PEER-REVIEWED PAPER

The potential of 3D printing to reduce the environmental impacts of production

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Abstract

This study evaluates the environmental impacts of 3D printing, and considers how the use of 3D printing technology in place of traditional production methods can improve the sustainability of production. The feasibility of 3D printing as an alternative to traditional production methods will depend upon the specific application. We identify the key strengths and weaknesses of the technology, and suggest that despite the limitations, 3D printing will continue to sustain growth in the industrial, retail and after-market support, biomedical and low-end consumer areas.

We find that use of electrical energy appears to be the largest environmental impact of 3D printers, but waste is still important, particularly as it represents a proportion of wasted energy as well as materials. Embedded energy in the manufacture of the product is more significant in low-use scenarios, and while transport is not significant, reductions in transport of products represent a convenience to the user/manufacturer.

We explore the range of factors that influence the comparative environmental impacts of mass production versus 3D printing, and provide initial guidelines on how to minimise environmental impacts of 3D printing. We also consider the impact positioning of the 3D printer in the supply chain has on environmental impacts, showing that high production applications result in the most favourable outcomes.

We conclude that there is scope for considerable improvement in the environmental impacts of 3D printing. The starting point can be a proactive consideration of environmental factors from the outset of production/product design. Greater research comparing economic and environmental impacts of different printing approaches and highlighting suitability of processes to specific design requirements could facilitate a shift toward lower impact 3D printing and maximise the potential of 3D printing to liberate designers from the boundaries of traditional production.

The status of 3D printing technology

3D printing, or "additive manufacturing", enables three-dimensional solid objects to be "printed" from a digital model by laying down successive layers of material. 3D printers were initially used in industrial environments to produce and refine prototypes ("rapid prototyping"). With reductions in cost, and improvements in technology, they are quickly finding new applications, particularly for short-run manufacturing where customisation is key. 3D printing can be very useful to manufacture complex geometries, precisely customised parts, parts in a variety of slight variations, or parts that need to be adapted frequently in their manufacturing lifecycle. For domestic users there is the potential to download or upload and share part designs.

Different materials and processes can be used for 3D printing, and printers can range greatly in size, from briefcase sized, to those large enough to print houses. The level of definition and the strength qualities of final printed parts can also vary considerably. The main printing types are listed in Table 1, and the variations in the environmental impacts of the various technologies are discussed later in this paper.

Table 1. 3D printing types.

Technology Type		Material	Process
Light polymerised	•Stereo-lithography (SLA), •Digital Light Processing (DLP) 3D Photografting •UV Inkjet printing	Photo polymer / liquid resins and gels	SLA uses lasers to produce a solid part from a liquid. DLP uses a DLP projector to expose light selectively to a container of liquid polymer. The exposed liquid polymer hardens, and the part is built in layers. The liquid polymer is then drained to leave the solid part. 3D photografting/multiphoton photopolymerisation uses a laser to trace designs at a micro-level in a block of gel. It has medical and pharmaceutical applications and can be used to artificially grow living tissue. The inkjet approach uses an inkjet printer to apply photopolymer in ultra-thin layers, with each layer cured by UV light.
Extrusion based	•Fused deposition modelling (FDM) •Fused Filament Fabrication (FFF)	Thermoplastics in filament form including ABS and PLA. Also possible with metal wire and wood based composite filaments.	Filament is melted and extruded via a heated nozzle in thin strips. Simultaneous printing of objects in different colours and materials is possible through the use of multiple extruder heads.
Granular material binding	•Selective laser sintering (SLS) •Direct metal laser sintering (DMLS) •Electron beam melting (EBM) •Powder bed printing.	Polymers including PA, PEEK, and PS, elastomers, metal alloys, and ceramic powders.	Granular systems typically use lasers to fuse (sinter) powder in layers to build up a part. The un-fused media serves as a support to the item being produced, reducing the need for temporary supports to be integrated into the design and removed during the finishing process. Electron beam melting (EBM) involves melting metal powder layer by layer with an electron beam in a high vacuum. The powder bed approach uses an inkjet printer to apply a layer of powder (plaster or resin) and inkjet print a binder in the cross-section of the part. This technology allows for the printing of full colour prototypes, as well as elastomer parts.

