboratory team's expertise and helpful tips from 3D printing software, so layer height was kept at 0.1 mm and print speed at 50 mm/s.

The filling percentage is an important parameter that affects printing time and also the quantity of material used to build a plastic part. The interior of an object fabricated by a 3D printer can be completely solid or partially hollow, similar to a honeycomb structure, thereby requiring less plastic material. The solid interior is expected to give to the plastic part the maximum mechanical strength; however, the 3D printer is capable of printing hollow inner structures that may provide similar mechanical strength using less material. All in all, the less the plastic part is filled, the shorter the printing time is; consequently, the fabrication time and energy consumption will vary depending on the filling percentage.

This experiment used fixed parameters of layer height, printer speed, and different filling percentages to evaluate energy consumption. Again, layer height was set at 0.1 mm, the print speed at 50 mm/s, and the filling percentage was set at 100% and 25%. During the experiment, a watt-meter, plugged into a desktop 3D printer power line, measured the energy consumption with 0.01 kWh resolution (Figure 7). The energy measurement started just after the base plate and heating process, exactly when the plastic material started to flow from the print head. The measurement ended when the print head stopped delivering plastic material to the object. The total energy consumption and printing time were collected. Finally, after the part had cooled, it was removed from the 3D printer and weighed on a scale with a 0.1g resolution. Excess material was removed and the part was weighed again. Although the excess material was required to produce the 3D printed part, the weight difference represented wasted plastic material.

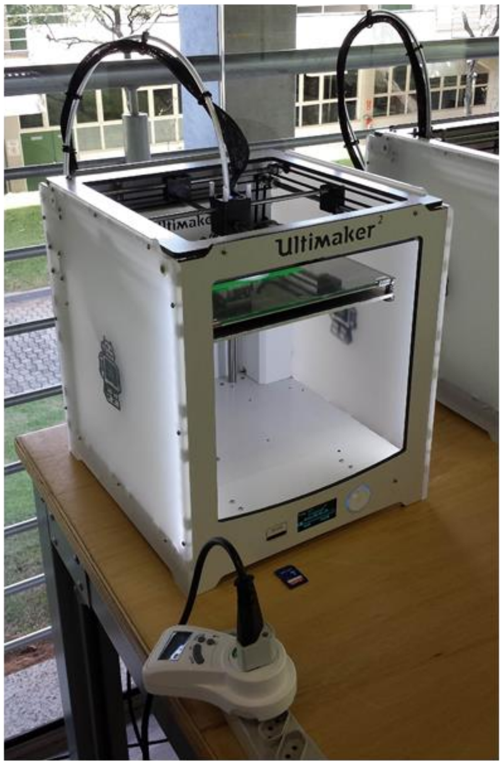


Figure 7. Desktop 3D printer and watt-meter plugged into a powerline.

It should be noted that the initialization printing step, which has an effect on energy consumption, was removed from this experiment, simply to reduce experimental variability. In order to fabricate an ABS plastic part, it is necessary to heat its base plate to a temperature of approximately 90°C to avoid the plastic deformation due to fast cooling when plastic leaves the print nozzle and touches the base plate. In parallel, the printer nozzle needs to be heated up to the transition temperature while the base plate is heating up. Therefore, the preliminary heating time from the base plate and nozzle were not considered in the individual measurement. Supposedly, heating timing and energy consumption may be different when different print jobs are compared. For instance, a desktop 3D printer may already be heated; then, the heating time and energy consumption are lower than in another situation where more heating time is required to print an object for the first time. Based on laboratory technician experiences and the researcher's own observation, heating time is around 5 minutes and consumes 0.02 kWh. Energy consumption may not be sufficient to significantly distort the results, but the measurements would be more accurate with the elimination of this source of variation from the experiment.

Life Cycle Impact Assessment

The objective of this methodology phase was to translate the life cycle inventory into environmental impact (Bauman & Tillman, 2004). The life cycle inventory calculation shows, for example, carbon dioxide emissions as well as many other greenhouse gases that contribute to global warming. When greenhouse gas emissions are calculated for both the conventional and distributed manufacturing system, it may be difficult to compare these systems and understand their contribution to the greenhouse effect and impact on global warming. In order to improve the readability of the results, the greenhouse gas emission results were gathered and converted into an aggregated second-level indicator, such as global warming, also known as a mid-point.

In addition, obtaining only a global warming mid-point may reveal only part of the story about differences between the environmental impacts of conventional and distributed manufacturing. The life cycle inventory needs to be translated into a few other mid-points in order to provide readers with a broader understanding. For example, ozone depletion is an important mid-point to characterize the impact of ozone emissions in the lower atmosphere. Although the ozone concentration in the upper atmosphere works as a shield against dangerous ultraviolet rays from the sun, in the lower atmosphere, ozone is a harmful pollutant that causes damage to plants and human health (Bauman & Tillman, 2004).

Converting measurements into mid-points is not necessarily an easy task; fortunately, there is a ready-made method available for LCA practitioners. For example, ReCiPe uses a baseline method for characterization as described in the Handbook on LCA by Guinée et al. (2002). This method is also known as CML-IA and it focuses on 18 mid-points and integrates them with damage indicators, or end-points, provided by Eco-indicator 99 (Heijungs, Goedkoop, Huijbregts, De Schryver, & Struijs, 2013). Although ReCiPe is widely adopted by LCA practitioners, it is a European method and it is possible that some considerations may fail to represent the reality of specific regions such as North America.

In order to develop a method that better represents the North American region, "U.S. EPA decided to begin development of software to conduct impact assessment with the best applicable methodologies within each category," resulting in the TRACI method (Bare et al., 2002). In this study, TRACI methods were used to determine the mid-points. This life cycle impact assessment was calculated for both conventional and distributed manufacturing scenarios using the software SimaPro and the Ecoinvent-3 database. TRACI was more suitable for the present study, considering that distributed manufacturing system was within the U.S.

Interpretation and Presentation of Results

For each mid-point, the contribution of unit processes was assessed to determine the relative influence of each unit process in overall mid-points results. Then, each mid-point from conventional and distributed manufacturing was evaluated and compared, and finally, they were compared among themselves to assess the overall environmental impact of conventional and distributed manufacturing.

Research Limitations

A few research limitation aspects potentially prevent this study from obtaining the most accurate and highest quality findings during LCA. These limitations are all related to the quality of estimation of the 3D printing process LCA inventory. It seems to be more critical to estimate the environmental impact of 3D printing due to the absence of information in the Ecoinvent-3 database and to its novelty aspect, which may interfere in life cycle inventory assumptions. The printer model definition, 3D printing energy consumption measurements and the failure rate of 3D spare plastic parts represent the potential limitations of this research.

