The Next Production Revolution
Implications for Governments and Business

PART I

Chapter 5

3D printing and its environmental implications

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This chapter examines the potential environmental sustainability implications of 3D printing (also called "additive manufacturing") as it displaces other manufacturing technologies, and lists top priorities for policy interventions to improve environmental sustainability. It considers several of the most widely used 3D printing technologies as they are today and describes trends related to 3D printing's ability to supplant other technologies in the near future as this method evolves. This analysis compares the environmental impact of today's typical 3D printing with two classic manufacturing methods, citing life-cycle assessments, scoring greenhouse gas emissions and other air pollutants, material toxicity, resource depletion, and other factors. It also explores how 3D printing will expand into more industries. While this chapter mostly concerns plastic processes, other materials such as metal are also considered. While widespread 3D printing would not automatically be an environmental benefit as practised today, technologies already exist that, if brought from the industry's fringes to its status quo, could dramatically shift manufacturing towards more sustainable production. Since the industry is at a crossroads, well-placed incentives today might establish beneficial technologies for decades to come, to make widespread 3D printing an important part of a more sustainable future.

Introduction

Additive manufacturing (hereafter 3D printing) has the potential to dramatically shift industrial manufacturing methods away from traditional technologies and democratise the production of manufactured goods. If scaled up across multiple industries in the next decade 3D printing also poses potential benefits and drawbacks for environmental sustainability. 3D printing groups together many different technologies and processes that use a digital file to build a physical 3D object by successively adding layers of material until the model is complete. As with other forms of manufacturing, 3D printing is largely a way of producing parts; most products are assemblies of many parts, only some of which can be 3D printed.

Traditional manufacturing methods being replaced by 3D printing are too numerous and varied to describe thoroughly; this chapter will only consider machining and injection-moulding. Machining begins with a block of material and cuts some away to produce the final shape. It can use a wide variety of materials, including plastics and metals, to produce high-precision parts with a fine surface finish. Modern machining is often computer-controlled and begins with the same type of digital file as that used by 3D printers. It does not require mould tooling, so each part produced can be unique, though it often requires skilled labour and generates significant material waste. Injection-moulding melts plastic and injects it into the cavity of a pre-existing mould, forming the part in seconds. The two halves of the mould then separate to allow part removal and reunite for production of the next part. Injection-moulding can use any thermoplastic, and can produce high-precision parts with a fine surface finish. Due to the mould tooling required, it generally cannot produce custom parts, but can produce thousands or millions of the same part at low cost and with little material waste.

Although 3D printing has gained recent traction in manufacturing and among the general public, the method is older than most of us realise, having been first developed in the 1980s. Widespread public awareness took hold in the early 2000s due to the expiration of early patents, which enabled low-cost desktop printing via the open-source movement. The industry as a whole is expanding rapidly thanks to the falling of printer and materials prices, rising print quality and the convergence of open-source and private innovation (Hornick and Roland, 2013).

The rapid growth of the industry has been called a "gold rush". This characterisation is corroborated by the doubling in the number of 3D printers sold between 2005 and 2011 (McKinsey, 2012). Sales are projected to exceed USD 10 billion per year by 2021 (Wohlers, 2014). Currently, the majority of 3D printing produces prototypes, models and tooling; only 15% directly produces parts in sold goods (Beyer, 2014). This trend is changing as the manufacturing segment of the industry is growing at 60% per year (Cohen, Sargeant and Somers, 2014). 3D printed goods are sold in high-value, small-run niches such as aerospace, jewellery and medical devices. Almost no full products are 3D printed, but commercial products contain 3D printed parts.

Many proselytise on 3D printing's sustainability, but few understand its true impact: much of its praise is unfounded, while much of its long-term promise is overlooked. In 2009, the US National Science Foundation convened 65 experts to write the Roadmap for Additive Manufacturing (RAM), which included a section on sustainability where they recommended that life-cycle assessment (LCA) be used to quantify environmental impacts of every major type of 3D printing and compare them to traditional manufacturing methods (Bourell, Leu and Rosen, 2009). Some aspects of 3D printing sustainability include its effect on transportation, manufacturing waste, manufacturing energy, use-phase energy and material recovery for a circular economy. Cases exist, such as General Electric's jet engine nozzle (Freedman, 2011), where 3D printed parts lower the environmental impact of the product in its use-phase. However, because such improvements are difficult to predict and may be limited to aerospace and automotive industries, this chapter focuses on environmental impacts arising from the manufacturing stage.

Impacts from printing plastic components for consumer products and prototypes receive the most attention in the chapter since these appear to be the largest market segments for 3D printing (Beyer, 2014). However, printing parts in metal and other materials will also be discussed, because one of 3D printing's potential benefits is expanding the use of alternative materials. Plastic is ubiquitous today because it can be shaped into nearly any form; 3D printing gives this same ability to many other materials.

3D printing technology applications thus far

3D printing encompasses a wide range of technologies, each a specific combination of print material and printer. For example, thermoplastic materials can only be printed by machines with heat sources to melt and extrude the plastics. Liquid epoxy materials hardened by ultraviolet (UV) light can only be printed by machines with UV light sources. Some systems are more flexible than others.

3D printed models are created using computer-aided design (CAD) software and/or 3D scanners to create digital 3D model files. These CAD files are loaded into printer driver software that runs the printer through whatever procedures are necessary to print the file. Some print driver software is specific to a certain printer or printer family, such as manufacturers Stratasys and Renishaw provide for their printers, while other print driver software is more universal, such as Ultimaker Cura (Ultimaker, 2016) or Microsoft Standard Driver (Microsoft, 2016). Printing processes vary in what they can produce; not all printers can produce all part types.

Many systems print support material in addition to the actual modelling material, in order to prevent parts from collapsing or warping while they are being formed. Many prints require additional support, depending on part geometries and the printing process. This can vary from zero support material to more support material than model material. The support material may or may not be the same as the model material, with various means of removing supports, depending on the process.

Printing processes

Many 3D printing processes exist – far more than can be adequately described in this chapter. Four of the most popular processes are described here: thermoplastic extrusion, inkjet, light-polymerised, and laser sintering, based on their ubiquity in 3D printing and potential for environmental sustainability.

Thermoplastic extrusion melts a solid filament of material through a heated nozzle onto a platform bed or stage to deposit material in the X, Y and Z dimensions. It includes fused deposition modelling (FDM), also called Fused Filament Fabrication (FFF), which is one of the earliest additive technologies and was the first to be open-sourced. FDM is generally lower-resolution than other technologies, but has the particular advantages of being simple, reliable, and low cost.

Common plastics used with this technology are acrylonitrile butadiene styrene (ABS), the same plastic used to produce Lego bricks; polylactic acid (PLA), a plant-derived and biodegradable plastic often used in food packaging; and polyethylene terephthalate (PET), the same plastic used to create most drink bottles and other common packaging. FDM can also be used with modelling clay, plasticine, rubber-like polymers, and eutectic metals.

FDM can be very low waste, when part geometry does not require additional support material. In principle it can extrude any thermoplastic, even with additives. Extrusion printers can only print one part at a time, and print time directly correlates to the amount of material printed.

Inkjet prints like a 2D inkjet printer, but instead of printing liquid ink on paper, it prints liquid binder onto a bed of powder, and then a mechanical wiper spreads another layer of powder over the bed to print the next layer.

It can print many different materials, from plaster to sugar (Molitch-Hou, 2015) to ceramics (fired after printing) to metal powders (sintered after printing). Experimenters at the University of California at Berkeley have used inkjets to print in sawdust, concrete, salt, starch, and more.

This method of printing can offer very high quality – both high resolution and full colour models. In theory, the process can be almost zero waste, because the powder can be reused and no support material is required. Of the few printing methods which have undergone full LCA, inkjet printing of green materials has shown some of the greatest potential for sustainability (Faludi et al., 2015b). However, experimental materials often do not yet meet quality standards for consumer products. Inkjet printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed.

Figure 5.1. **Experimentally printed part via ink jet**

Source: Faludi, J. et al. (2015b), “Does material choice drive sustainability of 3D printing?”, *https://waset.org/Publication/does-material-choice-drive-sustainability-of-3d-printing-/10000327*.

Light-polymerised printing uses liquid photopolymer that hardens when UV light strikes it. This includes stereolithography (SLA) using a UV laser, digital light processing (DLP) using a UV digital projector, and continuous liquid interface production (CLIP) using a UV projector with modified polymer chemistry. SLA, also known as optical fabrication or resin printing, is the oldest type of 3D printing. DLP generally prints faster, and CLIP is an order of magnitude faster.

A popular hybrid of photopolymer and inkjet methods is the PolyJet system, using inkjet print heads to print photopolymer onto a surface and then hardening it with a UV lamp. All these methods can make high resolution parts with excellent surface finishes, acceptable for commercial products.

SLA usually requires no support material; others vary by part geometry, and PolyJet requires more support material than other printers listed here. For SLA and DLP, unsolidified liquid polymer can be reused, though not infinitely. Polyjet ink waste is not reusable or recyclable, and current machines are high-waste, averaging 43% even before counting support material (Faludi et al., 2015a).

All 3D printing photopolymers today are somewhat toxic in their liquid form, frequently with a Hazardous Materials Identification System (HMIS) health score of two out of four (3D Systems, 2012), similar to many epoxies. However, they are usually considered non-toxic once solidified.

Photopolymer printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed.

Figure 5.2. **SLA (left) and PolyJet (right) printed parts**

Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*.

Laser sintering or melting binds a powder together in certain places by heating it with a laser. Most machines such as selective laser sintering (SLS), selective laser melting (SLM), and direct metal laser sintering (DMLS), use a bed filled with powder; the laser strikes the top surface to melt the powder together only in specified locations, then a mechanical wiper spreads another layer of powder over the bed to print the next layer. Other laser melting machines spray the powder from a nozzle while heat-fusing it, such as direct metal deposition (DMD) and construction laser additive directe (CLAD).

Laser melting machines can print in thermoplastics, metals, ceramics, or glass. The most common plastic is nylon and the most common metals are steel, aluminium, and titanium; exotic metal-ceramic alloys are sometimes used for aerospace parts.

Unmelted metal or plastic powder can be reused for later prints, perhaps five to ten times (Slotwinski et al., 2014; Dotchev and Yusoff, 2009), though this is often prevented by quality risk. Support material is not needed to fight gravity, but is often needed to prevent warping. When removed, support plastic is usually landfilled, but support metal is often recycled as machining scraps would be.

Laser sintering printers can print more than one part at a time, and print time correlates more strongly to part height than to the amount of material printed. Laser melting machines can have long warm up and cool down times, as well as significant time required for part removal, so there is an incentive to batch operations.

Figure 5.3. **A laser sintered metal sculpture**

Source: Grossman, B. (2003), "Oldest news", *www.bathsheba.com/artist/news_old_0.html* (accessed 1 May 2015).

Table 5.1 presents a snapshot of the different 3D technologies covered in this chapter in addition to details on how they function on their cost curve.

Table 5.1. **3D printing technologies: Advantages and drawbacks**

Process	Technology	High or low resolution printing	Materials used	Cost curve	Sustainability potential	Batch printing?
Thermoplastic extrusion	FDM, FFF Other extrusion technologies are similar	Low to medium resolution	Commonly ABS, PLA, PET, etc. Other extruders may use more exotic materials	Low to medium cost	Low to high energy use Can be low waste with self-supporting part geometry PET easily recyclable PLA compostable in specialised facilities ABS somewhat toxic and not recycled	No
Inkjet	Liquid binder on powder bed	High resolution. Can print full colour	Commonly plaster or ceramics Alternative materials: sawdust, concrete, salt, starch, sugar, etc.	Medium to high cost	Can be highly energy-efficient when printing in batches Low waste Potentially green materials, but not yet used for consumer products	Yes

Table 5.1. **3D printing technologies: Advantages and drawbacks** *(cont.)*

Process	Technology	High or low resolution printing	Materials used	Cost curve	Sustainability potential	Batch printing?
Photopolymer	SLA,CLIP, DLP, PolyJet	High resolution	Liquid polymer PolyJet can print in multiple materials at once	Low to high cost	Medium energy use; more efficient when printing in batches Liquid polymers somewhat toxic, but can be reused in all but PolyJet Most use little support and generate little waste, but PolyJet is high-waste Solidified polymer not recyclable	Yes
Laser sintering or melting	SLS, SLM, DMLS, DMD, CLAD	High resolution	Thermoplastics, metals, ceramics, glass Common plastic: nylon Common metals: steel, aluminium, titanium	High cost	High energy use; more efficient when printing in batches Most unused powder can be reused Support waste plastic usually landfilled; support waste metal often recycled	Yes

Source: Authors' analysis.

Near-term evolution of 3D printing technology

Several aspects of 3D printing have greatly improved over the past decade. The most important metrics include print quality, print size, print time and material choice. This section details trade-offs in printing technology relevant to the economic impacts and environmental consequences of 3D printing becoming widespread. If 3D technology is scaled up in the coming decades these considerations must be taken into account.