APPLICATIONS

3D printers are used in a range of industries – from automotive, to toy manufacturing, jewellery making and plastic packaging. In industrial settings, use to date has mainly been focused upon:

i. Rapid prototyping to evaluate product design before production, rather than to create final consumer products.

ii. The production of moulds or mould templates for use in mass production.

Whilst industrial use is expanding to include, for example, large-scale spare part manufacture, volume applications are still limited predominantly by print time. In other settings, made-to-measure prosthetics or pharmaceuticals can be printed, or scale models in architecture. A summary of applications of 3D printing is contained in Figure 1[1].

Forecasts for growth of 3D printing

3D printing is an emerging market, with an increasing number of companies competing for a share of expanding sales. The number of 3D printing companies has been on the increase since 2010. Major players include 3D Systems Corporation, Bits from Bytes, envisionTEC, EOS, Hewlett-Packard, MakerBot®, Objet and Stratasys. Printer prices have reduced substantially in recent years due to competition and economies of scale. In 2002 a budget 3D printer would cost around £20,000, whereas in 2014 a desktop device can be purchased for well under £1000. Similar reductions in costs are likely to be seen in industrial 3D printers. This has acted as a major driver to increase uptake, especially in the domestic market where sales are expected to increase by 75 % in 2014.

Sales growth in the EU to date has been strong. Given the large divergence in technology types, the sales growth of industrial 3D printers is more difficult to quantify but expectations are that businesses are now starting to see the potential in this technology and hence sales growth over the next few years is expected to be strong, Although views on future sales are mixed, there is broad agreement that the following areas will see growth in the near term:

- **Industrial** – 2013 growth rates greater than 100 % versus 2012 were expected, fuelled by reduced prices and sizes, expanded material options and diverse process options. Use of 3D printers for rapid prototyping and highly customized or small production runs will likely continue to be the main applications in the near term, but there will be growing interest from larger appliance, tool and industrial machinery producers. The potential for 3D printing to replace mass manufacture is limited to specific applications.
- **Retail/Service** – After-market support such as small appliance and auto repair saw early adoption in 2012. 3D printers