The printer model definition was limited by the data and printer available for the study. First, only one 3D printing market study was available with which to determine which printer model was more popular among home users. The existence of a variety of market studies could reveal nuances among printer models and user preferences that might affect this study's 3D printer definition. In addition, although this study selected the most popular printers according to the 3D Hubs report, it was also limited by the lack of opportunity to fabricate a spare plastic part using any other 3D printer model. On the other hand, printer selection should not be that critical among printers utilizing the same technology. All FDM printers need to heat ABS material to the same temperature to extrude it through a printer nozzle and deposit it into layers to make a plastic part. The highest amount of energy is spent in the heating process; for this reason, it is expected that all 3D printers that use FDM technology may have roughly similar energy consumption performances.

Energy measurements were also potentially limited by the equipment used. For instance, the energy consumption of 3D printing was measured because there was no information about 3D printing processes in the Ecoinvent-3 database. The energy measurements determined the environmental impact of the 3D printing process. The use of a watt-meter was the only feasible choice to measure energy in kWh while a 3D printer object was being fabricated; however, the calibration and resolution of equipment may offer a lack of accuracy, which would affect LCA results. Nevertheless, while energy measurements could be influenced by watt-meter equipment, when comparing watt-meter results with expected values (i.e., 3D printer specifications) it could be assumed that values were not significantly different. This assured confidence on measured values.

Lastly, plastic parts fabricated by 3D printers were expected to fail in greater proportions than parts manufactured by injection molding, but there is no reliable estimation about the differences in expected failure rate. No different failure rate could be associated to 3D printing in this study, which makes it biased toward reducing the environmental impact of 3D printing when compared to injection molding. Despite the nature of the limitations presented, their impact was potentially minimized considering the conservative bias of the LCA estimations. In this study, it was assumed that 3D printed and injection molded parts fail with the same rate. This is an evident advantage of the 3D printing process and distributed manufacturing. On the other hand, if conventional manufacturing proves to be a more environmentally friendly system, the bias toward distributed manufacturing will serve only to reinforce that LCA results were indeed favorable to conventional manufacturing.

Chapter III

Results

The results are presented in three distinctive sections: data collection, life cycle assessment, and 3D printing environmental impact—conventional and distributed manufacturing systems were compared in this final section.

The data collection section presents results from the research and experiments that were developed in order to determine the spare plastic part to be used in the study, the energy consumption of desktop 3D printing, and packaging density differences between shipping raw material and products not captured in the Ecoinvent-3 database.

The life cycle assessment section presents the results of the life cycle inventory for both the conventional and distributed manufacturing systems; in particular, it shows the life cycle inventory results obtained from the SimaPro software using the Ecoinvent-3 database, as well as data from the previous section. Moreover, characterization results are presented using TRACI mid-points in a numerical and graphical fashion.

Finally, in the 3D printing environmental impact section, the results from both conventional and distributed manufacturing are directly compared, with the objective of determining which TRACI mid-point categories have more influence on the environmental impact of 3D printing.

Data Collection

Spare Part Selection

The Thingiverse website has thousands of 3D printing designs produced by its users, including a specific section categorized as Household Replacement Parts, which was used to select the spare plastic part for this study. A systematic sampling procedure was applied, where the first 10 parts uploaded for each month, from January to May 2015, were selected for this study. After parts were gathered, an evaluation was conducted and only parts that represented a solution to replace a user's broken part were selected. The result was that 30 out of 50 parts were selected. On Thingiverse, users can vote about whether they like the part uploaded by other users. There is a "like" button that users can click if they like a specific uploaded 3D print design. This is a feature similar to the "like" button on YouTube or Facebook. The selected parts were ranked according to the number of "like" votes. Each 3D part uploaded by users is different. Because the aim was to find a part category that represented the spare plastic part environment, it was not necessary to choose one specific part, but instead one that could represent a category of larger application. For this reason, the individual results were aggregated into categories and then ranked by "like" voting counting (Figure 8).

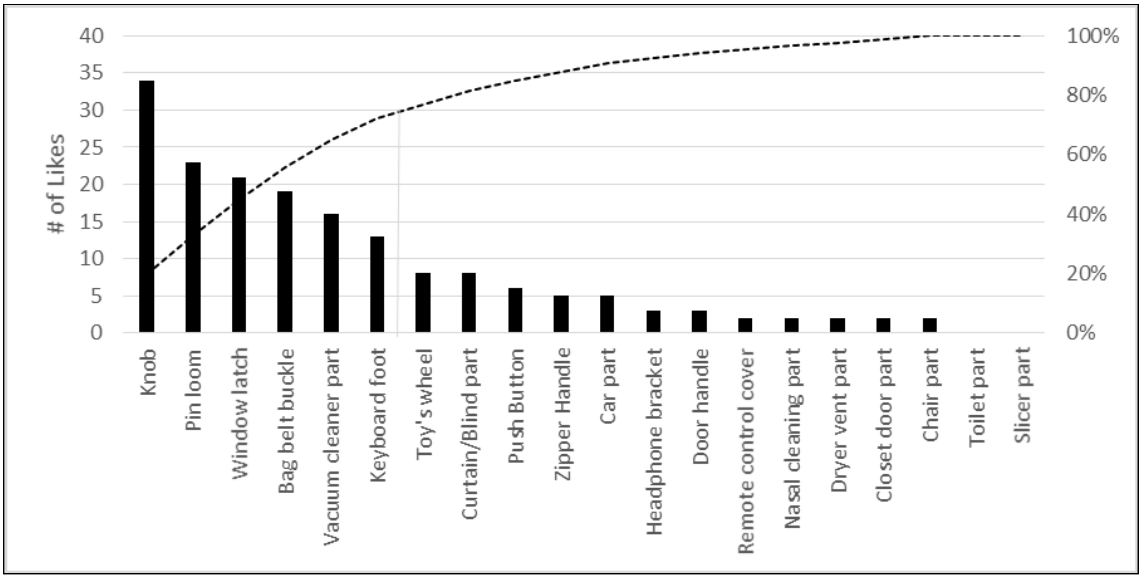


Figure 8. Number of "likes" per part category.

The pin loom was the most individually liked popular part among Thingiverse users; however, different types of knobs, aggregated into a single score, represented 20% of the total voting. Once they were aggregated into one single category, knobs became the spare plastic part category most liked among Thingiverse users, as well as the type of product with the most designs available in the repository. Knobs also had the highest incidence among other parts: while most of the parts were unique in their category, there were seven different knob parts designed by users with the intent of fixing broken parts. A knob design uploaded from Thingiverse (Figure 9a) commonly used in washing machines (Figure 9b) was selected to perform the experiment.