Choosing between print quality and time

3D printing is largely used for prototyping today because high-quality prints remain expensive. However, print quality has improved, and some printer types already print parts acceptable for finished products at a lower cost than other manufacturing methods (e.g. SLA-printed dental crowns) (Bammani, Birajdar and Metan, 2012). Print quality is determined by resolution, tolerance, structural robustness, smoothness of finish, dimensional stability, and other factors. It can also include special abilities, such as the capacity to print multiple colours or multiple materials in the same object. Comparing Figures 5.2 and 5.3 to Figure 5.1 shows how SLA, PolyJet, and SLS generally make higher resolution and smoother surface-finish parts than FDM or the experimental inkjet printing in salt.

Improving resolution often increases production time, thus also cost and energy use. For example, doubling FDM resolution means the print head must traverse twice as many layers, roughly doubling print time. Doubling SLA resolution means using a polymer that needs much longer exposure by the UV laser to harden, thus increasing print time. In both cases, the longer print times mean more energy use because the machine runs at similar power consumption for a much longer time. However, this may not be inevitable. A DLP printer with twice the resolution in the projector might not require noticeably more energy than a lower-resolution projector, because that component of the machine is a small fraction of total power use.

Print cost versus time

The largest barrier to high-quality, low-cost 3D printing at scale is long print time, though this barrier is beginning to diminish. Today, a hollow-shell part just 5 cm x 5 cm x 2.5 cm, such as in Figures 5.1 to 5.3, somewhat similar in mass to that of a mobile telephone case, can take hours to print as opposed to seconds in injection-moulding. While the industry has worked to speed up 3D printing, its main market so far has been prototypers, who appreciate but do not require high speed. The shift in 3D printing towards manufacturing has now made faster print speeds a higher priority for printer manufacturers.

Faster speeds are often simply achieved though larger versions of existing printers, so more parts can be printed at once, but some designs are revolutionary. The CLIP printer by Silicon Valley start-up Carbon3D claims to be 25 to 100 times faster than traditional 3D printers, printing the part described above in minutes rather than hours. This increase in speed can be attributed to the printer's chemistry, which allows a liquid photopolymer to harden continuously as the stage moves, rather than pausing for each layer as all other 3D printer types require (Rolland and Desimone, 2016). Another company, 3D Systems, was developing a printer claiming to be 50 times faster than current speeds in 2014 (McKenna, 2014), though at the time of going to press it had not been released. Such speed increases should greatly reduce the cost per part of 3D printing. Still, it is unclear how much or how fast prices will decrease for customers, because the razor and blade business model is common in the industry. For example, Carbon3D's photopolymer material may be expensive enough to only improve cost per part moderately, despite its large speed increase.

Considering print size

3D printing is expanding print sizes both to very large objects and very small objects. For very large objects, the architecture industry includes KamerMaker's canal house in the Netherlands (Wainwright, 2014) as well as WinSun's concrete panels for a 5-storey apartment building in China (Starr, 2015) and the University of California Los Angeles/Contour Crafting's partnership with NASA to build a moon base (Khoshnevis et al., 2012). For cars, Local Motors has prototyped an electric car with a 3D printed body, the Strati (Davis, 2014). On the small scale, most micro or nano 3D printing has actually been macro-scale printing of materials with micro- or nanoscale properties (Campbell and Ivanova, 2013). However, there has been actual printing at these scales as well. Hybrid microelectromechanical systems (MEMS) techniques have allowed the production of a robotic bee weighing just 90 milligrammes (Sreetharan et al., 2012), quantum-dot light-emitting diodes have been 3D printed (Kong et al., 2014), and lithium-ion batteries have been printed at the millimetre scale, with near-record high energy density (Sun et al., 2013).

In the coming years there will be more progress in the range of sizes 3D printers can produce at low cost. For economic and technical reasons, this evolution will probably come from the large scale rather than the small scale. Small-scale 3D printing is economically disadvantaged because all nanoscale manufacturing must be mass manufacturing if it is to produce useful amounts of a product. Computer chips often contain billions of transistors (Meindl, 2003), and millions of carbon nanotubes only fill a cubic centimetre (Andrews et al., 1999). 3D printers must become much faster to compete economically in this realm (Li et al., 2011). Technology limits play a part as well: lasers used for small-scale 3D printing are physically incapable of the higher resolution of some other nano-fabrication methods (Li et al., 2011). Hybrids of traditional and 3D printed steps in the electronics manufacturing process can be economic and environmental improvements (Miettinen et al., 2008), but decades will probably pass before 3D printing can fully replace the semiconductor industry for chip fabrication.

Figure 5.4. **Local Motors 3D printed car body**

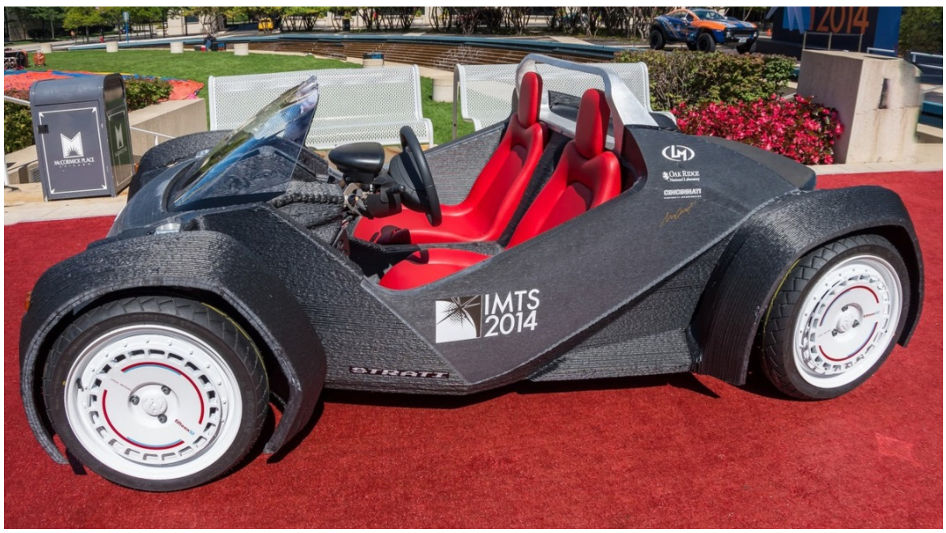


Photo © Local Motors, Inc.
Sources: Davis, J. (2014), "This is The world's first 3D printed electric car", *www.businessinsider.com/this-is-the-worlds-first-3d-printed-electric-car-2014-12#ixzz3QB6iqz5x* (accessed 15 January 2015); Local Motors, Inc.

Material choice and multiple materials

Expanding material choices allow greater market reach, and the 3D printing industry's material palette is expanding rapidly. The range of materials available for use with 3D printers include: plastics, metals, ceramics, paper and food. Even living human cells can be 3D printed today. They may also come in different states such as powder, resin, paste, or filament. Low-cost desktop FDMs can print flexible or rigid plastics, plastics that change colour with temperature, and plastics infused with wood fibre or carbon nanotubes (Krassenstein, 2014).

Most 3D printer manufacturers use a razor and blade revenue model, selling relatively high-cost proprietary materials. However, open-source communities and hackers frequently make and share new materials. For example, 3D inkjet users have online communities to share recipes for powder and binder mixes (such as vodka and starch, or sawdust).

Perhaps the most important material expansion in 3D printing in coming years will be the capability to print multiple materials in the same part or alter a material's properties from one zone in the object to another. Today, it is impossible to 3D print a mobile telephone – one can only print simple components such as the plastic case, then assemble the electronics into the case. In fact, the only whole products that can be 3D printed are materially simple things like plastic toys or metal jewellery. Everything else is printing components. Printing in multiple materials, however, lets a single part perform the role of whole assemblies of other parts. Researchers have printed pain-reducing splints, sound-absorbing chaises longues, and other multi-material products (Oxman, 2010), and some commercial printers can already print 14 materials at once (Stratasys, 2015). Still, industry is probably a decade or more from printing a working telephone, both because of material limits and the print size limits discussed above. Multi-material machines printing wiring within plastic parts have been experimentally proven (Silverbrook, 2004), and may soon emerge commercially. If so, it would greatly improve industry's ability to replace assemblies with printed parts.

Printing dissimilar materials together severely reduces their recyclability (Dahmus and Gutowski, 2007), which is problematic for sustainability. However, tuning the properties of a single material within the same part could provide an object that is recyclable, and which replaces an assembly of different materials not recyclable together. Similarly, if different printed materials are all compostable, such as some bioplastics or composites, then there is no need for separation (though injection-moulding could equally well co-mould two different compostable bioplastics). Even wiring could be compostable in the future, as conductive carbon inks can already be made biodegradable (Kilner, 1993). The same is true for incineration, where energy can be recovered from mixed plastics.

Box 5.1. **Print energy**

Trends in printer energy use are hard to predict, as energy prices are too low to drive the market. Desktop FDM machines use much less energy per part than commercial FDM machines (Faludi et al., 2014), but they also have low print quality unsuitable for mass manufacturing. Operating printers more efficiently, such as by SLA/SLS/PolyJet/inkjet machines printing multiple parts at once, or FDM machines printing hollowed parts, certainly reduces energy use per part along with print time per part (Baumers et al., 2013; Baumers et al., 2011b). However, trends driving down print times may or may not drive down energy use. The newly announced Carbon3D printer advertises print times 25 to 100 times faster than others (Rolland and Desimone, 2016), and its power use is probably on par with similar printers (though data has not been released), thus providing a revolutionary improvement in energy use per part. However, other emerging high-speed printer designs such as the system for Google's Ara telephone may achieve their speed gains at the cost of higher power consumption.

Industry expansion

3D printing will expand into many more industries in coming years, but it will be limited by a hyperbolic growth curve: easily entering markets with fewer units produced at high or moderate costs, but unable to penetrate markets with many units produced at very low costs. Thus its growth will affect certain market sectors most; for other sectors it will only affect start-ups and small business groups for some time. Its economics will probably have significant social impacts in both developed and developing countries.

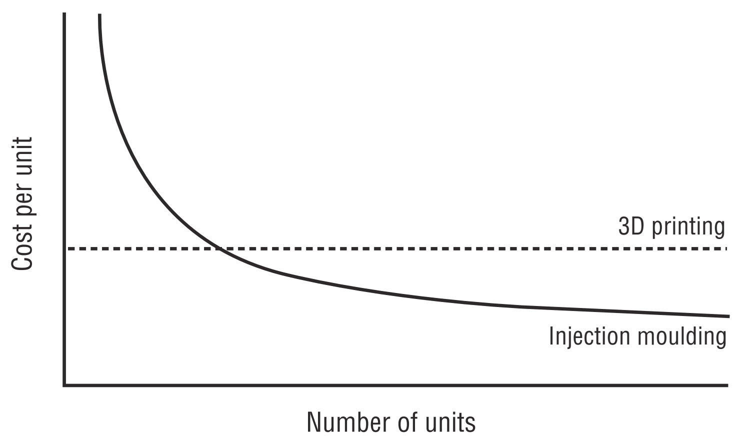
Prioritising costs or volume

3D printing has a higher cost per unit than traditional manufacturing methods, but no set-up costs between batches of different product lines; this determines the economics of manufacturers switching to 3D printing. Equipment costs vary widely, but both injection-moulding machines and commercial 3D printers range from tens of thousands to hundreds of thousands of dollars. Assuming that equipment costs amortise away to be roughly equal means that switching from injection-moulding to 3D printing becomes economical when higher costs per part are outweighed by avoiding batch set-up costs. This occurs when:

$$C_{3D} - C_{IM} < \frac{C}{N},$$

where N = number of units per batch, C = cost of tooling/set-up for a new batch, C_{3D} = cost per part of 3D printing N units, and C_{IM} = cost per part of injection-moulding N units (Askin and Goldberg, 2007). Supply chain costs such as transportation and logistics, which are also saved by 3D printing, can be considered part of the set-up cost for this simplistic model. Obviously the lower the 3D printing cost, the larger the market that should switch, but it is a hyperbolic, not linear, curve, as shown in Figure 5.5.

Figure 5.5. **Generalised cost curve of 3D printing versus injection-moulding**



Source: Authors' calculations.

For example, if tooling and set-up for the plastic apple shape in Figures 5.1 and 5.2 cost USD 10 000 and the price per part of injection-moulding is USD 0.50, then 3D printing costing USD 5.50 per part (over ten times the price per part for injection-moulding) is still economical for fewer than 2 000 units. But at 100 000 units, the price of 3D printing must fall to USD 0.60 per part for it to be as economical as injection-moulding. At 1 000 000 units, the price of 3D printing must fall to USD 0.51 per part (within one penny of the injection-moulding cost) for it to be economical.