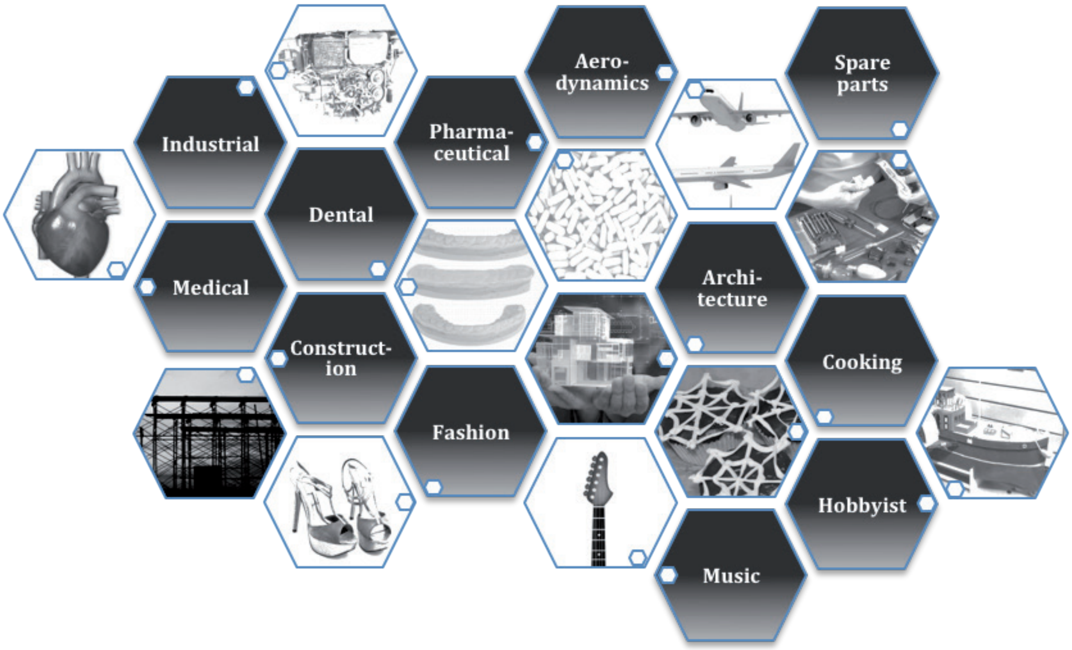

Figure 1. Applications of 3D printing. Image source: freedigitalphotos.net.

are used to print spare parts on demand, reducing inventories and customer waiting time.

- **Biomedical** – 3D printing will continue to grow where services are tailored precisely to patient ergonomics.
- **Low-end consumer** – Sales will continue in niche areas (mainly hobbyist/artistic applications), with the dominant process single colour thermoplastic extrusion as the 3D printing industry has been focussed on reducing costs and improving the usability of products to encourage increased domestic uptake. Domestic use of 3D printers will continue to gain ground as both suppliers and users invent new applications.

There are great uncertainties in estimating expected sales of IT products. Whilst some current estimates suggest that the global 3D printing market will reach $5.7 bn by 2018[2], and that it will be one of the fastest growing industries in the US, others suggest more moderate growth taking into account technical limitations. A recent report stated "while 3D printers are expected to experience considerable growth in the long run, for the foreseeable future it will likely remain a specialized application that for the most part will complement, not replace, traditional forms of production".[3] Dramatic forecasts of a third industrial revolution due to 3D printing may not come to fruition in the short to medium term. However, the industry will continue to grow in the highlighted niche applications.

Strengths and Weaknesses of 3D printing

3D printing has been hailed as the catalyst for the next industrial revolution[4] and the "democratisation of manufacturing"[5], being viewed as having the capacity to shift manufacturing to a more local level - from mass-production to mass-customisation[5]. However, in reality the balance of pros and cons is more complex, and the technology is unlikely to have as strong an influence on traditional manufacturing as many sources have suggested. The diagram below summarises the non-environmental strengths and weaknesses, opportunities and threats related to 3D printing (environmental issues are discussed in the subsequent section).

Environmental impacts of 3D printing

Environmental considerations relate to energy and resource use, as well as emissions and waste. The balance of lifecycle impacts of 3D printing has been investigated in some initial studies in the area, with the conclusion that electricity in the in-use phase is the dominant environmental impact[6]. However, there are many uncertainties and variations in such analyses. Whether 3D printing has lower or increased environmental impact to alternative manufacture methods depends which manufacture technique the 3D printer is replacing and the impacts being taken into account in the assessment. For example, a UC Berkley study found that 3D inkjet printers had significantly worse ecological lifecycle impacts than traditional CNC machining for the high-production scenario they investigated, but that an FDM-style 3D printer had significantly lower impacts than CNC, and that injection moulding out performed all the other options in terms of environmental impacts[6]. Another study[7] compared SLM (laser metal sintering with traditionally machining and found that energy use at the production stage was comparable, but that savings were found at i) the material production stage because less material is used and ii) at the in-use phase (reduced fuel needs when parts are used in automotive or aeronautic applications), because parts are lighter.

Caution is necessary when making comparisons – a focus purely on environmental impacts does not take into account the practical considerations of part manufacture – for example, whilst injection moulding can be much lower impact, it is only suitable for higher volume production runs due to the cost of creating injection moulds.

Figure 2. SWOT analysis of 3D printing in comparison to traditional mass production.