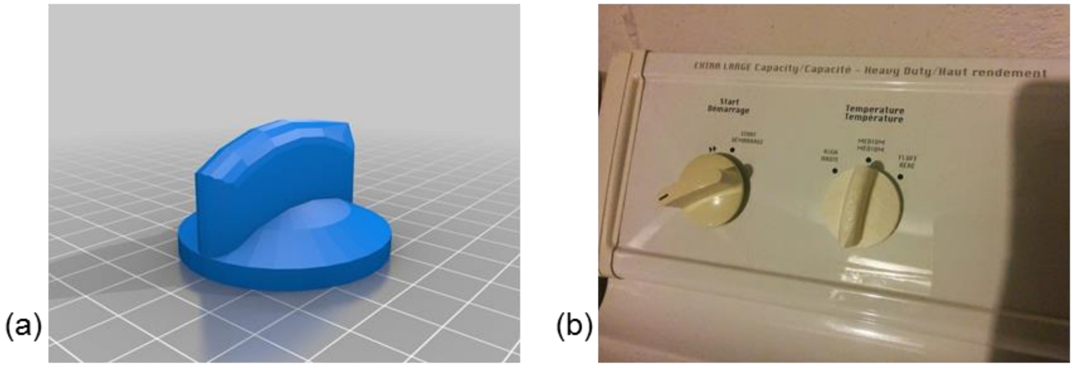


Figure 9. Washing machine knob design and its application. (a) Knob design in 3D model. (b) Two knobs installed in a washing machine; the left is an original knob; the right is fabricated by a desktop 3D printer. Both figures were adapted from (Thingiverse, 2015).

3D Printing Energy Consumption

The following observations were made as a result of the experiments conducted in this study using a desktop 3D printer, with the objective of determining the energy consumption of a 3D printer. It should be noted that external temperature was controlled due to the air conditioning system in the laboratory, but it was not measured during the experiment. In addition, the energy required to pre-heat the 3D printer base plate, where the objects were made, was not measured in order to reduce the variability of the experiment.. Two washing machine plastic knobs were fabricated by the desktop 3D printer Ultimaker 2 using a layer resolution of 0.1 mm and printer speed of 50 mm/s. One knob was fabricated with a filling percentage of 100%, and the other with 25%. At the end of the experiment, cumulative energy consumption was measured and parts were weighed. The results show that printing time, energy consumption, and part weight are higher for the filling percentage of 100%. Waste weight does not seem to be significantly different between 100% and 25% (Table 5).

Table 5. Energy consumption to fabricate an ABS part.

Plastic filling (%)	Printing time (min)	Energy (kWh)	Part weight (g)	Waste weight (g)
100	140	0.44	13.3	0.6
25	74	0.24	6.0	0.5

The washer knob was fabricated by Ultimaker 2 desktop 3D printer using ABS filament with a diameter of 2.85 mm, and following printing parameters: layer height 0.1 mm and printer speed 50 mm/s.

During the experiment, energy consumption was measured every two minutes to observe the consumption behavior differences between the different filling percentages. Despite differences in filling percentage, the energy consumption rate was similar, indicating that filling percentage does not affect the amount of energy consumed per unit of time. However, the printing time was significantly shorter for the 25% filling, which consequently reduced the total energy consumption (Figure 10).

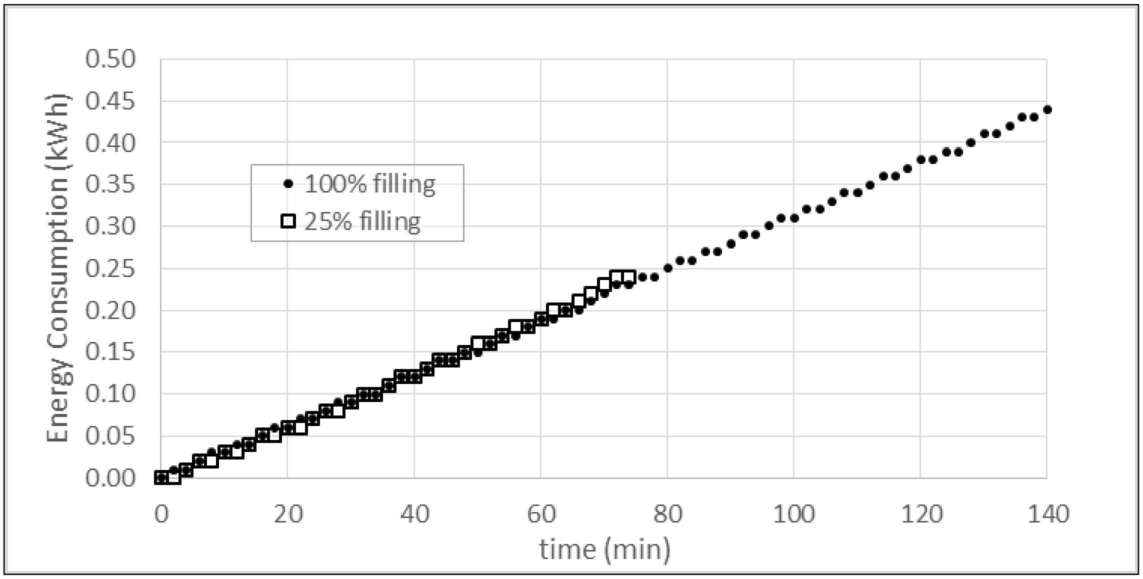


Figure 10. Energy consumption of the 3D printing process of a washing machine plastic knob using the Ultimaker 2 desktop 3D printer.

Packaging Factors

For transportation life cycle inventory calculations, the Ecoinvent-3 database considers the transport of one unit of mass per unit of distance to represent its functional unit. The common functional unit used by Ecoinvent-3 is tons per kilometer (tkm); however, the database does not take into account packaging density variations. Assuming that the ABS pellet package has a density of 1.05 g/cm³ and the ABS filament package has a density of 0.4325g/cm³, approximately 2.4 more trucks or ships are necessary to transport the same amount of ABS material from filament suppliers to 3D printer users than are required to move plastic raw material from suppliers to injection molding manufacturers. In order to properly assess the life cycle impact of the injection molding process, one original plastic knob was ordered from the spare part retailer. It arrived by regular mail, inside a paper envelope of 16 x 24 cm, delivered by the United States Postal Service directly to the researcher's home. The original plastic knob weight was 8.6 g and the total package weighed 27.2 g. Considering the total weight of 8.6 g of an original plastic knob part, the estimated packaging volume of 50.625 cm^3 (4.5 x 4.5 x 2.5 cm) density is 0.1699 g/cm^3. Therefore, approximately 6.2 more trucks or ships are needed to transport the knobs from the manufacturer to end users than are required to transport raw material from suppliers to injection molding manufacturers.

Life Cycle Assessment

The LCA compares original plastic knobs manufactured by conventional manufacturing to plastic knobs fabricated by 3D printers in a distributed manufacturing system. Original knobs are different in weight and inner filling when compared to 3D printed knobs. While original knobs are solid ABS parts designed with empty spaces in their interior to reduce weight and accommodate molding processes, 3D printed knobs are solid blocks that can be totally or partially filled with plastic. This LCA compares the original knobs with 3D printed knobs with 100% plastic filling.

Conventional Manufacturing

The TRACI mid-point results for the conventional manufacturing system were expressed in 10 different categories. The results show that the overseas transport process has a higher environmental impact than all other unit processes (Figure 11). Analyzing the global warming mid-point, 2.078 kg CO2e is generated to produce 0.618 kg of ABS plastic parts. While the injection molding process is responsible for 44% of kg CO2e, the overseas transport has an impact of 55% CO2e. In fact, if product transportation could be avoided entirely, almost half of the environmental impact of global warming could be reduced. Appendix 1 presents the complete results.