In industry, these cost crossovers can occur at a range of values. While some studies have found cost crossovers in the tens of parts for metal casting (White and Lynskey, 2013; Atzeni and Salmi, 2012), or hundreds of parts for plastic injection-moulding (Bhasin and Bodla, 2014; Sculpteo, 2014), Conner found that for some parts, plastic SLS can already be less expensive than injection-moulding for runs of fewer than 10 000 parts (Conner et al., 2014). Thus 3D printing will continue to expand rapidly from the prototype market to small-run production, as it is currently doing, but will have much more difficulty expanding from small-run production to mass manufacturing, until 3D printing costs become radically lower.

Bhasin estimated that 3D printing costs would fall by roughly one-third by 2020 (Bhasin and Bodla, 2014), which is not enough to approach cost crossover for millions of units. Bhasin also showed that although 3D printing could radically reduce costs of product transportation, logistics, warehousing, and other holding costs, these are only a small percentage of most products' total cost, meaning that they will not significantly speed up industry takeover. Thus, 3D printing is not likely to replace injection-moulding at the largest scales for at least a decade or two, even after it has become the default production technology for small-run parts. If technical breakthroughs occur this timeline would be shortened, but it will still be limited by simple industry inertia. In the 2D paper printing industry, digital printing became commercially available in the early 1980s, but did not become widespread until the mid-1990s, with many companies taking five years or more from initial use to full integration in production systems (Parnell, 2007).

This conservative assessment should not be taken as an underestimation of 3D printing's growth curve; many industries produce parts in the thousands or fewer. High-technology industries such as aerospace, defence and certain medical devices often produce parts in the mere hundreds. Some of these parts are already being made by 3D printers more economically than with other methods, as mentioned in the introduction. Mass-customised products such as individually fitted hearing aids and tooth fillings are already cheaper to 3D print because each unit is different even though they are produced in the millions. The potential exists for medical prosthetics and elite sporting equipment to be the next frontier in low-volume printing.

Other industries that have not yet been penetrated by 3D printing, but where this is likely in the next several years include those manufacturing toys, precision machinery, optics and miscellaneous luxury goods. Objects produced in a five- to ten-year timeframe may encompass designer housewares, furniture and clothing. These industries all have what McKinsey calls a relatively high "value density" and "labour density" (McKinsey Global Institute, 2012), meaning they are relatively high value per mass of material, and a relatively high percentage of the cost of manufacturing is from labour, which 3D printing reduces or eliminates. Toys may be an especially likely sector, because they are a highly volatile seasonal market with unpredictable demand for "must-have" items.

3D printing can also increase production instantly to arbitrarily high levels, without the need to manufacture and store goods in warehouses beforehand. Another advantage is the elimination of tooling costs on several production lines on short notice. The production of furniture and clothing are more difficult to predict because most 3D printer research and development is not focused on those markets. One example from the textile industry is Nike's Flyknit shoe line which uses 3D computer-controlled knitting, and been a great commercial success (Townsend, 2012).

Prioritising costs or size

Product size will continue to be a limitation. Smaller parts are more cost-effective to 3D print because print time and material consumption are the dominant costs for 3D printing. Both relate to the size of parts printed; smaller parts are more economical to 3D print. In this vein, the jewellery industry is becoming another early adopter of 3D printing, since it is often an industry producing few units at a high cost per unit. In contrast, the automotive industry is unlikely to have 3D printing as a significant percentage of production for a decade or more, because it requires many large parts in addition to high-volume production at medium to low margins. However, this assumption is inconclusive. Automotive tooling already constitutes approximately 18% of the 3D printing industry and innovations like the Strati vehicle may shift the industry towards finished parts.

The architecture industry poses the largest size challenge, but may also be a golden opportunity for 3D printing, as the industry is primarily bespoke and highly labour-intensive. As mentioned above, 3D printing has entered the industry. However, as promising as these initial efforts are, the building industry is notoriously conservative. Even if today's 3D printers were unequivocally higher quality and lower cost than manual construction, it would probably still take a decade for the innovation to penetrate the market without policy incentives. Any such incentives would probably encounter political resistance, due to the number of jobs that would be lost as a result of automated construction. At the other size extreme, integrated circuit electronic parts are too small for 3D printing to penetrate soon. They have much higher-value density than toys or clothing, but sophisticated circuitry will remain beyond the range of 3D printing for the foreseeable future.

Box 5.2. **Social impacts in developed and developing countries**

Significant social impacts will accompany the environmental consequences of 3D printing. One evolution will be the shifting business landscape. Access to 3D printers can empower start-ups and small manufacturers. Developed countries may see a "reshoring" of production. Developing countries may see an uptick in entrepreneurialism. However, it will exacerbate the loss of jobs in manufacturing.

Start-up companies in any industry begin by producing parts in the thousands or fewer. 3D printing's economical production of small-run parts will enable more companies to start manufacturing with less capital. It will also allow companies of any size to spend more time in product development, making small runs of products and getting feedback from clients in order to improve them before producing in higher quantities. As global trends show increasing "fragmentation of demand" where more versions of products have shorter product cycles, this becomes an increasing share of markets (McKinsey Global Institute, 2012). However, this can have the negative side effect of enabling more planned obsolescence.

One socio-political disadvantage of 3D printing lies in the elimination of skilled manufacturing labour through automation. A sample prototype for Berkeley research (Faludi et al., 2014) took several hours of skilled machinist labour to create with the help of a highly automated computer-numeric-control (CNC) mill, but only took a few clicks of a mouse to 3D print. This trend will probably mirror the transformation of the 2D paper printing industry in the 1990s. That industry lost many jobs, but new jobs emerged. "Computerised typesetting programs inevitably brought deskilling, but original skills, learned and used by workers over many years of rapidly changing technology, did remain relevant, and the acquisition of new skills associated with computerisation was regarded favourably" (Parnell, 2007). It is unclear how many jobs will disappear or merely change for manufacturing transitioning to 3D printing.

A benefit of 3D printing's reduction of labour costs is potential "reshoring", the practice of returning manufacturing from low-wage countries to high-wage countries (Tavassoli, 2013). The extent of this reshoring is difficult to predict, but it will probably follow the growth curve of industry penetration listed above: first high-margin, low-volume industries, then lower-cost, higher-volume industries. Recall, however, that 3D printing generally only produces

Box 5.2. **Social impacts in developed and developing countries** *(cont.)*

parts, not whole products, and will continue to do so until multi-material printing becomes far more sophisticated (which will take many years). Products will still require assembly somewhere, and this may limit the extent of reshoring. Still, potential exists for large gains, as 3D printing can fabricate complex parts that would previously have been assemblies, thus enabling less assembly labour.

Some have touted 3D printing as a boon for developing countries (Birtchnell and Hoyle, 2014), because of the potential to eliminate supply chains, thereby solving distribution issues in countries with little infrastructure. This optimistic outlook ignores the economic damage that reshoring production to developed nations would have on developing economies, but proponents have generally focused on extremely rural areas, where the "poorest of the poor" live, which would not be producing offshored goods. Proponents forget that printers today are limited mostly to producing parts, not whole products, and more importantly that the printers themselves need supply chains for maintenance and repair of both themselves and the computers required to 3D model the objects being printed. If a village does not have a supply chain for a simple plastic part, it certainly does not have a supply chain for a computer motherboard. Since the 1970s and 1980s the developing world has seen many well-intended solar electrification projects fail due to a small component breaking with no means to repair it (Dichter, 2003). As Birtchnell admits, 3D printing for development is optimistically a decade off because it requires affordability, "flexibility" (reparability and upgradability), simplicity, scalability, and quality to enter the "Goldilocks zone" of usefulness (Birtchnell and Hoyle, 2014). Design for development usually refers to its demographic as "the base of the pyramid" because it is a very large number of people with very little money. The cost curve described earlier shows that this is the opposite of 3D printing's advantages.

Still, 3D printing for development could prove quite beneficial in different scenarios in the major cities of poor countries. Developing countries have leapfrogged past wired telephones to cell phones with enormous economic and social benefits to millions of people; a similar leapfrogging could happen with small urban manufacturers. The greatest benefit for developing countries is probably the same as in developed countries: allowing start-ups or small businesses with little capital to begin manufacturing on a small scale, then using the earnings to finance expansion into mass manufacturing. Instead of 3D printing taking the place of centralised manufacturing and distribution networks, 3D printing could take the place of venture capitalists. Then, once entrepreneurs are producing at scale with traditional manufacturing methods, they can produce products for large numbers of people with little money, helping economic development at scale. 3D printing will have the added benefit of helping developing world start-ups to circumvent supply chain infrastructure limitations until they have grown enough to afford their own infrastructure. But because the 3D printer itself needs infrastructure and a supply chain, it seems more useful as a stepping stone than a destination. Future studies should investigate these scenarios compared to rural manufacturing.

Likely environmental impacts of widespread 3D printing

Widespread 3D printing will not uniformly increase or decrease the environmental impacts of manufacturing. Changes will depend on the specific item produced. Most products require multiple parts made through a mix of manufacturing methods, e.g. moulding, casting, stamping and bending, extruding and welding. The impacts of these technologies are varied and highly dependent on the parts being produced. Therefore, to accurately forecast the environmental implications of replacing these with 3D printing, studies should compare 3D printing to each sequence of technologies it replaces, for each relevant product type and material. The 2009 RAM recommended such research (Bourell, Leu and Rosen, 2009), though few such studies have been published to date. This chapter discusses only two benchmarks: 3D printing compared to machining and injection-moulding.

Broad generalisations about the advantages of 3D printing in comparison to machining or injection-moulding cannot be accurately made. Environmental impacts vary widely depending on printer type, part geometry, machine utilisation rate (idle time and efficiency of bed packing for many printer types), print set-up and material. Given these caveats, for a "typical" hollow-shell plastic or metal part, 3D printing is generally lower-impact per part than machining, but higher impact per part than injection-moulding at scale. The largest environmental impacts generally come from printing energy and material use, although this varies by printer, material choice, and usage scenario. In addition, the technology is changing rapidly, meaning that some experimental systems today may be substantially lower-impact than other manufacturing methods, but more research is required to support these claims.

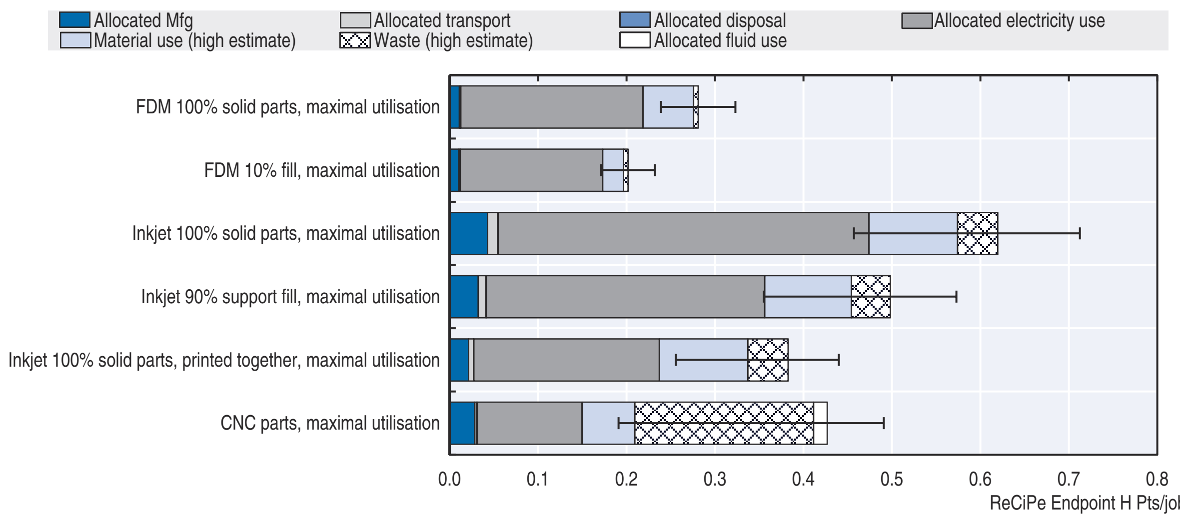
3D printing compared to traditional machining

The next five to ten years will probably see 3D printing supplant much (perhaps even most) machining of parts, but this is unlikely to create large shifts in the environmental impact of the manufacturing sector on a global scale, because machining's market niche is small. Machining is the main method for prototyping and producing limited amounts of complex-geometry custom parts. 3D printing is already significantly altering these markets for both plastics and metals. For plastics, prototypes and small-run production parts are 3D printed by FDM, SLA, and SLS; for metals, they are printed by e.g. DMLS, SLM, DMD or CLAD. Boeing alone has already replaced machining with 3D printing for over 20 000 units of 300 kinds of parts (Davidson, 2012). However, machining is a small niche – statistics from the US Bureau of Economic Analysis show machining categories to comprise less than 1% of total manufacturing dollars (BEA, 2014).[1] Thus, even dramatic environmental improvements from replacing machining with 3D printing will not noticeably reduce manufacturing sector impacts on a global scale.