IN-USE ENERGY IMPACTS

It has been observed that energy use is the biggest lifecycle impact of 3D printers[6], with them even being referred to as "energy hogs"[8] consuming a "frightening amount of electrical energy"[8]. There are three main user groups to consider:

- **Industrial** – Used traditionally for production of moulds and for rapid prototyping, (where use would be sporadic, and they would be powered on for distinct jobs and switched off after the job was complete), use is now expanding into new applications, such as large-scale manufacture of lightweight metal parts for aeronautical and automotive industries (where printers could be under intensive use).
- **Retail/Service** – Including 3D printing shops, spare parts providers/installers, printing cafes or even supermarkets offering printing facilities. Where a 3D print shop is servicing many orders, the printer could be in constant use during shop open hours. The concept of 'agile' or 'bursty' 3D printing could also facilitate reduction of environmental impacts in this area. The concept is that printing plants could be configured to operate around the clock focusing print time where excesses of renewable energy occur, maximising the potential of the electricity networks to handle renewable generation loads and making the most of cheap energy supplies[8].
- **Consumer** – Use is likely to be very sporadic, and much less than standard 2D printers, although it may increase slightly into the future as new applications are found for 3D printing. It has been estimated that a domestic 3D printer could require 50 to 100 times more electrical energy than mass injection moulding to produce an object of the same weight[8].

Utilisation levels are key to reducing impacts

A lifecycle study found that in contrast to a high production scenario, printing just one part a week and leaving the machine on the rest of the time, had roughly ten times the impact per part compared to using the same machine at maximum utilisation[6]. In an industrial environment use of the minimum number of printers to process the maximum quantity of jobs can substantially reduce the environmental impacts of 3D printing by amortising the impacts of printer manufacture, and reducing wasted energy use whilst idle[6].

The impact of utilisation levels on energy consumption will depend upon the specific printing technology. Some printers require extensive idle energy in the form of atmosphere generation, warm up and cool down between jobs, whilst others are able to print nearly without interruption. Laser sintering and EBM printing technologies require considerable preparation energy consumption, whilst FDM does not benefit significantly from full capacity utilisation and can be used to generate output part-by-part without incurring a significant energy efficiency loss[9].

For domestic printing, a preferred approach is centralised use of 3D printers in a retail situation rather than occasional use in the home.

Energy impacts depend on the machine design

The following factors can have an influence on 3D printing energy impacts in an industrial environment:

- **Build volume:** This will determine the number of parts that can be printed simultaneously on a specific printer. There will be energy efficiency gains for machines that are able to print more parts at once. A "parallel manufacturing factor" can be calculated to show how well the energy investment of printing can be amortised over multiple parts included in each build. A factor of 0.34 was found for one industrial 3D printer studied, implying that if multiple parts are manufactured per build instead of one, only 34 % of the energy needs to be invested per part[10]. The range of improvement in production of multiple parts is wide, varying depending upon the 3D printing technology, from 3 % to 98 %[9].
- **Layer thickness:** Low layer thicknesses will provide improved surface finish and higher geometric tolerances, but are likely to result in lower process speed and higher energy consumption, due to the greater total number of layers required to build the part.
- **Material type:** Variation in specific heat capacities and material densities will have an influence on energy required in the printing process. Printers using materials that can be worked with at lower temperatures are likely to have lower impacts.
- **Process speed:** Mass production of standard parts (for example via injection moulding) is faster than 3D printing particularly for high volume production runs. In fact, it has been stated by experts working at an industrial level printing spare parts for gas turbines that "slow build-up rates are the biggest obstacle to overcome in order to make this a real disruptive manufacturing technology"[11]. There is EU funded work underway to address these aspects[12]. Process speed can vary considerably between printers due to build volumes, layer thickness etc. The longer the process speed, the higher the energy impacts are likely to be per-part.

There is also another aspect of in-use energy to consider – the usage of the 3D printed part itself. Recent studies have found that 3D printed metal parts can enable lower weight parts to be engineered for the automotive and aeronautical industries transport. 3D printed parts can be up to 50 % lighter than machined parts, and were found to result in carbon savings in the aeronautical parts-use stage equalling 'three to four orders of magnitude more' than the amount of CO_2 emitted to make them[7].