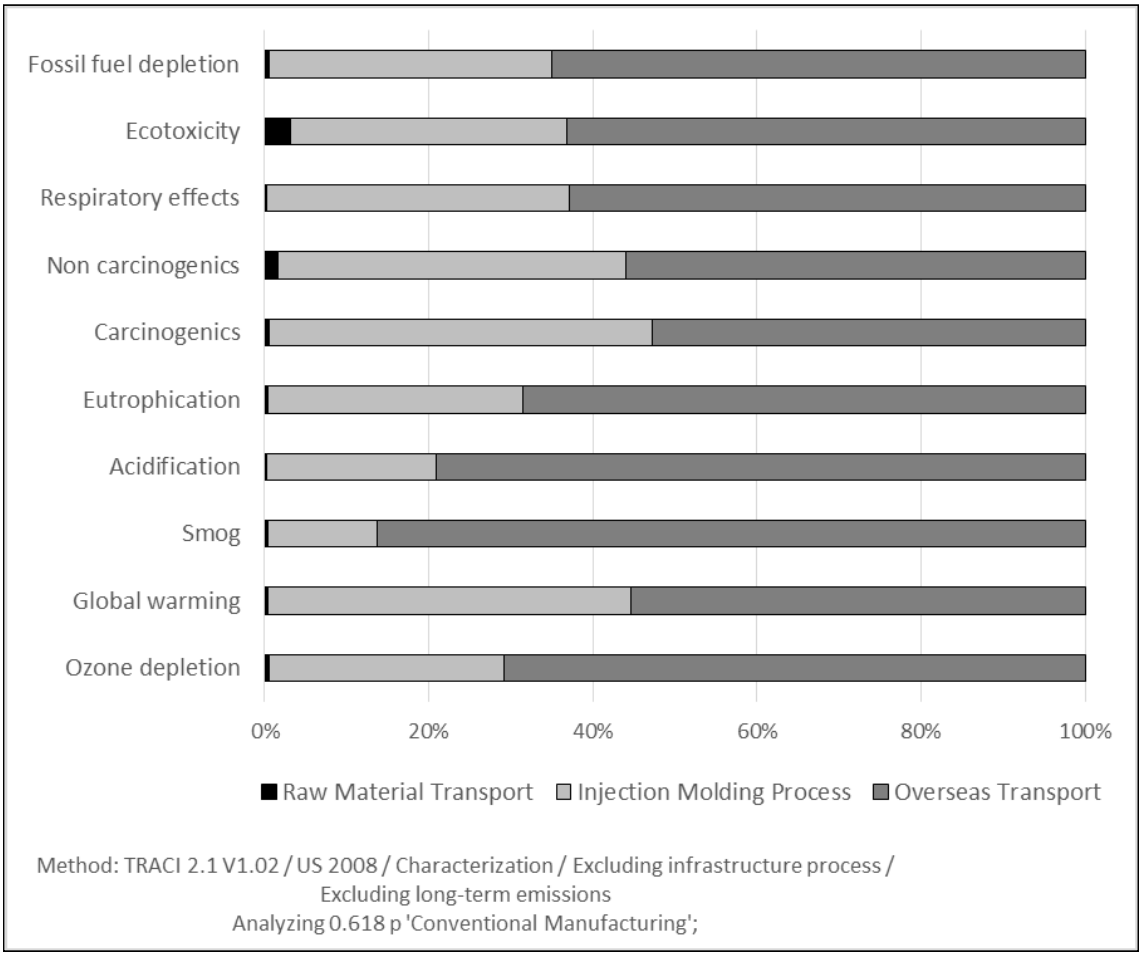


Figure 11. TRACI mid-points from conventional manufacturing.

Distributed Manufacturing

The distributed manufacturing system TRACI mid-points were also expressed in 10 different categories. The 3D printing process is the unit process that has a major environmental impact in all categories. The environmental impact is significant and represents no less than 70% in all categories (Figure 12).