3D printing generally produces parts with lower environmental impacts per part than machining, but there are many exceptions – some part geometries are more efficient to machine than to print, different printers have very different impacts per part, and even a given printer can have very different impacts per part depending on several factors. For plastic parts, two studies (Faludi et al., 2015a; Faludi et al., 2014) showed that changing printer utilisation causes more variation than the difference between 3D printing versus machining. Machines which predominantly sit idle have far higher environmental impacts per part than machines producing parts 24 hours per day, seven days per week, whether they are 3D printers or milling machines. Thus, maximising utilisation is a top priority for sustainability in 3D printing. These studies also showed that some 3D printers have higher impacts per part than others due to higher energy use, waste, and material toxicity. Finally, comparing the two studies shows that producing hollow-shell part geometry rather than solid-block geometry reduces environmental impacts per part for 3D printing, but increases them for machining. Thus, some solid-block geometries can be machined for less impact than they can be if 3D printed, even if 3D printing is lower-impact for other parts.

For example, Figures 5.6 and 5.7, derived from the aforementioned studies, show LCA comparisons of machining via a CNC mill versus several 3D printers, all producing parts 24 hours per day, seven days per week. The LCAs use the ReCiPe Endpoint H method (Goedkoop et al., 2009), which creates a single overall environmental impact score from 17 different types of impact, including climate change, acidification, eutrophication, atmospheric particulates, fossil-fuel depletion, mineral depletion, human toxicity, and others. These impacts can be grouped by the stage of the life cycle under which they occur: impacts relating to manufacturing, transport and disposal of the printer or CNC mill, impacts associated with electricity use during part creation and/or idling, impacts from materials use in the final parts produced, impacts arising from waste materials (be it model material or support material), and finally, impacts of the mill's fluid use.

Figure 5.6. **Environmental impacts of one CNC mill versus two 3D printers, all running at maximal temporal utilisation, making solid parts**



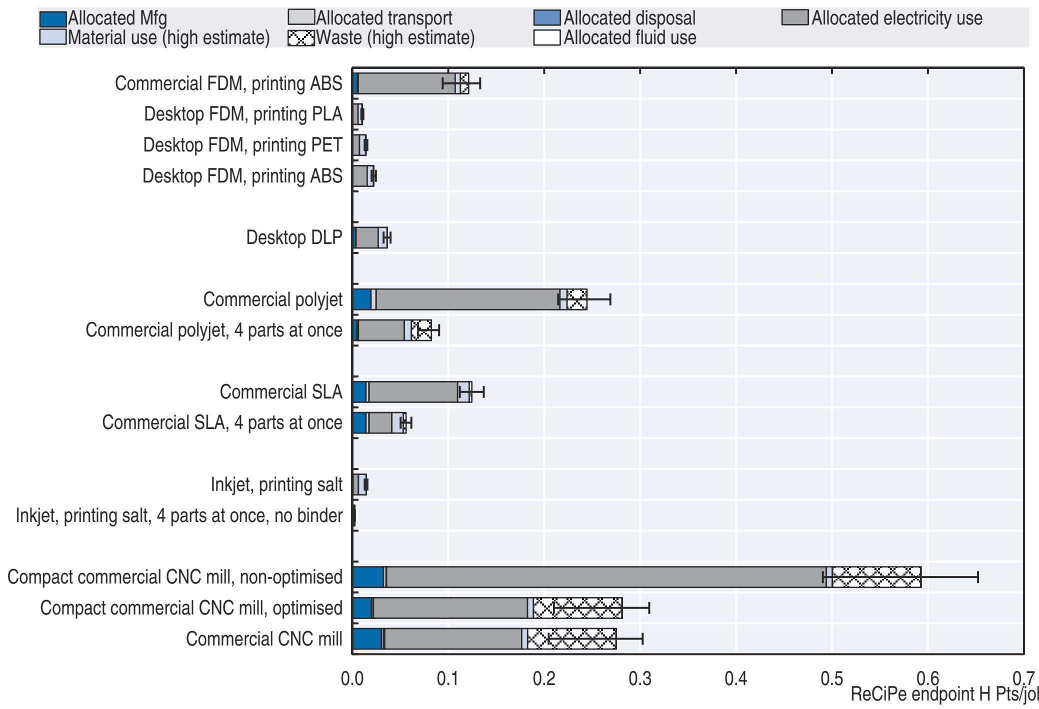
Note: The black horizontal line at the end of each bar represents the error range.
Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*.

StatLink http://dx.doi.org/10.1787/888933473851

Figure 5.6 shows one CNC mill making solid-block plastic parts, compared to two different scenarios of a commercial FDM printer and three different scenarios of a PolyJet printer making the same solid-block parts. The CNC mill performs better than two scenarios of the PolyJet, and is within error bars of the commercial FDM. However, Figure 5.7 shows two CNC mills making hollow-shell parts, compared to eight 3D printers in 11 scenarios making the same hollow-shell parts. There, the CNC mills always have higher environmental impacts than all the 3D printers (though sometimes within error bars). Figure 5.7 more fairly represents most plastic consumer product parts, such as a telephone case, but a few product categories are solid plastic.

Figures 5.6 and 5.7 also show the wide variation among printers and scenarios. Some printers have far lower impacts per part than others, and the impacts change based on part type and machine utilisation. Policy makers should keep in mind that this is not a monolithic field. For example, the inkjet printing in salt has the lowest impact of all machines shown, reducing impact by over 90% compared to machining, but PolyJet printing sometimes scores worse than machining. Unfortunately, today some of the lowest impact machines, such as the desktop FDM, have the poorest print quality. Conversely, some of the highest-impact machines, such as PolyJet, have some of the best print quality.

Figure 5.7. **Environmental impacts of two CNC mills versus eight 3D printers, all running at maximal temporal utilisation, making hollow parts**



Note: The black horizontal line at the end of each bar represents the error range.

Source: Faludi, J. et al. (2015a), "Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment", *http://dx.doi.org/10.1108/RPJ-07-2013-0067*; Faludi, J et al. (2015b), "Does material choice drive sustainability of 3D printing?", *https://waset.org/Publication/does-material-choice-drive-sustainability-of-3d-printing-/10000327*.

StatLink http://dx.doi.org/10.1787/888933473864

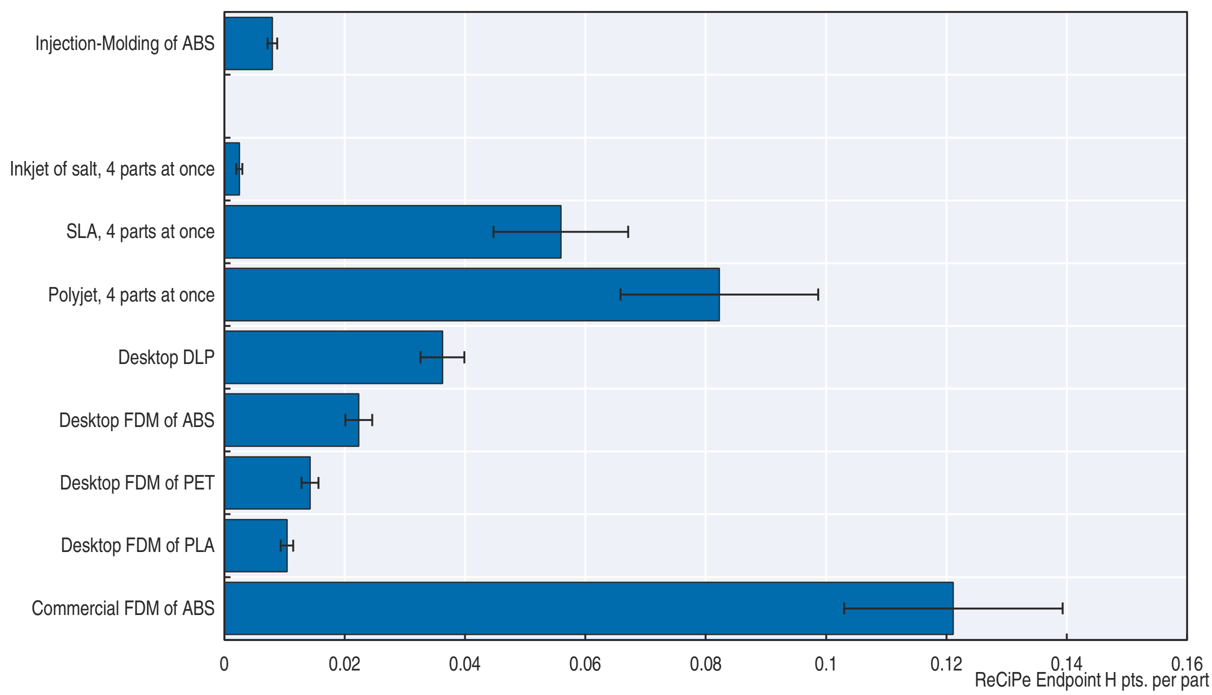
In both graphs above, the environmental impacts of 3D printing are largely dominated by energy use during printing. For CNC mills, however, material waste is a significant, sometimes dominant, impact. Thus, switching from machining to printing will reduce material waste impacts, but may not reduce energy impacts. It is possible to increase energy impacts beyond the savings in waste impacts. The embodied impacts of producing the machines are insignificant for any printer or CNC mill when producing parts 24 hours per day, seven days per week, though this is no longer true at low utilisation (not shown in these graphs, but in the cited studies) (Faludi et al., 2014; Faludi et al., 2015b).

Other studies have confirmed a wide variation in energy use per part across different printer types and scenarios, including metal printers such as SLS, DMLS, SLM, CLAD; they also confirm that while 3D printing is often lower energy use per part than machining, some circumstances can cause it to be higher (Yoon et al., 2014; Serres et al., 2011; Morrow et al., 2007). High utilisation can also be extremely important for metal printers. Baumers showed that energy use during laser sintering is "job-dependent, time-dependent, geometry-dependent, and Z-height-dependent" (Baumers et al., 2011a) and that high utilisation reduced energy use per part from as little as a few per cent to as much as 98%, depending on the printer type (Baumers et al., 2011b).

3D Printing versus injection-moulding

Injection-moulding is the most common manufacturing method for plastic consumer product parts. The potential for major changes in environmental impact due to replacement by 3D printing could be significant if they happen on a large scale. For example, Figure 5.8 compares the environmental impact of injection-moulding (based on standard LCA data) to that of different 3D printing technologies (based on empirically measured data from Figures 5.6 and 5.7). Rather than dividing each bar into components of e.g. energy or waste, the graph displays one bar per printer and material type.

Figure 5.8. **Environmental impacts per part of injection-moulding versus several kinds of 3D printing at maximal utilisation**



Note: The black horizontal line at the end of each bar represents the error range.
Source: Authors' calculations.

StatLink http://dx.doi.org/10.1787/888933473878

In Figure 5.8 injection-moulding has lower environmental impacts per part than any 3D printing technology in widespread use today, for large print runs. Injection-moulding's fixed impacts, such as creating tooling and set-up time, are amortised across hundreds of thousands or millions of parts produced. Desktop FDM of PLA plastic causes 20% higher impacts than injection-moulding of ABS (although this is nearly within uncertainty margins), while one commercial FDM of ABS causes roughly ten times higher impacts. This does not apply to small production runs, such as hundreds of parts (Telenko and Seepersad, 2012); both economics and environmental impacts can favour 3D printing for small-scale production. These results do not include increased exposure to toxic particulates of personnel in offices or homes with 3D printers rather than industrial environments with safety measures (Stephens et al., 2013). Some researchers have shown that 3D printers powered by solar panels or printing in PLA can have lower impacts than injection-moulding

ABS (Kreiger and Pearce, 2013), but these arguments may not capture the full picture, because injection-moulding machines can be solar-powered or use PLA plastic with equivalent ease to 3D printers. If they were operated in such a way their impacts would be similarly lower.

The only technology in the graph above that scores better than injection-moulding is 3D inkjet printing in salt. This is a low-energy process using chemistry instead of melting to bind material together. This is an experimental material that currently does not match the resolution or surface finish of injection-moulded parts. However, its score shows an almost 70% reduction in impact per part. A compromise between this method and more conventional technologies could be an environmental improvement over injection-moulding.

The inkjet printing method is well-established and commercially successful, warranting further research and development to improve print quality without compromising environmental impacts. This technology presents low operating costs, because rather than buying an expensive proprietary powder and liquid from the printer manufacturer, the powder and liquid are an open-source recipe of common inexpensive materials such as fine-ground salt, maltodextrin, isopropyl alcohol, and water. While at an individual level expertise is required to prepare the ingredients, at scale such materials would be inexpensive and comparable to the cost of plastic granulate for injection-moulding.