MATERIAL IMPACTS

3D printing materials include glass, starch, ceramics, organic materials, elastomers, resins and metals. However, there are limitations on the variety of materials that can be included per-print. 3D printers cannot synthesise materials with specific physical properties such as Pyrex cookware, or print electronic components such as processors or memory. However, there have been some early developments in 3-D printing electronics using conductive[13] ink and the most recent high-end commercial printers have more varied material choices. In the short to medium term, 3D printers are limited to producing objects compiled of a small number of distinct materials – or in most consumer printers just a single material. Whilst basic colour printing can be achieved with some 3D printers, the capability to mix colours in the same way as traditional inks to produce an extended palette of colours has only become a reality in high-end commercial machines[14]. A recent report concluded that "to produce even a subset of consumer goods used in the average household would require dozens to hundreds of different feedstock materials, many of which are not suited to the processes used in 3D printing"[3].

For consumer and small-scale industrial printers, there are some more environmentally sound feedstock options in the form of corn-starch polymer, wood-based composite, and recycled plastic feedstock in contrast to the previously prevalent ABS feedstock. The characteristics of these feedstocks are explained below:

- **PLA:** A corn-starch based corn-based and bio-degradable plastic, becoming the standard feedstock for consumer 3D printers[6] Its lower heating requirements (both in production and use of the feedstock) mean reduced energy consumption. It has lower emissions, better print quality due to reduced shrinkage and lower embodied energy impacts (27–59 MJ/kg compared to 95 MJ/kg for ABS). Compared to ABS it has reduced strength and durability due to a lower melting point and usually slightly higher cost.
- **Recycled plastic:** There is uncertainty about the potential to recycle waste material and printed parts due to potential changes in the material properties post-printing and pigments that if used may interfere with plastic separation processes[8], although there are products in development that are intended to enable a closed loop recycling process by shredding and/or extrusion of waste prints into new filament. Extrusion devices can save over 90 % of the costs of purchasing filament, and can enable production of filament on demand, in whatever length or colour is required for a specific job[15]. However, the use of additional devices needs to be balanced with their added embodied energy and in-use energy impacts. In addition, in November 2013 an initiative was launched called 'The Ethical Filament Foundation', with the goal of producing 3D printing filament from recycled plastic waste whilst providing stable incomes for waste pickers in developing countries.[16]
- **Wood-based composite:** This is a mixture of 40 % wood with a polymer binder that smells and behaves in a way similar to wood, including potential to cut, sand and paint like wood[17]. It can require less energy than plastic feedstock[6].

In terms of lifecycle studies into 3D printing to date, material waste has not been identified as a dominant lifecycle impact[6]. Waste volumes will vary by machine type – FDM-style machines can have negligible waste where support structures are not required, whilst inkjet-style 3D printers waste around 40 % of their material, not counting support material[7]. Whilst literature on 3D printers often states that waste levels are "near zero", due to parts being constructed using only the necessary amount of material, 3D printers do not necessarily compare favourably with traditional production techniques in terms of waste. Whilst they may generate less waste than CNC machining (which could result in levels of waste as high as 95 %[18]), there may still be waste material generated in the form of the print bed and supports necessary for complex geometries, resulting in waste levels higher than injection moulding[8]. This waste material in the form of support structures could in some cases be greater in mass than the final part, depending on geometry and orientation[6]. Whilst this waste itself does not represent a large proportion of environmental impacts, the energy use related to printing of the waste materials can still be significant[6].

The sintering approach of many industrial printers, where lasers fuse powder in layers to build up a part, can reduce waste related to supports as the un-fused media acts as a support to the item being produced. However, this advantage applies to metal sintering rather than polymer laser sintering, where the unused powder cannot be reused as it can be for metal processes[7].