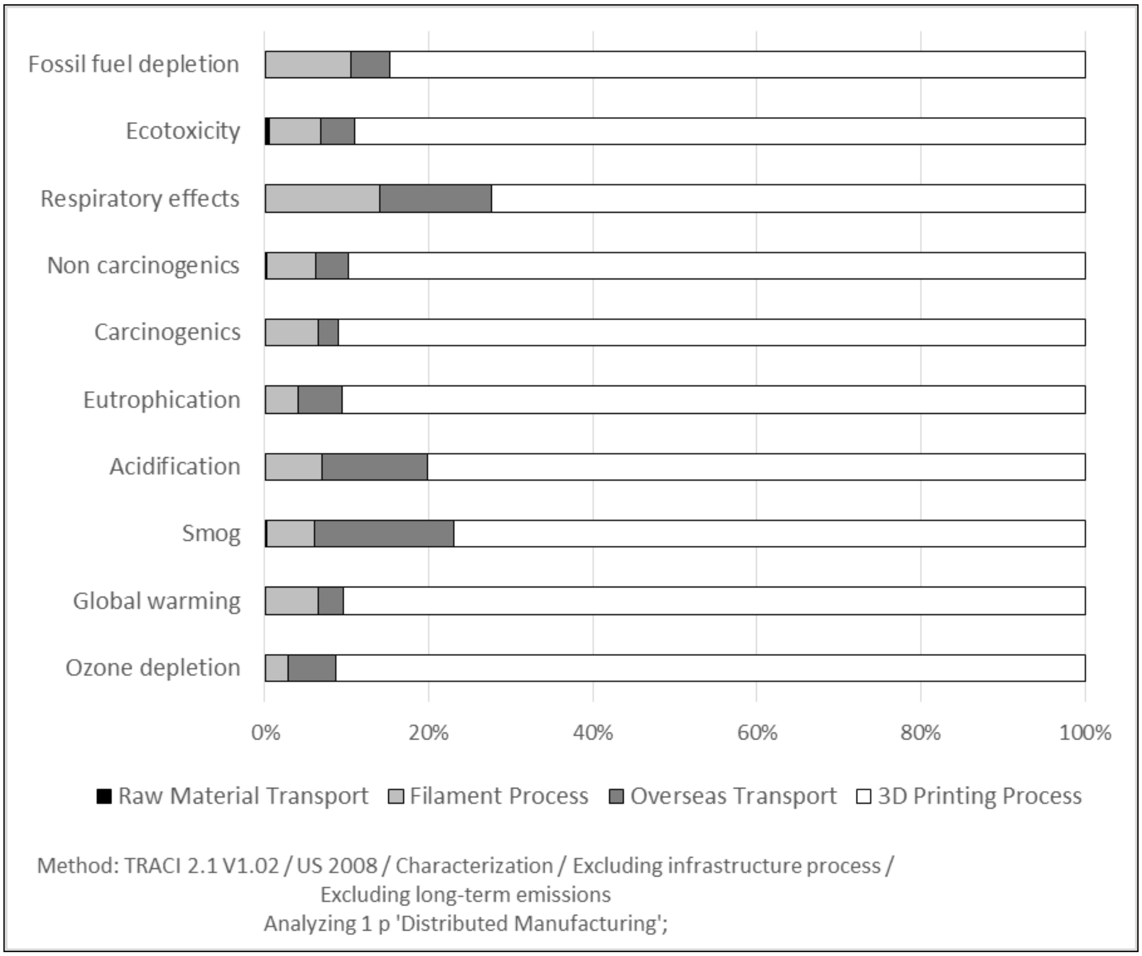
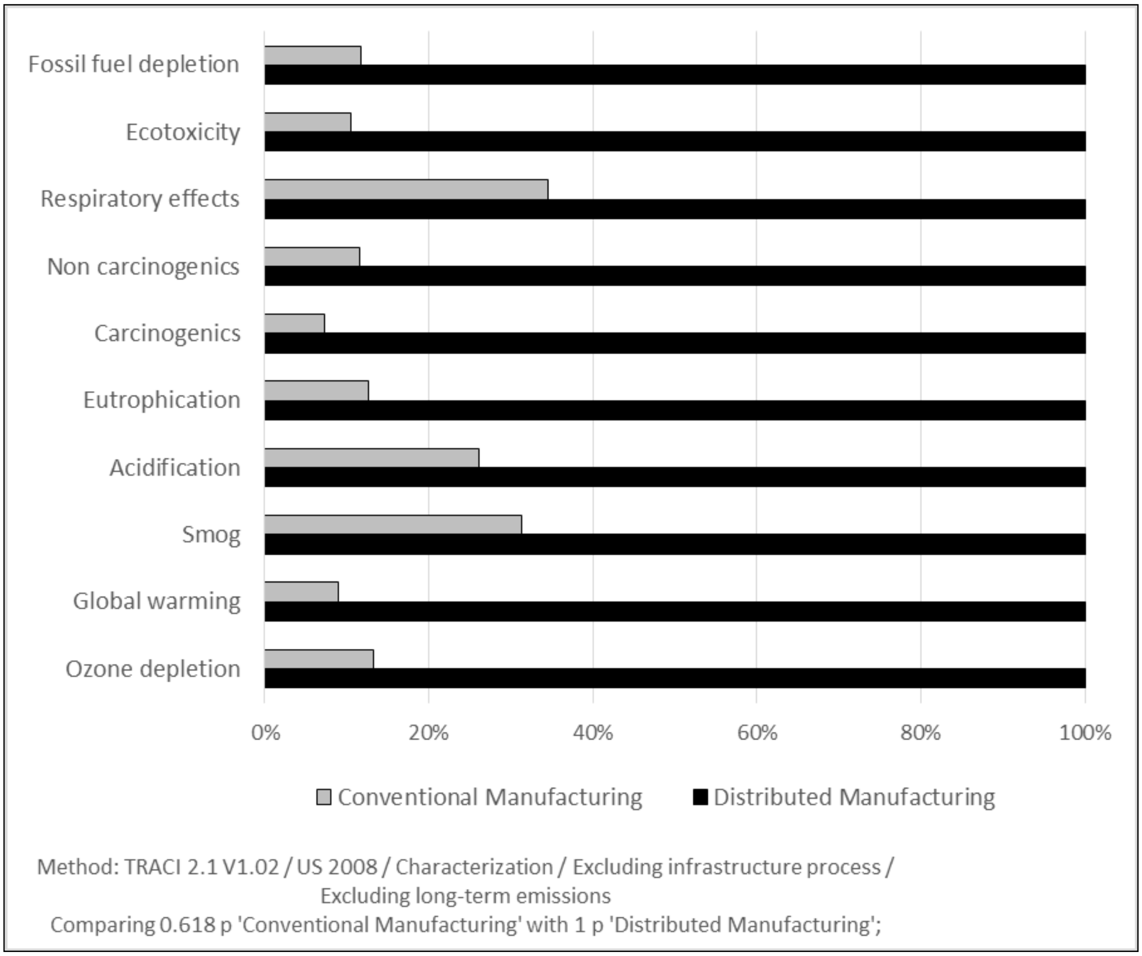


Figure 12. TRACI mid-points from distributed manufacturing.

Unlike conventional manufacturing, overseas transportation has no significant impact on the distributed manufacturing system, while the major contribution comes from the 3D printing process due to its energy consumption. For example, the global warming mid-point has 23.017 kg CO2e—which is 10 times higher than conventional manufacturing—and the major impact, 90% of kg CO2e, comes from the 3D printing process. Appendix 2 lists the complete results.

3D Printing Environmental Impact

All environmental impact mid-points from distributed manufacturing are significantly higher than those of conventional manufacturing (Figure 13). Although the differences are not equal for all mid-points, these comparative results show that conventional manufacturing has a lower environmental impact than distributed manufacturing for every TRACI mid-point.



Method: TRACI 2.1 V1.02 / US 2008 / Characterization / Excluding infrastructure process / Excluding long-term emissions
Comparing 0.618 p 'Conventional Manufacturing' with 1 p 'Distributed Manufacturing';

Figure 13. Conventional and distributed manufacturing mid-points comparison.

Global warming is one of the mid-points of main interest in this study because the expectation was that, by avoiding product transportation, distributed manufacturing could deliver a lower environmental impact due to greenhouse gas reductions. For this reason, this study compared the unit process impact on the global warming mid-points of both conventional and distributed manufacturing. The results show that the environmental impact caused by 3D printing energy consumption is several times higher than the environmental benefits achieved from avoiding product transportation. Moreover, the filament process required to produce the secondary raw material for 3D printing has more impact on the global warming mid-point than injection molding does (Figure 14).