Impacts on greenhouse gas emissions

Widespread replacement of injection-moulding with 3D printing could notably increase or decrease greenhouse gas emissions on a global scale. These changes would probably be gradual. In terms of global resource depletion, 3D printing is unlikely to make significant changes even in the long term.

For greenhouse gas emissions, all industry worldwide accounts for roughly 29% of emissions, with other major sources being buildings, transportation, and agriculture (Ecofys, 2013). Statistics on what percentage derives from injection-moulded plastics are difficult to find, but comparing LCA data from two sources (Hendrickson et al., 1998; Bjorn and MacLean, 2003) suggests plastic injection-moulded products may account for 0.5% to 2% of global greenhouse gas emissions. Shrinking all of these emissions by 70% would be a noticeable improvement, and increasing them ten-fold would pose a severe problem. However, even with these large differences in technology impacts, the global-scale consequences of shifting from injection-moulding to 3D printing will probably occur slowly. As previously described, 3D printing's cost curve implies that printing will only replace injection-moulding for small-run production in the next several years, taking over moderate production volumes as costs fall and quality improves, with great difficulty (and therefore many years) replacing high-volume low-cost production.

As regards resource depletion, worldwide plastic use for injection-moulding totals approximately 39 million tonnes per year (Thiriez and Gutowski, 2006). The percentage of total world material extraction this represents is uncertain, but for the United States, less than 5% by mass of total material extraction is petroleum products (Matos, 2012), and of that less than 3% is used to make plastics (US EIA, 2014); therefore, all plastic use (including injection-moulded plastic) comprises perhaps 0.1% of total material consumption by mass. As the difference between 3D printing material use and injection-moulding material use are within a factor of ten of each other, switching to printing is unlikely to make significant differences on the global scale.

Potential for environmental sustainability

Widespread 3D printing can potentially help the environment in many ways, though probably not in the ways most propounded today. Two popular fallacies are that 3D printing could virtually eliminate the negative externalities associated with transportation and waste; and 3D printing is also likely to reduce plastic recycling rates. Green 3D printing realities lie more in aligning economic incentives with environmental impacts, enabling lean production, expanding material alternatives, and increasing energy efficiency in the use-phase of some products. It can be a step closer to industry building as nature does by using compostable biopolymers to solve waste concerns. It also has the potential to benefit society by providing more people with access to the means of production.

Green 3D printing misconceptions

One popular fallacy is that 3D printing will drastically reduce externalities related to transportation of goods, because manufacturing will shift away from centralised factories to regional factories or even consumers' own homes. This is not quite true, and even if it were true, this effect would not have a large aggregate environmental impact. It is not quite true because 3D printers today can only print parts, not whole products, unless those products are extremely simple. Most products must still be assembled in factories, out of a combination of printable and non-printable parts, and shipped to customers. Even for printing 100% on site, feedstock materials for 3D printers still need to be transported, even for multi-material printers that can print whole products rather than just components. 3D printing could indeed reduce transport for businesses selling many different products all made from one material. For example, an automotive repair shop might stock 500 different components made from the same steel alloy, and could radically reduce their transportation impacts by only shipping and warehousing that steel alloy powder to print different parts on demand. Furniture shops might indeed reduce their costs linked to shipping bulky items that are mostly air, instead shipping compact spools of wood-plastic composite.

Even when transport reductions are large, their impacts are usually small compared to manufacturing impacts. Multiple studies (Hanssen, 1998; Hunter, 2013; Apple, 2014) have shown that for most consumer products (be they electronics, furniture, car parts, housewares, clothing, etc.), transportation generates a small percentage of the product's total cradle-to-grave environmental impacts, with occasional exceptions. Even if 3D printing did entirely eliminate transportation related externalities via molecular-scale local material sourcing (Stephenson, 2003), it would barely matter for most products. Aside from a few exceptions, the environmental impacts of manufacturing and energy use during product life are far more important, making these areas a priority for policy makers.

Another persistent fallacy is that 3D printing will automatically be more sustainable because it "eliminates waste" whether of final products or input materials. Some types of 3D printers can indeed produce parts with almost no waste. For example, when FDM machines print parts with no support material, waste can be a fraction of a per cent of part mass. SLA and inkjet machines can also be run with negligible waste. However, long part geometries with steep overhangs can require more support material than actual model material (i.e. greater than 50% waste). Most 3D prints fall in between these extremes, requiring a small to moderate amount of support material.

However, support material is not the only source of waste; other sources vary by printer type. A PolyJet printer wastes 43% of all its liquid polymer in both model and support material, so a print requiring as much support material as model material would actually cause 65% waste (nearly twice as much waste as the final part). Moreover, liquid PolyJet model material is more toxic per kilogramme than standard injection-moulding plastics like PET or ABS. For plastic sintering, Telenko and Seepersad calculated that "up to 44 per cent of the material that enters the SLS process might be wasted" (Telenko and Seepersad, 2012). For metal sintering, Kellens reported unused powder losses of 20% of part mass (Kellens et al., 2011), with the rest reused. Even some FDM printers generate excessive waste through poor design choices. For example, the 3D Systems Cube desktop FDM printer uses proprietary cartridges of printing filament. The cartridges are produced from two types of plastic over-moulded, which renders the cartridge unrecyclable (Grenchus et al., 1998). Since the mass of plastic comprising the cartridge is greater than the mass of printing filament within, this causes over 50% waste even if the printer is operated at perfect efficiency. Such situations are rare, and some manufacturing methods produce more waste. Machining a hollow part from a block of plastic typically creates large amounts of waste, often over 80%, therefore 3D printing can be generally assumed to cause less waste compared to such methods. However, mass-manufactured plastics are typically moulded, not machined.

Injection-moulding is an efficient process: waste or scrap rates are reported ranging from 10% (Thiriez and Gutowski, 2006) to 5% (Olmsted and Davis, 2001) to 1% (Frischknecht et al., 2005). Thus, while some 3D printing wastes less than injection-moulding, some wastes significantly more. Even if waste were always reduced, it would not always be important. As shown in Figures 5.6 and 5.7, energy use is by far the largest environmental impact of 3D printing. Increasing energy use per part produced can overwhelm material savings to increase total environmental impacts. When printers do reduce total environmental impacts, they do so by combining low waste with low-impact material choice and low-energy processing.

Aligning economic incentives

The clearest way in which 3D printing is likely to improve manufacturing sustainability is by aligning economic incentives with environmental impacts. In traditional production, both prototyping and mass manufacturing, complexity of design is more expensive than materials or energy. This has led to material and energy inefficiency when producing parts. In 3D printing, by contrast, materials are expensive, but design complexity is free. In the coming years this should lead to parts made complex to save material. Software already exists to optimise part geometry for minimum material mass while fulfilling specified physical requirements such as stresses of given directions and magnitudes (Within, 2011). Energy is less expensive, but for printer operators, energy use is proportional to print time, effectively causing energy to be expensive and incentivising printer operators to save energy through the complexity of print setups. However, there is no such incentive for printer manufacturers to design energy-efficient printers. At the time of going to print, there was not a strong correlation between power use and print time within a given printer type (Yoon et al., 2014). Thus, the incentive to save energy is weaker than the incentive to save material mass.

Enabling lean production

Lean production can benefit from 3D printing. Another aspect of economic incentives aligning with environmental impacts is that the cost to print the millionth part is the same as the cost to print the first part. This is unlike injection-moulding and other mass-manufacturing methods, where the millionth part is far less expensive than the first part, even though it consumes similar amounts of material and energy. Since 2D digital printing has allowed such on-demand production for two decades, product packaging can be made to order along with 3D printed products, avoiding waste there as well. This is the true way in which 3D printing can "eliminate waste" – by eliminating overproduction. Warehousing extra inventory incurs financial costs, but for mass manufacturing these costs are usually much less than machine set-up and tooling costs, so parts are mass-manufactured in advance and held in warehouses for predicted levels of demand that may or may not ever come. By contrast, for 3D printing, there are virtually no set-up or tooling costs, and thus warehousing costs become significant. This enables leaner manufacturing and reduces the economic incentive to overproduce. The extent of this benefit varies by market sector, but unsold goods may average 4-5% of most sector revenues (Bot and Neumann, 2003). This does not even include reduction of work-in-progress parts within a factory, which can be significant.

However, expectations of avoiding overproduction from eliminating economies of scale should be tempered by expectations of adding overproduction from the ease of printing, as described earlier. This will include both excess parts printed and many failed prints, which is a form of waste. Because 3D printing is such a rapidly expanding field, operators often push the limits of printers or operator expertise, which results in a higher failure rate than status-quo manufacturing methods. Today, failure rates can be high for some applications (Baumers, Holweg and Rowley, 2016). However, in the long run this is not likely to be a significant problem, because industry is already working diligently to reduce failed prints for customer satisfaction purposes. Coming years will see improvements with no policy intervention needed.

Encouraging the use of green materials

3D printing will probably expand the number of sustainable materials available to manufacturers, and/or the range of physical properties possible with sustainable materials. Some of this will be due to 3D printing's technology, some due to its economics. One frontier will be the availability of "tunable" materials, capable of changing physical properties according to printing parameters.

Today's ubiquity of plastic is largely due to the fact that it can be shaped into nearly any form; 3D printing could give this same advantage to many other materials. Printed materials today include not only plastics and metals, but ceramics, food, bonded powders of salt, sawdust, or starch, even living human tissue. Even within more traditional plastic printers, specific processing details can encourage different materials. For example, the thermo-physical properties of PLA bioplastic are more favourable than ABS plastic for FDM printing, thus FDM has coincidentally encouraged PLA use. Alternative metals and ceramics can also be enabled by 3D printing. The jet engine nozzle cited in the introduction was 3D printed in a cobalt chromium ceramic alloy, an exotic material which was not previously feasible for such a part because it was not suited to prior manufacturing methods (Beyer, 2014). When searching for new materials, the greatest environmental promise will come from the production of objects from abundant, renewable, non-toxic ingredients using low-energy processing methods.

Today, unfortunately most 3D printing materials are not environmental improvements over the status quo, and some are worse. For example, powdered metals require more energy to produce than the ingots used by other manufacturing methods (Granta Design, 2009). As mentioned earlier, the UV-cured resins used for SLA, DLP, and PolyJet are somewhat toxic in their liquid form (3D Systems, 2012), but usually considered non-toxic once solidified. ABS plastic has been rated as fairly hazardous to produce and is rarely recycled municipally (Rossi and Blake, 2014), and 3D printing in a home or office can expose bystanders to inhaled particulates (Stephens et al., 2013), but it is common in injection-moulding as well. One existing success story is PLA bioplastic: considered expensive and problematic by mass manufacturers, it has become one of the most common materials for hobbyist FDM printing because its physical properties are amenable to the process, as described below.

Economic differences may enable green materials in 3D printing as much as technological differences. Alternative materials such as PLA are frequently more expensive per unit than status-quo materials, due to smaller-scale production, but labour costs often far outweigh material costs. 3D printers can greatly reduce labour costs, thus enabling some companies to use higher-cost materials while still lowering overall manufacturing costs.

Another economic incentive for green materials in 3D printing is the removal of economies of scale. Complexity is expensive in traditional manufacturing, but material mass is not, thus encouraging a small palette of consistent materials used en masse. 3D printing lowers the cost of switching from one material to another, because no tooling is required. One part can be printed in thermoplastic on one printer while the next part is printed in sawdust on another printer, or perhaps even the same printer configured differently. Many 3D printing companies even unintentionally incentivise users to experiment with alternative materials, by using the "razor and blade" business model. They sell printers at relatively low margins to make most of their profits from high-margin proprietary materials used for printing. This, along with the industry's connections with the hacker culture and "maker" culture, encourages people to experiment with their own materials.

Green materials in 3D printing are limited by technical availability, commercial availability, substitutability, print quality, and acceptance in industry. Technical availability includes the compatibility of new materials with the various 3D printing methods. For example, wood cannot be used for SLA processes because it does not bond on exposure to UV light. Commercial availability includes the production scale and cost of these materials: sawdust and salt have been proven to work technically, but lack commercial distributors. Substitutability consists in matching a material's properties to its use. For example, even though PLA can be printed by the same printer that prints ABS, many professionals disdain PLA because ABS has a higher melting point and other characteristics they desire. Thus PLA has largely been limited to hobbyist markets. Print quality includes many factors, such as the colour of recycled plastics being contaminated from mixing two different colours, or inkjet printing of salt not providing as smooth a surface finish as PolyJet printing. Even if all of these challenges can be overcome, acceptance in industry can lag by years due to sunk costs, economies of scale, or conservatism. While experiments in greener materials and methods are tiny fractions of the market now, they could be encouraged by policy or development funding. The industry's current explosive growth rate provides an opportunity to dethrone entrenched materials and printing methods.