EMISSIONS

3D plastic printers are high emitters of ultra fine particles (UFPs) and the fumes emitted contain toxic by-products as a result of the plastic being heated to high temperatures[19]. ABS performs worse than PLA, creating "mild, tolerable fumes while being extruded … which may be dangerous for people (or pet birds) with chemical sensitivities or breathing difficulties"[20]. The levels of UFPs emitted by 3D printers appear to be the same as cooking indoors, but further work is necessary to determine exactly what UFPs 3D printers are emitting[19] in order to assess the health risk. Fans can be used to divert fumes, but may adversely impact the operating temperature and therefore the print result.

TRANSPORTATION

Many sources have highlighted the environmental advantages of the capacity of 3D printers to reduce the supply chain by eliminating the need for transportation of parts and goods. Some sources suggest that a significant proportion of manufacturing capacity currently based in Asia may be enabled by 3D printing to relocate closer to source markets, with a corresponding reduction in freight[5]. Also highlighted has been the ability of 3D printing to manufacture up to 50 % lighter parts, resulting in fuel savings during in transportation at various points in the lifecycle[18]. However, whilst transportation requirements could contract to some degree, there will still be impacts in terms of the transportation of the printer to the user/factory, the feedstock to the printer location, and the transport of any complex electrical components for use in printed devices to the point of assembly. Even if transportation could be eliminated, it would not result in major reductions in environmental impact as transport represents a "tiny" proportion of lifecycle environmental impacts[6].

EMBODIED ENERGY

Wider impacts embodied in a 3D printer include the extraction of the raw materials to produce them, the assembly process, and the sales process (heating and cooling retail space etc.). Embodied energy impacts for printing devices can be relatively high, due to the use of complicated electronics, metals and plastics. However, embodied energy is normally overshadowed by the energy used during the operation of printing devices that require the use of heat. The embodied impacts of the manufacturing, transport, and end of life stages of 3D printers have been found to represent a small proportion of the environmental impacts in high use scenarios, although they become more significant in low-use scenarios[6].

DURABILITY

The feasibility of a 3D plastic modelled vs. injection moulded part depends upon the strength required of the part. Injection moulding at high temperatures into a pre-defined mould means that parts can have greater structural integrity than those produced via a 3D layering process, although there are advances being made in this area[3]. The layer-by-layer construction of printed parts results in laminate weaknesses as the layers do not bond as well in the Z axis as they do in the X and Y plane. In many cases the part orientation when printed is an important consideration if it is to be placed under sheer or stress loading. As such, depending upon the application, 3D printed parts may require more frequent replacement, with corresponding additional impacts in material and energy use than their traditionally mass-produced alternatives.

In the area of 3D printing metal, the sintering process needs to be optimised, and even after additional finishing processes such as heat treatment the strengths achieved are lower than (but of the same order as) cast steels. In addition, due to finishing processes to ensure adequate strength (e.g. annealing) there may be dimensional instabilities in parts. There are likely to be environmental pay offs between greater durability and additional energy impacts.

It has been said that EBM (see Table 1) produced parts have better strength than those produced via metal sintering techniques that operate below melting point, but they are still likely to have lower strength than traditional processes such as injection moulding or metal casting, where strengths can be very even across parts, due to a relatively consistent material structure

CONCLUSIONS ON ENVIRONMENTAL IMPACTS

It is not possible to conclude whether 3D printing would result in a reduction of impacts over mass manufacturing – the answer will vary depending upon application and usage levels. Major barriers for 3D printing to replace traditional manufacture techniques include dimensional integrity in high strength parts and time required to produce each part. In the service/retail sector, where trained professionals are using printers at maximum volume to produce highly customised parts, and there is a cost priority to reduce waste etc., the impacts could be lower than manufacturing parts via mass production. Consumer use of printers in the home however, may result in an increased environmental impact compared to traditional production, whereby embodied energy is greater, the printers sit in idle mode for longer, many trial/superfluous parts are printed, and parts are less durable so need to be printed more often.