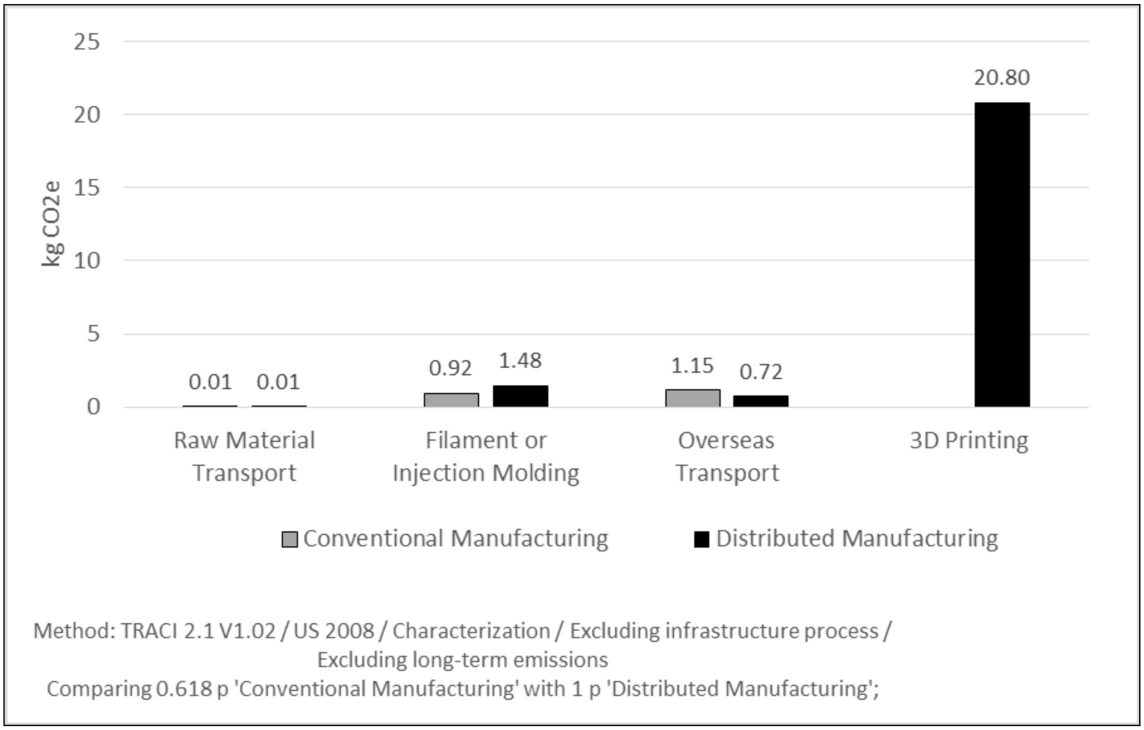


Figure 14. Conventional and distributed manufacturing global warming mid-point.

Chapter IV

Discussion and Conclusions

The findings from this study suggest that the environmental impact of ABS-made spare plastic parts fabricated at home by a desktop 3D printer is higher than that of similar ABS parts made by conventional manufacturing. The environmental impact comparison using the Ecoinvent-3 database and TRACI mid-points has demonstrated that all environmental impact mid-points of distributed manufacturing are significantly higher than those of conventional manufacturing.

In conventional manufacturing, overseas transport has a major environmental impact; therefore, the idea that the environmental impact of conventional manufacturing could be reduced by avoiding overseas transportation is plausible. When 3D printing offered a possibility to home users to print their own products, this stimulated 3D printing enthusiasts, authors, and researchers to believe that 3D printing could also be a sustainable technology capable of reducing the environmental impact of manufactured products (Gibson, Rosen & Stucker, 2009; Lipson & Kurman, 2013; Despeisse & Ford, 2015). Unexpectedly, the environmental impact caused by energy consumption used by fabricating plastic parts with desktop 3D printing is significantly higher than any benefit obtained from removing the need to transport products overseas in the conventional manufacturing model. Because 3D printing consumes a significant amount of energy, the idea that fabricating products at home can be beneficial for the environment is not based on facts, and is in fact contradicted by these empirical results and anlyses.

The environmental impact of fabricating a part at home is highly influenced by the energy consumption required for a desktop 3D printer to fabricate a plastic part. In this study, the energy required to fabricate a washing machine knob made of ABS material was 0.44 kWh, which yields 31.6547 kWh per kg of ABS using a desktop 3D printer. Simply compared to conventional manufacturing, to produce 1 kg of plastic, injection molding requires 2.8758 kWh according to the Ecoinvent-3 database, which is 11 times less energy than what is required by a 3D printer (Hischier, 2007). Because injection molding can produce the same quantity of parts with 0.618 kg of ABS as the 3D printing process produces with 1 kg of ABS, the environmental impact of 3D printing compared to injection molding is 22 times higher. While the injection molding global warming mid-point impact is 0.92 kg CO2e, the 3D printing process alone has an environmental impact of 20.8 kg CO2e. The environmental impact of distributed manufacturing is even higher because the plastic filament process is not considered here.

Removing material from a spare plastic part may save energy, but it makes the part weaker and increases the probability of a part needing to be replaced more times than if an injection molded part was used. The capability of 3D printing to produce hollow parts, and thereby consume less material, has been an argument in favor of 3D printing. Supposedly, consuming less material than conventional manufacturing can offer a sustainable advantage to 3D printing. In fact, by producing a knob with 25% plastic filling, energy consumption and weight are reduced, as is the environmental impact, but conventional manufacturing still has a lower environmental impact. Moreover, Ahn et al. (2012) have demonstrated that the compressive and tensile strengths of FDM 3D plastic parts are lower than those of injection molded parts. In addition, fatigue test comparisons demonstrated that 3D plastic parts, considering a fixed stress, fail after fewer cycles than injection molded parts do (McKeen, 2009; Lee Huang, 2013; Ziemian et al., 2015). Consequently, if parts were fabricated with less material, they would be even weaker and would still have an environmental impact considerably higher than parts made with conventional manufacturing. Taking into account that the scope of this study was to assess spare plastic parts, the durability of a part is a key element of a functional unit. Thus, the weaker the 3D part is, the more additional parts need to be considered in the functional unit, offsetting the benefit of reducing energy consumption.

While previous research suggests the potential of lowering the environmental impact by using desktop 3D printing and distributed manufacturing, the present work shows that distributed manufacturing does not have a lower environmental impact if realistic assumptions are made. Using different assumptions, Kreiger and Pearce (2013) compare conventional and distributed manufacturing using different materials and relying on the ability of 3D printing to produce hollow parts as an environmental advantage. Conversely, the present study considered that 3D parts are naturally weaker than injection molded parts; therefore, comparing hollow parts with injection molding parts is not a viable assumption since they become more fragile and their reduced lifetime should be considered in LCA. In addition, conventional plastic parts do not necessarily weigh the equivalent of a 100% 3D printed part as Kreiger and Pearce assume in their study. Conversely, in this study the original injection molded part weighed significantly less than the 100% filled 3D printed part; failing to consider this in an LCA clearly biases results toward a lower environmental impact of distributed manufacturing. In summary, when parts from the same material and weight are compared, even in Kreiger and

Pearce’s study, conventional manufacturing has a lower environmental impact than distributed manufacturing does.

This study has also shown that technology and the supply chain understanding are important factors in determining whether desktop 3D printing is beneficial for the environment, but relying on partial information may cause misleading conclusions. The results of this study demonstrate that products fabricated by desktop 3D printers are not more environmentally friendly than those made by injection molding when similar products are offered by conventional manufacturing. Worse still, if a home user fabricates a part that is not currently being manufactured by conventional manufacturing, naturally, the fabrication of a totally new product will have a higher environmental impact than not manufacturing any part will. An exception can be made if the energy used by 3D printing is far cleaner than energy use in conventional manufacturing, or if 3D printing technology evolves to consume less energy. In summary, desktop 3D printing technology may evolve and become more sustainable than conventional manufacturing, but, certainly considering today’s technology and environmental impact of energy production, conventional manufacturing is more sustainable than fabricating products at home using desktop 3D printers.