Tunable materials may open wide possibilities for sustainable materials by allowing a small number of ingredients to fulfil the roles of many. This can help avoid the need for mining exotic materials, simplify toxicity screening, and perhaps improve recycling or composting. Tunability can include both true tuning of material properties, or uniform material properties in a structure that is geometrically tuned to provide different properties in different regions. For a geometry example, today many products use a "living hinge," an area where a part is thinner than elsewhere, allowing the part to bend at that location even though the material is the same there as in thicker locations (Mraz, 2004). For a material example, the castable cellulose pulp material Zelfo allows "values for density from 0.5 g/cm^3 (gramme per square centimetre) to 1.5 g/cm^3, for tensile modulus from 1 500 MPa (megapascal) to 6 550 MPa, and for tensile strength from 7 to 55 MPa" (Svoboda et al., 2000). It is also recyclable and biodegradable.

An example of using sustainable and tunable materials in 3D printing is the Massachusetts Institute of Technology (MIT) method, water-based digital fabrication (WBDF), originally called "water-based robotic fabrication". It polymerises compostable polysaccharides such as starch or cellulose with water in a robot arm extruder (Mogas-Soldevila, Duro-Royo and Oxman, 2014); these are renewable raw materials. Its extrusion process is chemistry-based, so its printing process can use much less energy than melting plastic. Its chemistry is water-based, so it involves far fewer toxins than standard plastics (all three of the main ingredients of ABS are toxic, even though ABS itself is generally considered harmless to the end user; similarly, the UV-activated photopolymers used by SLA, PolyJet, and DLP are considered toxic until solidified). WBDF is not only compostable, but dissolves in water within minutes (however, this property would probably be changed to normal compostability for commercial goods, as it would be inconvenient for many applications). Finally, its material properties can be "tuned", adjusting strength and rigidity in different areas according to the printing process. This tuning allows one material to replace multiple different materials. Funding for research and development is needed to improve print quality and material properties for such methods, so they can become viable commercially. If successful in 3D printing, such technologies might also expand into injection-moulding and other plastics manufacturing.

Composting and recycling possibilities

Some experimenters hope 3D printing will encourage recycling, but market forces are largely driving the opposite; compostability is another treatment option, for non-metallic parts, but this also has some drawbacks. Several printing technologies require non-recyclable polymers, and as the future brings more multi-material printers, these printers will make even recyclable plastics unrecyclable by making them inseparable from each other. However, recycling may be enabled by 3D printers reducing part count in products, reducing material variety or using expensive materials. Some 3D printing can and does use recycled material. Composting 3D printed products could in theory increase in the future, but there are also a number of risks and it is not clear whether this treatment option would be superior to incineration in state of the art facilities.

Recycling for 3D printing suffers from the same problem all recycling does: sorting. Proponents argue that 3D printing can increase recycling rates because recycling to local 3D printing, rather than centralised municipal-scale systems, avoids transportation costs. However, this will be insufficient motivation because transportation costs are low (Bhasin and Bodla, 2014). The primary barriers to recycling are not transportation but sorting and quality control to ensure usable material. Plastics come in thousands of different polymers, grades, colours, and mixes of additives for flexibility, strength, UV-resistance, or other properties. Metal types and grades also vary widely. Recyclers today rely on hundreds of thousands or even millions of dollars' worth of sorting infrastructure, including multi-stage sorting tools using water baths, magnets, electrostatic charge, and other systems, spectrometers to identify plastics and metals, conveyors and storage of materials, etc. Such infrastructure has inherent economies of scale impractical for small local operations, and only materials with sufficient economic value can justify the cost of the separation process.

To overcome the sorting problem, desktop recycling and 3D printing could use a predictable source of plastic, such as PET bottles, but the best candidates for such recycling are also the most ubiquitously recycled in municipal waste streams already. Predictable waste streams from Extended Producer Responsibility (EPR) programmes are generally highly mixed materials; they will be equally hard to sort for 3D printing as for other manufacturing methods today. Today, most companies participating in EPR programmes, such as Waste Electrical and Electronic Equipment recycling (WEEE), rely on third parties to perform their material recycling, because producing high-quality raw materials from recovered products is a specialised task with economies of scale (Mayers, 2007). 3D printing does not change these economics, except perhaps to allow more expensive materials through reduced labour costs.

Home desktop recycling and printing could be a closed-loop system of manufacturing single-material objects and then grinding them into raw material when the user tires of them, but this would require people to tire of old objects at the same rate at which they print new ones, and to make all objects in the same single type and colour of plastic. Alternatively, it would require users to hold their own personal storehouse of different plastic spools. It is unrealistic to expect such scenarios on a large scale. Such capability has always existed in the clothing sector, and while home recycling of clothes into fabric for new homemade clothes was widespread 100 years ago, it is at best a hobbyist market today. Purchasing new clothing is easier than sewing clothes at home, and clothing is inexpensive enough that the money saved by recycling fabric fails to equal the value of time spent designing and creating clothing. Just as with home sewing, some hobbyists will 3D print their own parts at home for the joy of making them, but it will be a small niche.

Besides these barriers to recycling, many 3D printing materials are difficult or impossible to recycle. The printing processes offering the highest quality, and thus most often entering commercial manufacturing, are generally the least capable of using recycled material. All photopolymer printers (such as SLA, PolyJet, inkjet, and DLP) use non-reversible chemical processes, thus the materials are inherently non-recyclable. Metal printers raise difficulties for recycling due to tight quality tolerances for input materials, though it is not impossible. Unused metal powders in SLM, DMLS, and other processes degrade in quality each time they are reused (Slotwinski et al., 2014), and such powder is currently not produced from recycled metal because it requires extremely high purity (Yadav, Dirstine and Pfaffenbach, 2004). FDM printers are the only widespread printer type that use recycled materials with ease.

Recycling examples and promise

Multiple researchers, hobbyists, and start-ups have 3D printed with recycled materials. Desktop devices such as Filabot (Biggs, 2013) and Extrusionbot (Sevenson, 2014) grind waste plastic into granules and extrude it into filament for FDM printers. Such processes may even be lower energy than municipal recycling (Kreiger et al., 2013). One group measured a desktop recycler's energy use to be roughly 38 megajoules per kilogramme (MJ/kg) of recycled ABS plastic (Baechler DeVuono and Pearce, 2013), which is at the low end of commercial recyclers' energy use (38 MJ/kg to 43 MJ/kg) (Possamai, 2007). As described above, 3D printing generally causes much more energy use per part than injection-moulding, so desktop recycling for 3D printing is unlikely to be a net environmental benefit even if the recycling phase is low-energy, but future technologies could change this. On the industrial scale, two architectural start-ups print with recycled material – as mentioned before. KamerMaker uses recycled plastic; it also eliminates other building materials such as sheetrock and waterproofing membrane. WinSun uses recycled glass and other concrete aggregate in cement, and metal powder printers (e.g. SLM, SLS and DMLS) can reuse unmelted powder for non-aerospace applications.

Printers that bind particles with an adhesive (such as WinSun's) can be quite tolerant of diverse materials, ameliorating the sorting problem. The disadvantage of such methods is that they down-cycle material into a lower-quality mixture which cannot be expected to have high-performance physical properties. However, this has been acceptable for decades in many industry sectors, such as recycled plastic decking or other architectural materials. There is not yet enough data to predict whether 3D printing is more economical or higher quality than existing forms of mixed plastic recycling.

3D printing may theoretically enable increased recycling by reducing the number of parts in a product and reducing the number of different materials, through complex geometries and tunable materials. This is speculation, but is based on well-accepted general principles. First, a core principle of designing products for recyclability is to reduce the number of parts used, to save labour cost of disassembly (Possamai, 2007). 3D printing can create highly complex parts, allowing it to replace many simple parts with a single complex part. Second, another core recyclability principle is to reduce the number of different materials in order to reduce sorting (Dahmus and Gutowski, 2007; Possamai, 2007). Advanced 3D printing can include geometric variations that can somewhat vary the flexibility, strength, and other properties of a part from one location to another, despite it being the same material throughout. Some printing processes, such as WBDF, even allow tunable material properties depending on the printing process. Thus multiple materials could in theory be replaced by single materials in some cases.

Composting versus recycling

In the long term, composting could be another route to a circular economy, as it can accommodate mixed materials that are inseparable. Recycling of 3D printed parts appears unlikely to become more widespread in the future because, as described before, more printers will print multiple materials simultaneously as technology advances. This is useful economically, but destroys recyclability. Compostable materials allow biological recycling regardless of different aesthetic, physical, and electrical properties. This need not limit the material palette available to designers and engineers, as nature demonstrates a vast array of physical and chemical properties in the materials comprising plants and animals, all of which are compostable. On the other hand, there are also a number of limitations and risks to compostable materials, which may result in making incineration a more attractive treatment option. For example, biodegradable plastics, if mixed together with conventional plastic, can disrupt established and well-functioning plastic recycling, as well as encourage littering (because consumers assume they will degrade quickly).

Many 3D-printable materials can already be composted in some municipal-scale facilities: PLA bioplastic, composites of wood fibre and bioplastic, starch, even biodegradable conductive composites that could be used as wiring (Van Wijk and Van Wijk, 2015; McDonald, 2016; Ray, 2013; Kilner, 1993). 3D printed food is obviously compostable, though not structural enough for most product applications. As mentioned above, MIT's WBDF material is both structural and dissolves in water in minutes. The University of Wageningen and designer

Eric Klarenbeek collaborated to 3D print furniture out of oyster mushroom mycelium with a PLA shell (Fairs, 2013). Ecovative has sold a similar mycelium-based material for packaging since 2007, which biodegrades in 30 days by ASTM D6400 standards (Ecovative, N.D.). While no commercially available structural 3D printing materials compost so easily, focused research and development could create them.

Some compostable bioplastics, such as PLA, are already in widespread use and are already more sustainable to produce than petroleum-based plastics, both in terms of embodied energy and toxins. PLA has much less embodied energy than most plastics (~27 MJ/kg in 2007) (Vink, 2007), with Dow aiming to reduce it to 7 MJ/kg (Vink et al., 2003), as opposed to the ~40 MJ/kg for recycled ABS listed earlier, or ~100 MJ/kg for virgin ABS) (Granta Design, 2009). PLA has also been shown to emit fewer toxic fumes than ABS while FDM printing (Stephens et al., 2013). However, to be composted, PLA needs municipal-scale facilities which reach high temperatures; these are not common globally today, and thus PLA is not yet compostable in most cities today. In the long term, such compost facilities are likely to become as common, or even more common, than recycling facilities because their indifference to sorting makes them less expensive per unit of waste diverted (roughly USD 50/tonne) (Renkow and Rubin, 1998) rather than USD 75/tonne for recycling) (Bohm et al., 2010). Even today, more cities in the United States have municipal compost services than services that recycle ABS plastic kerb-side, as municipal recycling optimises for the highest-volume plastics such as PET.

Local-scale plastic recycling for 3D printing may perhaps be more successful in developing countries than in developed countries, due to limited infrastructure and differing costs of labour versus materials. Developing countries often lack municipal recycling systems, leaving the economic niche unfilled. Also, materials are more expensive compared to labour than in developed countries, so there is more incentive to recover and sort materials. Indeed, whole neighbourhoods make their living hand-sorting open dumps in some places today (Gill, 2009). Thus composting may not have the same cost advantage over recycling as in developed countries. Finally, low-income consumers often have lower quality requirements for goods if they are inexpensive enough, so it is easier to meet needs with the FDM technology that enables desktop plastic recycling into 3D printing. However, these trends may not be strong enough to favour recycling over composting even in developing countries.

Legacy product repair

The most important way that 3D printing could encourage material reuse is not through recycling, but through repair. Many legacy products are discarded because a single component breaks and there is no longer a supply chain to replace it. These components are often single-material plastic or metal parts, which 3D printing is already well suited to replace. The primary barrier to ubiquitous printing of replacement parts is intellectual property (IP): both the accessibility to end users of 3D models for printing, and the legal right to print models that are available. Some websites such as Thingiverse are already open repositories for free downloads of 3D models to print replacement parts for dishwashers, refrigerators, bicycle accessories, and more. The 3D models are legally ambiguous, arguably not violating IP laws because they are reverse-engineered, but challenges came as early as 2011 (Coetzee, 2011). Businesses may learn to monetise such sites for IP rights, just as Napster's illegal music sharing evolved into paid subscription services such as Pandora or Spotify.

Policy could easily encourage 3D printing for repair, as several companies are already in a position to provide this service, including billing and royalty payments. It is merely a question of legal rights and contracts. Thingiverse could charge a fee for users downloading the file to print at home, and send royalties to the original product manufacturer. Companies such as Shapeways, which provide a web-based interface to mail-order 3D printed parts, do not even require the end user to have a printer in their home. It is unclear whether such markets will be large enough to avoid significant amounts of discarded products, as repairs require not only parts, but labour – often skilled labour. Still, it is a worthwhile experiment, as it requires no new technology or investment, only legal clarity for existing entities to engage in such practices.