Reducing the impacts of 3D printing

ENERGY USE

Energy is the area where the biggest savings can be made. In order to reduce the impacts of in-use energy, the following could be considered:

- **Reduce active print time per part:** Reduce the time necessary to print designs by the following best practices:
  - **Hollow parts and supports rather than solid:** Some printers can print parts that are 90 % hollow[6].
  - **Optimised layer thickness:** Larger layer thicknesses mean faster process speed and lower energy consumption, due to the reduced number of layers required to build the part. The largest layer thickness should be chosen to achieve the acceptable level of surface finish and geometric tolerance.
  - **Optimised orientation:** Parts can be oriented to facilitate the fastest possible printing – for example, a tall part may print more quickly in a horizontal orientation, or it may be possible to eliminate supports by carefully orientating the part, reducing waste impacts[6].
  - **Maximum parts per print (build volume):** The printer bed can be filled with the maximum number of parts so they can be printed more quickly than would be possible individually. Small-scale FDM machines get no benefit from this but lifecycle impacts per part for an inkjet style 3D printer could be as much as halved[6]. For metal sintering, printing multiple parts can result in reductions in per-part energy of 3 to 98 %[9].
- **Optimise Utilisation levels to reduce idle/standby time:** Optimise printing so that the fewest number of printers are used, each operating the maximum number of print jobs per machine. For sporadic printing, technologies like FDM are more appropriate, and for printing methods such as laser sintering and EBM, the number of parts per print job, and the printing volumes should be maximised to reduce non-active energy impacts.

MATERIALS

Whilst material choice does not have as strong an influence on in-use energy impacts as the actual printing process chosen itself (comparisons between printers have shown similar per-part energy impacts for metal and plastic prints[9]), materials still have an impact on the overall environmental impact. It is important to select the lowest impact material for the job, aiming to optimise for the following:

- **Shrinkage:** Reduced shrinkage means better printing tolerances and less failed prints.
- **Emissions:** Lower emissions mean less toxicity risk to users and those in the printer's vicinity.
- **Embodied energy:** For example, for plastic printers, the ideal would be a feedstock derived from renewable sources and biodegradable (e.g. corn-based PLA), or from recycled plastics. Where this is not possible feedstocks would be easily recyclable.
- **Finishing needs:** The use of materials that require additional finishing processes means greater additional process energy requirements.
- **Heat capacity/melting point and density**: For some processes, energy in use may be reduced by optimising melting point against strength requirements of the part to be printed.

WASTE

The following measures would help to reduce waste impacts of 3D printing:

- **Selection of the lowest-waste printing technology/model:** Some 3D printer technologies use less waste than others. More detailed information is necessary in order to compare between technologies and models effectively, but initial findings suggest that for plastic printing, FDM-style machines generate much less waste than inkjet-style, and that sintering approaches result in much more waste for polymer processes than they do for metal processing.
- **Purchase of feedstock from suppliers that offer cartridge and/or waste return:** For plastic printing, this can reduce consumption of raw materials and materials to waste – it is important that printers have the flexibility to use recycled feedstock.
- **The use of a shredding and extrusion devices to enable creation of recycled feedstock from failed prints and support structures, and/or other plastic materials diverted from the waste stream:** The embedded energy and additional energy use with such devices would mean that they would only have the potential to reduce environmental impacts in high volume print environments. Recycled feedstocks can result in economic savings also.
- **Refine printer set up to ensure achievement of the best print quality:** For example, positioning of the filament drum above the machine in a plastic printer can decrease the friction of the feed to the heated nozzle.

Conclusions

Dramatic forecasts of industrial revolutions where mass manufacture is replaced by localised 3D printing should be viewed with some scepticism – it is not something that is likely to happen in the short to medium term, due to current restrictions in materials, cost and usability. The feasibility of 3D printing as an alternative to traditional production methods will depend upon the specific application. 3D printers facilitate the production of highly customised parts, but at the expense of production time and cost, and are therefore best suited to small production runs. There is also the issue of dimensional instability in the production of high-strength parts, which represents a significant barrier to larger scale adoption of the technology. Despite these limitations, 3D printing will continue to find niche uses in the short term and sustain growth in the industrial (rapid prototyping, mould production and applications where reducing part weight is a priority), retail and after-market support (print shops and spare parts servicing), Biomedical (patient customisation) and low-end consumer areas.