However, the fact that desktop 3D printers are not more environmentally friendly than conventional manufacturing should not stop the exploration of other benefits of 3D printing. The benefits of experimentation, learning, and collaboration offered by 3D printing are limitless and those benefits may outweigh the environmental impact caused in a broader perspective. For instance, building 3D printed limb prostheses for users who do not have the means to afford costly regular prostheses could offer users more comfort and enhance their ability to deal with the adversities of daily activities. In fact, everything that is produced that is not expected to be a substitute for something that is already produced has an environmental impact; however, enhancing people's abilities and helping them to be included in society may have economical and social benefits that can outweigh the environmental impact caused by the consumption of ABS and energy.

In addition, preventing people from using desktop 3D printers because they consume too much energy is like preventing students from using paper and pencils because they are made of wood. Desktop 3D printers are enabling a whole community of makers in a way that resembles the genesis of personal computing technology, which is a significant accomplishment by itself, but fabricating plastic parts at home does not seem to be more sustainable than buying products from retailers when the environmental impact of producing electricity is considered. Paper manufacturing has possibly evolved from extracting wood from natural resources to produce paper from forests that have been planted and dedicated to paper production. Similarly, energy production may evolve to a model with less environmental impact that is less dependent on fossil fuels; then, the environmental impact of the energy consumed by desktop 3D printers will be reduced and desktop 3D printing may become environmentally friendly in certain cases. The benefits of desktop 3D printing are undeniable in terms of developing prototypes, designing learning tools, and fabricating prostheses; therefore, further research investigating the ways in which to reduce the environmental impact of desktop 3D printing should be conducted.

Further research could evaluate different desktop 3D printer models and printing settings to investigate how energy consumption could be improved. The present work did not substantially explore the effect of different printing settings on energy consumption. The investigation was limited to few key printing parameters whose combination would provide a useful perspective regarding their influence on energy consumption and part design. Further research may also consider improving the understanding of printing parameters by conducting experiments to discover whether there is an optimal configuration that minimizes energy requirements and, consequently, reduces environmental impact. Finally, a combined analysis of mechanical tests and failure rate could improve the understanding of the relevance of the chosen printing parameters—and especially the plastic filling percentage—regarding the mechanical resistance of 3D parts and their relation to the parts' lifetime.

Appendix 1

TRACI Mid-Points per Unit Process from Conventional Manufacturing

Impact category	Unit	Total	Raw Material Transport	Injection Molding	Overseas Transport
Ozone depletion	kg CFC-11 eq	3.5E-07	2.1E-09	1.0E-07	2.5E-07
Global warming	kg CO2 eq	2.1E+00	8.4E-03	9.2E-01	1.2E+00
Smog	kg O3 eq	4.0E-01	1.4E-03	5.3E-02	3.4E-01
Acidification	kg SO2 eq	2.9E-02	5.2E-05	6.0E-03	2.3E-02
Eutrophication	kg N eq	1.5E-03	5.9E-06	4.7E-04	1.0E-03
Carcinogenics	CTUh	1.2E-08	6.6E-11	5.4E-09	6.1E-09
Non carcinogenics	CTUh	9.2E-08	1.5E-09	3.9E-08	5.2E-08
Respiratory effects	kg PM2.5 eq	2.5E-03	6.3E-06	9.1E-04	1.6E-03
Ecotoxicity	CTUe	8.5E-01	2.6E-02	2.9E-01	5.4E-01
Fossil fuel depletion	MJ surplus	3.4E+00	1.8E-02	1.2E+00	2.2E+00

Appendix 2

TRACI Mid-Points per Unit Process from Distributed Manufacturing

Impact category	Unit	Total	Raw Material Transport	Filament Process	Overseas Transport	3D Printing Process
Ozone depletion	kg CFC-11 eq	2.7E-06	3.3E-09	7.3E-08	1.6E-07	2.4E-06
Global warming	kg CO2 eq	2.3E+01	1.4E-02	1.5E+00	7.2E-01	2.1E+01
Smog	kg O3 eq	1.3E+00	2.2E-03	7.6E-02	2.2E-01	9.8E-01
Acidification	kg SO2 eq	1.1E-01	8.5E-05	7.6E-03	1.4E-02	8.9E-02
Eutrophication	kg N eq	1.2E-02	9.5E-06	4.7E-04	6.5E-04	1.1E-02
Carcinogenics	CTUh	1.6E-07	1.1E-10	1.0E-08	3.8E-09	1.5E-07
Non carcinogenics	CTUh	8.0E-07	2.4E-09	4.7E-08	3.2E-08	7.2E-07
Respiratory effects	kg PM2.5 eq	7.2E-03	1.0E-05	9.9E-04	9.7E-04	5.2E-03
Ecotoxicity	CTUe	8.1E+00	4.3E-02	5.2E-01	3.4E-01	7.2E+00
Fossil fuel depletion	MJ surplus	2.9E+01	3.0E-02	3.1E+00	1.4E+00	2.5E+01

References

3D Hubs. (2015, September). 3D Printing Trends September 2015. Retrieved September 29, 2015, from https://www.3dhubs.com/trends

Ahn, S., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248–257. http://doi.org/10.1108/13552540210441166

Anderson, C. (2012). *Makers: The New Industrial Revolution*. Crown Business.

ASTM International. (2012). *Standard terminology for additive manufacturing technologies: Designation F2792 - 12a*. West Conshohocken, PA: ASTM International.

Atzeni, E., Iuliano, L., Minetola, P., & Salmi, A. (2010). Redesign and cost estimation of rapid manufactured plastic parts. *Rapid Prototyping Journal*, *16*(5), 308–317.

Bare, J. C., Norris, G. A., Pennington, D. W., & McKone, T. (2002). Traci. *Journal of Industrial Ecology*, *6*(3-4), 49–78. http://doi.org/10.1162/108819802766269539

Bauman, H., & Tillman, A.M. (2004). *The Hitch Hiker's Guide to LCA*. Lund: Studentlitteratur AB.

Bechthold, L., Fische, V., Hainzlmaier, A., Hugenroth, D., Ivanova, L., Kroth, K., Römer, B., Sikorska, E., Sitzmann, V. (2015). *3D Printing: A Qualitative Assessment of Applications, Recent Trends and the Technology's Future Potential* (No. 17-2015). Center for Digital Technology and Management (CDTM). Retrieved from http://www.e-fi.de/fileadmin/Innovationsstudien_2015/StuDIS_17_2015.pdf

Brooks, G., Kinsley, K., & Owens, T. (2014). 3D Printing As A Consumer Technology Business Model. *International Journal of Management & Information Systems (IJMIS)*, *18*(4), 271–280.

Cura [Computer software]. (2015). Retrieved from https://ultimaker.com/en/products/cura-software

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J. G., & Thiede, S. (2015). Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production, 107, 615–625. http://doi.org/10.1016/j.jclepro.2015.05.009

Clay, K. (2013, June 19). 3D Printing Company MakerBot Acquired In $604 Million Deal. Retrieved December 31, 2015, from http://www.forbes.com/sites/kellyclay/2013/06/19/3d-printing-company-makerbot-acquired-in-604-million-deal/

Crump, S. S. (1992). U.S. Patent No. 5,121,329. Washington, D.C: U.S. Patent and Trademark Office.