Saving use-phase energy

It may be that 3D printing's most important contribution to sustainability will come not from manufacturing impacts, but from saving energy in the use-phase of products' lives. This is speculation, as such savings may only accrue in aerospace, automotive, or other industries where use-phase energy impacts dominate the entire product life cycle, and where such energy use depends heavily on the mass of material in the product.

The higher complexity of manufacturing enabled by 3D printing can allow for lower-mass parts, which can save fuel in transportation products. For example, General Electric's 3D printed parts for the jet engine described earlier reduce weight, improving fuel efficiency by 15% (Beyer, 2014). Even if the manufacturing of the parts themselves has a greater environmental impact than previous methods such as machining or welding, these large use-phase energy savings can easily overcome increases in the manufacturing phase. Such weight savings would also reduce lifetime impacts of trucking and cars, but would not reduce impacts for other product categories, such as consumer electronics or buildings. However, there are other potential routes for use-phase energy reduction.

The higher complexity enabled by 3D printing can also improve the efficiency of fluid flow and heat transfer for some systems. For example, the SpaceX SuperDraco engine achieves more efficient fuel combustion by having its "regenerative cooling" fluid channels within the walls of the combustion chamber, rather than welded to the outside, as was required for previous manufacturing methods (Post, 2014; Dankhoff, 1963). Use-phase energy efficiency may even be enabled for other sectors, such as architecture. Roughly 90% of an average building's lifetime environmental impact is from its energy use (Faludi, Lepech and Loisos, 2012), and air leaks through gaps in construction are a major culprit (Liaukus, 2014), especially at corners and joints. Though it has not yet been demonstrated, in theory printing all of a building's walls as one continuous piece could help avoid such leaks.

Social benefits and the need for green 3D printing to scale

One of 3D printing's sustainability impacts may be social, not environmental. Economic empowerment is a significant part of sustainability. 3D printing empowers small businesses and others with limited access to capital by radically reducing economic barriers to entry into manufacturing. Anyone with a moderate-quality computer and CAD software can create 3D models for parts, then have the parts printed in high quality without the expense of tooling a mass-manufacturing line. Printing is often even less expensive than traditional forms of prototyping, such as machining (Beyer, 2014). Such empowerment of small businesses could help to reduce income inequality in developed countries, and help developing countries to industrialise.

The widespread replacement of injection-moulding for mass manufacturing would probably be an environmental problem with current 3D printers, but the replacement of machining for hollow-shell parts would probably bring about environmental benefits if two conditions are met: greatly reducing energy use per part printed, and reducing the embodied impacts of printing materials. These goals can be achieved through many strategies, e.g. maximising utilisation, eliminating toxic chemistry and reducing material waste. Table 5.2 lists some specific strategies for these goals by printer type.

Table 5.2. **Strategies for more sustainable 3D printing by printer type**

Printer type	Strategies to minimise material impacts	Strategies to minimise printing energy	Strategies to minimise idle energy
Photopolymer	Eliminate toxic chemistry Develop compostable biopolymers Minimise support material Tune material properties through printing process	Print more parts simultaneously Minimise print time Design for efficiency	Share printers to minimise idle time Low-power idle mode
Inkjet	Expand/improve compostable biopolymers Tune material properties through printing process		
Metal laser sinter/melting	Produce powders from recycled metals Improve reusability of metal powder Minimise support material Tune material properties through printing process		
Extrusion	Expand/improve compostable biopolymers Hollow parts and minimal support material Tune material properties through printing process	Chemically solidify materials rather than melting thermoplastics Hollow parts and minimal support material Minimise print time Design for efficiency	

Source: Authors' analysis.

Table 5.2 shows that because 3D printers vary so much in their design and operation, few sustainability strategies apply to all printer types equally. Reducing energy use per part made is the top priority for sustainability in 3D printing, but it can require different strategies for different printer types. One energy-reduction strategy common to all printers is minimising idle energy. Idle energy can be reduced both by having printers automatically enter low-power sleep states when they finish printing, and/or by sharing fewer printers among more users. Also common to all printers is simply designing them for energy efficiency. The relative low cost of electricity today means that many printers lack simple energy-saving features such as insulation around heated components. The final energy-reduction strategy common to all printers is reducing print time. Many 3D printers use the majority of their electricity to simply keep support systems running, the additional power for printing is often small (Faludi et al., 2015b). Thus more parts could probably be printed with less energy per part if print times were reduced, even if more print heads, lasers, etc. were required.

A material impact reduction strategy common to all printers is tuning material properties, as (in theory) all types of 3D printers should enable this in the future, albeit by different means. Much of the table lists technology-specific strategies. For extrusion printers, energy savings correlate to material savings, so hollowing parts and minimising support material save both material and energy. Extrusion printers can also significantly reduce energy use by chemical solidification rather than melting plastics. Photopolymer, inkjet, and laser sintering machines can reduce energy per part by maximising the number of parts per print, because they can print several parts using almost the same energy as printing a single part, regardless of material use. For material impact reduction, most printers can minimise support material, but inkjet printers do not generally need support material, so it is not a priority for them. Reducing toxicity is a higher priority for photopolymer systems than others because non-toxic materials already exist for other printer types. Compostable biopolymers are one option for photopolymer printers because photopolymers are inherently unrecyclable, and incineration with energy recovery is another. Compostability is already possible for some inkjet and extrusion printer materials, though today options are limited. Development is required to expand commercially available choices and improve physical performance of such materials, if they can be produced at competitive cost and ways can be found to deal with their potential to disrupt existing recycling systems. Metals are not generally compostable, so metal sinterers should improve material recyclability, both in terms of powder reuse and producing powder from recycled metal.

An example of 3D printing's potential is the Solar Sinter by Markus Kayser. It functions similarly to SLS, but instead of sintering plastic or metal powder with a laser, it uses a large Fresnel lens to sinter sand into glass with the heat of the sun. Its motors and electronics are powered by solar panels and the sand used is non-toxic, abundant, local, and requires no energy-intensive processing before use in the printer. The Solar Sinter was merely a demonstration project, probably not practical for industry, but it can serve as a beacon for what is possible. Even without such extreme measures, some commercial 3D printers today are capable of printing non-toxic, abundant, renewable, compostable materials with low-energy printing processes – close to the ideal for sustainable manufacturing. For example, inkjet printing in salt or sawdust, or MIT's WBDF.

Policy priorities and mechanisms to accomplish environmental policy goals

Policy mechanisms

This section outlines the priority areas to improve the environmental implications of 3D printing. Table 5.3 highlights some of these areas. The table lists high, medium and low-priority goals for printer design, materials, printer operation, IP and use-phase energy efficiency. These priorities serve the goals of minimising energy use and waste, as well as transitioning to materials which are non-toxic, abundant, renewable, and low-embodied-energy, with useful end-of-life.

The 3D printing industry is at an inflection point, meaning that interventions implemented now rather than a few years from now would have greater impact. Some possible interventions include banning specific practices, taxes, subsidies, certification systems (eco-labels), and preferential purchasing programmes. Interventions in other industries could also fix impacts in the 3D printing industry: since its largest impact is from the electricity to print parts, converting national electrical grids to 100% renewables (as is already being done in some countries) could cut printing impacts by perhaps 75%. Of course, such measures would also improve other electricity-intensive manufacturing methods. 3D printing industry interventions should primarily target printer design, materials, and operation. As mentioned above, interventions encouraging 3D printing of parts in industries such as aerospace in order to reduce use-phase energy demand should target those industries, not the printing industry, because 3D printing is just one possible means to improved fuel efficiency. The following sections consider several policy mechanisms for directly influencing the 3D printing industry.

Table 5.3. **Priorities for improving environmental impacts of 3D printing**

Focus area	High priority	Medium priority	Low priority
Printer design	**1. Design for minimal idle time (ease of sharing, minimal set-up/clean-up time)** High leverage and simple to implement. **2. Automatic low-power standby** High leverage and simple to implement.	**1. Low-energy printing process (chemical bonding, not melting)** Moderate to high leverage, but requires significant investment and must be combined with energy-efficient equipment systems. **2. Energy-efficient equipment systems (insulation, motors, electronics)** High leverage, but requires significant investment.	**Design software and hardware to minimise material use and waste** High leverage, but market incentives already exert pressure in this direction.
Printing materials	**1. Non-toxic, compostable photopolymers for SLA, DLP, PolyJet, CLIP printers** High leverage and large installed base of photopolymer printers. **2. Improved physical performance/print quality/compostability for existing biopolymers in low-energy print processes** Commercialising existing materials requires less investment than developing new materials.	**Chemical bonding (not melting) of compostable biopolymers, such as MIT's WBDF, for extrusion printers** High leverage, but requires replacing or retrofitting existing extrusion printers (more expensive than simply replacing chemicals in photopolymer printers).	**1. Tunable material properties through printing process, for all printers** Leverage uncertain, still experimental. Could simplify recycling, composting, and toxicity screening, but requires significant investment. **2. Infinitely reusable metal powders produced from recycled material** Probably lower leverage than reducing energy use, and probably requires significant investment.
Printer operations	**1. Sharing printers for more utilisation of fewer machines** High leverage and simple to implement. **2. Optimal bed packing for photopolymer, inkjet, and laser sintering printers** High leverage and simple to implement.	**Minimising support material for all printers** Leverage varies by printer type; implementation can be inexpensive (e.g. improving software algorithms) or expensive (e.g. improving hardware capabilities).	**1. Avoiding failed prints** Leverage varies by application; already strongly incentivised by existing market forces. **2. Hollowing parts for extrusion printers** Leverage varies by application; already strongly incentivised by existing market forces.
IP	**1. Rights for third parties to print replacement parts for products (paying reasonable royalties as needed)** Unclear leverage, but requires only simple legal action with precedent in other industries. No technology development required.		

Source: Authors' analysis.

Bans and taxes

Bans of particular 3D printing-specific practices would probably be unproductive, because of redundancy with regard to existing bans and the difficulty of measuring performance. Negative environmental impacts that are easily measured are largely covered by existing bans. For example, photopolymers and other chemicals used in printing are often somewhat hazardous, as mentioned earlier, but no more so than many other manufacturing processes. All industry chemicals must already comply with existing chemical bans such as the European Union's Restriction of Hazardous Substances Directive (RoHS) and limits set by the Registration, Evaluation, Authorisation and Restriction of Chemicals regulation (REACH) in Europe. While there are strong arguments for the necessity of stricter chemical regulations, any chemical classes used in 3D printing that legislators wish to ban should probably be banned throughout industry, not just for 3D printing.

The impacts of 3D printing can also be difficult to effectively measure at the printer level. Even parts printed with large amounts of energy in the manufacturing phase may reduce use-phase impacts of the products they are used in, such that the total environmental impact is much lower. For example, in aerospace or ground vehicles light weighting improves fuel efficiency. Thus a ban on printers above a certain energy intensity per part printed could inadvertently ban the production of environmentally beneficial parts. Besides these factors, bans are often seen by industry as more of a threat than other policy measures such as voluntary certification systems, and thus meet more political resistance.

Taxes on 3D printing-specific practices would also probably be unproductive, for the same reasons listed for bans. While carbon taxes can be effective for incentivising energy reduction in manufacturing (Larsen and Nesbakken, 1997; Veugelers, 2012), such taxes should not be limited to 3D printing. Instead, they should apply to whole state economies to provide maximum effectiveness and cause the least shifting of impacts from one industry to another. If industry-wide taxes are considered, the one most relevant to 3D printing would be a carbon tax, as the largest single impact of 3D printing is usually emissions from fossil-fuel-derived electricity.

Grants and investments

Government agencies have spent hundreds of millions of dollars on 3D printing, both in research and technology adoption. Focusing government grants and investments on sustainability could significantly move the industry. For example, MIT's Center for Bits and Atoms was founded by a USD 13 million National Science Foundation grant in 2001. In 2014 Spain granted Hewlett Packard over EUR 21 million for 3D printing research and development. In 2013 and 2014, the UK government granted over GBP 60 million to 3D printing projects. The People's Republic of China (hereafter "China") is investing CNY 1.5 billion (USD 245 million) on the industry over seven years. In 2014, US President Obama pledged that "11 agencies that collectively grant over USD 2.5 billion annually to small businesses across the country… are committing to leverage the programs to support maker innovations".

Overall, these grants have not targeted sustainability concerns. However, if they did, the major funding involved could certainly push 3D printing towards sustainability, similar to investment in clean energy industries (Veugelers, 2012).

University grants or discounts can be particularly high leverage to build a market share for environmentally preferable printers. Students who learn their trade using a certain technology or brand of product often prefer that product throughout subsequent decades of their careers, through the persuasiveness of commitment (Cialdini, 1993). This tactic is used by firms as large as Microsoft, Autodesk, and Apple. Universities have also received tens of millions of dollars in government grants for 3D printing. If such funding were contingent on the 3D printers meeting a certain green label standard, or contingent on research being directed towards sustainability, it would probably have great leverage. In addition, university students tend to be environmentally aware, so universities would probably be easier to persuade to follow such strictures than national governments.

Investments in green materials for 3D printing would probably also benefit other industries, such as injection-moulding or other plastic forming. PLA bioplastic can be injection-moulded as well as 3D printed, and new materials might also be usable in other manufacturing processes. Compostable biopolymers and tunable materials may again have more advantages here than recycling materials, because different manufacturing methods often require different material properties.

Preferred purchasing programmes

Environmentally responsible procurement policies can move markets, but they require credible standards for their preferences. The US and other governments' policies, e.g. purchasing only EnergyStar certified computers, have moved markets because governments are very big customers. However, Li and Geiser concluded that an environmentally preferable purchasing policy cannot be achieved alone, and depends on other independently functioning policy instruments such as ecolabelling (Li and Geiser, 2005) In order to avoid cronyism or the appearance thereof, and to integrate well with other policies, preferential purchasing of 3D printers should be contingent on objective measures, such as third-party sustainability certification systems (eco-labels).

Voluntary labelling systems

Voluntary ecolabelling is probably a necessary, but not sufficient, condition for shifting the 3D printing industry towards sustainability. The 2009 RAM requested "government-driven incentives for development of sustainability metrics" (Bourell, Leu and Rosen, 2009). Sustainability certifications can move markets powerfully – over three billion square feet of buildings have been Leadership in Energy and Environmental Design (LEED) certified (USGBC, 2008) and over 100 million EnergyStar certified products are sold per year in the United States alone (Banerjee and Solomon, 2003). However, consumers care much less about sustainability than they do about cost, quality, and user experience in many markets (Ottman, Stafford and Hartman, 2006). 3D printing is currently one of these markets. Still, voluntary certifications can become powerful tools with the addition of preferential procurement policies. The US federal government requires all new buildings to be LEED certifiable, which has had "a huge impact on national construction trends" (Nelson, 2007). The voluntary label becomes the threshold for mandatory (or preferential) policies.

Voluntary eco-labels for 3D printers should use multiple criteria and have multiple grades of certification, similar to the Electronic Product Environmental Assessment Tool (EPEAT), LEED, and Cradle to Cradle labels. Multiple criteria encourage industry to consider sustainability more holistically, rather than making unfortunate substitutions of one environmental impact for another. Multiple grades of certification encourage both laggards and leaders to improve, while single-threshold certifications only drive improvement to that single level. Certification criteria should include the various policy priorities listed above for printer design, materials, and operation. For example, the certification system could encourage energy efficiency by scoring printers according to their energy use per gramme of printed model material. Because of the complexities of 3D printing conditions, such scoring would probably depend on a set of benchmark geometry parts, part orientation, bed packing, and other factors. Separate certifications might be developed for 3D printer designers and 3D printer operators. For example, printer operators most determine the percentage of bed packing and the percentage of time a printer is printing versus idle, while printer designers most determine what materials a printer may use.

Cases where the environmental impacts of printing are high, but where the parts reduce use-phase energy enough to compensate, will probably be too difficult to predict or measure in a certification system for printer design or operation. Instead of attempting to write such scenarios into a 3D printer ecolabel, these circumstances should be dealt with by environmental standards related to the final product instead, such as fuel efficiency standards for vehicles. If voluntary 3D printing eco-labels are used by government procurement policies, such policies should allow exemptions for these cases.

Conclusions

3D printing could dramatically shift industrial manufacturing methods away from traditional technologies and widen access to the means of production of manufactured goods. Additive manufacturing will also pose potential benefits and drawbacks for environmental sustainability if it is scaled up across multiple industries in the next decade. Widespread 3D printing's sustainability will probably be a complex set of trade-offs compared to other manufacturing methods – beneficial in many ways, but negative in others. It already reduces manufacturing-phase environmental impacts in some applications, such as certain types of prototyping or small-run production, and reduces use-phase environmental impacts in some applications, such as saving weight in aerospace parts. However, sustainability has not been a priority for all but a few outliers in the 3D printing industry, and most standard printers operating in typical conditions cause higher impacts per part than injection-moulding plastic at high volumes.

Environmental impacts of present manufacturing technologies are highly varied and dependent on the parts being produced. Future studies should compare 3D printing to each major technology they replace, for each relevant product type and material. In the absence of such studies, this chapter examines two technologies: machining and injection-moulding. These were chosen to represent two ends of the spectrum, from single-unit prototyping to mass manufacturing. Even in these limited circumstances, the environmental impacts of 3D printing processes vary too widely to make unequivocal declarations. For "typical" circumstances, life-cycle assessments show that 3D printing a hollow-shell part causes lower environmental impacts per part than machining the same part from a block of plastic or metal, but 3D printing causes higher environmental impacts per part than injection-moulding the same part in mass quantities. However, these results depend on printer type, utilisation, part orientation, part geometry, and other factors to such a degree that they are often untrue.

Typically, environmental impacts of 3D printing are primarily due to energy use. Secondarily, they are due to toxicity and resources embodied in printing materials and finally are also caused by material waste, with small percentages due to production of the printers themselves. Some experimental systems already have far lower environmental impacts per part than injection-moulding – perhaps 70% lower in some circumstances. However, industry is not trending towards such systems, but rather towards systems with much higher (double, quintuple, or larger) impacts than injection-moulding. Thus, policy should encourage lower-impact technologies.

Expansion of 3D printing into other industries depends on its near-future evolution in print time, cost, quality, size, and material choice. The largest factor driving and limiting its expansion is the cost curve of switching from mass-manufacturing methods to 3D printing. This curve is not linear but hyperbolic. Thus it is rapidly penetrating high-cost, low-volume industries such as prototyping, automotive tooling, aerospace, and some medical devices; it will more slowly penetrate moderate-cost, moderate-volume industries, and low-cost, high-volume industries will not switch to 3D printing for decades, if ever. The expansion of 3D printing will have consequences for economies outside of the manufacturing sector as well. Its automation will further reduce employment in manufacturing, requiring shifts to other employment sectors, but it will democratise production, encouraging entrepreneurship. Its main benefit to developing nations is unlikely to be in helping the poorest of the poor in rural conditions. Instead, it will more likely be in helping urban entrepreneurs with little access to capital start small-scale manufacturing and self-fund later expansion into low-cost mass manufacturing.

As previously described, 3D printing aligns some economic incentives with environmental impacts, making material use expensive while complexity is almost free, which incentivises the reduction of material use and waste through sophisticated design. In addition, printer operators have an economic incentive to reduce printing energy by reducing print time. However, printer designers have no such incentive. The final alignment of economic incentives is the enabling of lean manufacturing by eliminating economies of scale that encourage overproduction. However, a counter-trend is that easy desktop 3D printing will encourage some overproduction similar to (though much less severe than) that which easy desktop publishing caused for paper use. Besides these economic incentives, 3D printing enables material experimentation, which can encourage the use of more sustainable materials, and can also drive large reductions of energy use by printing via chemical processes instead of melting. However, market incentives for sustainable materials and low-energy printing processes are weak to non-existent.

- First, 3D printing can align economic incentives with environmental impacts, encouraging less material and energy use through more sophisticated design. Part of this alignment of incentives is the enabling of lean production.
- Second, 3D printing can enable more sustainable material choices because:
  - It allows many materials to achieve the ease of shaping previously enjoyed only by plastics.
  - It lowers barriers to switching between materials by reducing economies of scale. It can enable fewer chemical ingredients to produce more variation in material properties by varying printing processes.
  - Its labour cost reduction can allow for the use of more expensive materials while still lowering total production cost.
- Third, 3D printed parts can improve use-phase impacts of some products, allowing a reduction of total lifetime impacts even if manufacturing-phase impacts are higher. This can happen in two ways:
  - By printing replacement parts for legacy products that would otherwise be discarded due to lack of a supply chain for repair parts.
  - By reducing weight in a vehicle or otherwise improving a product's use-phase energy efficiency. Such energy savings can be quite large compared to manufacturing impacts, especially in the aerospace industry.

Finally, 3D printing may have social benefits by democratising production. For these potential benefits to scale, the chapter identifies specific factors that policies should target for different printing technologies.

3D printing's environmental benefits are not a foregone conclusion, they must be encouraged. For example, 3D printing does not inherently encourage material recycling; many printing materials and methods actively discourage it. While experimenters have created desktop plastic recycling for desktop printers, this is unlikely to scale, due to the difficulty of sorting materials. Market forces may favour compostable materials in the long run, especially as printers trend towards printing multiple materials in the same part. Many printable compostable materials already exist today. On the other hand, incinerating these materials and recovering the energy that is contained in them may be another option that avoids some of the issues that can result from the use of compostable plastics.

3D printing can encourage efficient material and energy use through lean production. The use of recyclable materials could also be a policy objective. Another very practical environmental benefit would be to advocate for the legality of printing spare parts for existing products, to lengthen the lives of products no longer supported by their original manufacturers.

The negative environmental impacts of 3D printing are largely due to energy use, toxicity and material choice. Technologies exist today that can radically reduce 3D printing's impacts – to roughly 70% less according to the ReCiPe method for life-cycle impact assessment (LCIA) per part than injection-moulding – through low-energy printing of abundant, non-toxic, renewable, compostable ingredients, with tunable physical properties. Preliminary findings suggest that the net impact on the environment would depend upon a number of variables including printer type, utilisation, part orientation, part geometry, and other factors. That said, 3D printing has great potential for environmental sustainability.

To encourage sustainability in 3D printing, policy interventions should primarily encourage low-energy printing processes and low-impact materials with useful end-of-life. Some ways in which printer design and operation can minimise energy use per part are by using chemical processes rather than melting material, automatically switching to low-power states when idle, and by maximising utilisation, both sharing fewer printers among more users and, for some printer types, printing more parts simultaneously. Low-impact materials refer to materials that are non-toxic, abundant, renewable, low-embodied-energy, and enable a useful end-of-life. Some ways in which printers can minimise material impacts are by using compostable biopolymers with high print quality, and as mentioned above, by chemically bonding rather than being melted. Printer design and operation can also reduce waste by minimising support material, hollowing parts, and avoiding failed prints. In addition to these priorities, policy should enable 3D printing of repair parts for legacy products without existing repair supply chains, by clearing legal intellectual property barriers.

Policy mechanisms to achieve these priorities should include targeting financial grants or investments (either existing programmes or new funds) to commercialise research in these directions. They could also include a voluntary certification system to label 3D printers with different grades of sustainability across multiple characteristics, similar to EPEAT, Cradle to Cradle, or LEED certifications. This voluntary certification system could be combined with preferential purchasing programmes by governments and other large institutions.

Expansion of 3D printing into other industries depends on its near-future evolution in print time, cost, quality, size, and material choice. The largest factor driving and limiting its expansion is the cost curve of switching from mass-manufacturing methods to 3D printing. This curve is not linear but hyperbolic. Thus it is rapidly penetrating high-cost, low-volume industries such as prototyping, automotive tooling, aerospace, and some medical devices; it will more slowly penetrate moderate-cost, moderate-volume industries, and low-cost, high-volume industries will not switch to 3D printing for decades, if ever. The expansion of 3D printing will have consequences for economies outside of the manufacturing sector as well. It also has the potential to economically empower small businesses, but could also eliminate jobs in both developed and developing countries. Automation will further reduce employment in manufacturing, requiring shifts to other employment sectors, but it will democratise production, encouraging entrepreneurship. Its main benefit to developing nations is unlikely to be in helping the poorest of the poor in rural conditions. Instead, it will more likely be in helping urban entrepreneurs with little access to capital start small-scale manufacturing and self-fund later expansion into low-cost mass manufacturing.

3D printing's potential for environmental sustainability is high. Two of the most touted sustainability benefits, eliminating waste and eliminating transportation, are largely fallacies; however, there are many sustainability benefits that could be quite real, if pursued.

While widespread 3D printing would not automatically be an environmental benefit as practised today, technologies already exist that, if brought from the industry's fringes to its status quo, could dramatically shift manufacturing towards more sustainable production. Today's rapid industry growth may set the path for decades to come, so policy interventions now could have a great deal of leverage.

In its current state, 3D printing is not a net environmental positive, but must rather be guided by strong environmentally focused policies from the fringes of the manufacturing industry to the mainstream while ensuring that it is not singled out among other industries. Since the industry is at a crossroads, well-placed incentives today might establish beneficial technologies for decades to come, making widespread 3D printing an important part of a more sustainable future.

Note

1. Machining as such is not mentioned in BEA input-output tables (BEA, 2014). This estimate considers the weigh that a range of machining-related sectors (Machine shops; Turned product and screw, nut, and bolt manufacturing; Metal cutting and forming machine tool manufacturing; Cutting and machine tool accessory, rolling mill, and other metalworking machinery manufacturing; Hardware manufacturing; Other fabricated metal manufacturing) have on the total value of the manufacturing sector. As in 2007 the manufacturing sector had a total value of USD 914 819, machining-related activities represented about 0.05% of this figure (BEA, 2014).

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