D'Aveni, R. A. (2013). 3-D Printing Will Change the World. Harvard Business Review, 91(3), 34–34.

Deckard, C. R. (1989). U.S. Patent No. 4,863,538. Washington, D.C: U.S. Patent and Trademark Office.

Despeisse, M., & Ford, S. (2015). The Role of Additive Manufacturing in Improving Resource Efficiency and Sustainability. In S. Umeda, M. Nakano, H. Mizuyama, H. Hibino, D. Kiritsis, & G. von Cieminski (Eds.), Advances in Production Management Systems: Innovative Production Management Towards Sustainable Growth (pp. 129–136). Springer International Publishing.

Dongguan Changhong Bobbin Co., Ltd. (2015). ABS /1.75MM 3.0MM empty plastic spool for 3D printer filament. Retrieved November 15, 2015, from http://dgchxp.en.alibaba.com/product/60135941190-221463765/ABS_1_75MM_3_0MM_empty_plastic_spool_for_3D_printer_filament.html

Faludi, J., Bayley, C., Bhogal, S., & Iribarne, M. (2015). Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. *Rapid Prototyping Journal*, *21*(1), 14–33. http://doi.org/10.1108/RPJ-07-2013-0067

Feygin, M. (1988). U.S. Patent No. 4,752,352. Washington, D.C: U.S. Patent and Trademark Office.

Frauenfelder, M. (2013). *Make: Ultimate Guide to 3D Printing 2014*. Maker Media, Inc. Retrieved from http://proquest.safaribooksonline.com.ezp-prod1.hul.harvard.edu/book/hardware/3d-printing/9781457183669

Gebler, M., Schoot-Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*, 158–167. http://doi.org/10.1016/j.enpol.2014.08.033

Gershenfeld, N. (2012). How to Make Almost Anything: The Digital Fabrication Revolution. *Foreign Affairs*, *91*(6), 43–57.

Gibson, I., Rosen, D. W., & Stucker, B. (2009). *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* (2010 edition). London ; New York: Springer.

Heijungs, R., Goedkoop, M., Huijbregts, M., De Schryver, A., & Struijs, J. (2013). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Ministry of Housing, Spatial Planning and Environment. Retrieved from http://www.pre-sustainability.com/download/ReCiPe_main_report_MAY_2013.pdf

Hischier, R. (2007). Life Cycle Inventories of Packaging and Graphical Papers. (ecoinvent-Report No. 11). Dübendorf: Swiss Centre for Life Cycle Inventories.

Hopkinson, N., & Dickens, P. M. (2003). Analysis of rapid manufacturing-using layer manufacturing processes for production. *Journal of Mechanical Engineering Science*, *217*(C1), 31–39.

Horn, T. J., & Harrysson, O. L. A. (2012). Overview of current additive manufacturing technologies and selected applications. *Science Progress*, *95*(3), 255–282.

Hull, C. W. (1986). U.S. Patent No. 4,575,330. Washington, D.C: U.S. Patent and Trademark Office.

International Organization for Standardization (1997). 14040: 1997. *Environmental management-Life cycle assessment-Principles and framework.* European Committee for Standardization.

Kreiger, M., & Pearce, J. M. (2013). Environmental Life Cycle Analysis of Distributed Three-Dimensional Printing and Conventional Manufacturing of Polymer Products. *ACS Sustainable Chemistry & Engineering*, *1*(12), 1511–1519.

Lee, J., & Huang, A. (2013). Fatigue analysis of FDM materials. *Rapid Prototyping Journal*, *19*(4), 291–299. http://doi.org/http://dx.doi.org.ezp-prod1.hul.harvard.edu/10.1108/13552541311323290

Lipson, H., & Kurman, M. (2013). *Fabricated: The New World of 3D Printing*. John Wiley & Sons.

Makerbot. (2015). Makerbot website. Retrieved October 4, 2015, from http://store.makerbot.com/replicator2x.html.

Mani, M., Lyons, K. W., & Gupta, S. K. (2014). Sustainability Characterization for Additive Manufacturing. Journal of Research of the National Institute of Standards and Technology, 119, 419. http://doi.org/10.6028/jres.119.016

Manyika, J., Chui, M., Bughin, J., Dobbs, R., Bisson, P., & Marrs, A. (2013). *Disruptive technologies: Advances that will transform life, business, and the global economy*. McKinsey Global Institute.

McKeen, L. W. (2009). *Fatigue and Tribological Properties of Plastics and Elastomers, 2nd Edition*. Butterworth-Heinemann.

Ports.com. (2016). Sea route & distance. Retrieved from http://ports.com/sea-route/#/?a=14803&b=682&c=Port%20of%20Shenzhen,%20China&d=Port%20of%20Boston,%20United%20States

RepRap. (2015). Prusa i3 – RepRap Wiki. Retrieved October 4, 2015, from http://reprap.org/wiki/Prusa_i3

Sachs, E. M., Haggerty, J. S., Cima, M. J., & Williams, P. A. (1993). U.S. Patent No. 5,204,055. Washington, D.C: U.S. Patent and Trademark Office

Swift, K. G., & Booker, J. D. (2013). *Manufacturing Process Selection Handbook*. Butterworth-Heinemann.

Thingiverse. (2015). Thingiverse website. Retrieved March 31, 2016, from http://www.thingiverse.com/thing:664098.

Torwell Macromolecule Material Limited. (2015). 3mm ABS 3D printing filament 31 colors,1kg, 0.3kg, 0.5kg, 2kg available for 3D printer. Retrieved November 15, 2015, from http://torwell3d.en.alibaba.com/product/60111540905-221460437/3mm_ABS_3D_printing_filament_31_colors_1kg_0_3kg_0_5kg_2kg_available_for_3D_printer.html

Ultimaker. (2015). Ultimaker 2 Specifications. Retrieved November 22, 2015, from https://ultimaker.com/en/products/ultimaker-2

Walls, S., Corney, J., & Vasantha, G. (2014). Relative Energy Consumption of Low-Cost 3D Printers. In *Proceedings of the 12th International Conference on Manufacturing Research (ICMR201 4* (pp. 97–102). Southampton: Hampshire Press Ltd. Retrieved from http://www.solent.ac.uk/conference-centre/events/icmr-2014/conference-registration.aspx

Wittbrodt, B., Glover, A. G., Laureto, J., Anzalone, G., Oppliger, D., Irwin, J., & Pearce, J. (2013). Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. *Mechatronics; Mechatronics, 23*(6), 713-726. doi:10.1016/j.mechatronics.2013.06.002

Ziemian, S., Okwara, M., & Ziemian, C. W. (2015). Tensile and fatigue behavior of layered acrylonitrile butadiene styrene. *Rapid Prototyping Journal*, *21*(3), 270–278. http://doi.org/10.1108/RPJ-09-2013-0086