Generally speaking, use of electrical energy appears to be the largest environmental impact of 3D printers, but waste is still important, particularly as it represents a proportion of wasted energy as well as materials. Embedded energy (materials and energy used in the manufacture of the product) will be more significant in low-use scenarios such as home use of 3D printers. Transport is not significant, but reductions in transport of products represents a convenience to the user/manufacturer. Health impacts of emissions during the printing process are still unclear.

In terms of the comparative environmental impacts of mass production versus 3D printing, these will depend upon the process being replaced, the 3D printing technology, the production volumes required, and the material type used. Environmental impacts can be minimised by optimising part orientation and number of parts printed simultaneously, by minimising waste in support materials, by ensuring high usage of the minimal number of printers, and by optimising material selection and processing for strength, surface finish, embodied energy and melting point. In particular, in recent comparative studies, FDM processes showed a greater potential for reduced environmental impact in small print volume scenarios compared to other technologies.

The positioning of the 3D printer in the supply chain has an impact on print volumes and transport impacts. Printers used in high production scenarios to produce highly customise parts are likely to be more economical than mass production methods, without adverse additional environmental impact. Printers used in industrial environments in low usage scenarios, for example in the traditional application of rapid prototyping, will have more significant embodied and in use energy impacts per printed part. Printers used in home applications are likely to result in less efficient prints (greater waste in multiple print attempts, greater standby time) but can reduce the transport impacts of goods. However, as these transport impacts are a lot less significant than the energy in use and waste impacts, a preferred means of making 3D printing available to the consumer is the use of 3D print shops, where printing machines can be under high utilisation and operated by skilled staff.

There is scope for considerable improvement in the environmental impacts of 3D printing. The starting point can be a proactive consideration of environmental factors from the outset of manufacturing process/product design. Greater research comparing economic and environmental impacts of different printing approaches and highlighting suitability of processes to specific design requirements could facilitate a shift toward lower impact 3D printing and maximise the potential of 3D printing to liberate designers from the boundaries of traditional production.

Glossary

3D	Three-dimensional.
ABS	Acrylonitrile butadiene styrene, a thermoplastic.
CAD	Computer aided design – the use of a computer system to create, modify, analyse, or optimise a design.
CNC	Computer numerical control – the computer-based automation of machine tools.
CENELEC	the European Committee for Electrotechnical Standardisation, responsible for European standardisation in the area of electrical engineering.
DLP	Digital Light Processing is a printing method that uses a projector to expose light selectively to a container of liquid polymer in layers. The exposed liquid polymer hardens, and the remainder drained to leave the solid part.
DMLS	Direct metal laser sintering is a granular printing method using lasers to fuse (sinter) powder in layers to build up a part. The un-fused media supports the item being produced. SLS and DMLS similar, although SLS is used to refer to the process as applied to a range of materials (plastics, glass, ceramics etc.) whereas DMLS refers to the process as applied to metal alloys.
EBM	Electron beam melting is a printing method that involves melting metal powder layer by layer with an electron beam in a high vacuum.
EC	European Commission.
EPS	External power supply – an external component used to supply mains power to a product.
EU	European Union.
FDM	Fused deposition modelling is printing method that creates 3D prints by laying down material in layers on a platform, usually using a plastic filament feedstock. Once a layer is “laid” either the modeling deck is lowered by a fraction of an inch, or the extruding head is raised. Examples include RepRap or Makerbot. 3-D inkjet printing in contrast uses the same method as many 2-D inkjet printers, depositing a thin layer of ink powder on paper and then applying a binding agent in specific patterns to fuse the powder to the paper e.g. Objet Polyjet technology.
FFF	Fused Filament Fabrication is a printing process in which filament is melted and extruded via a heated nozzle in thin strips. Printing of objects in varied colours and materials is possible through the use of multiple extruder heads.
LCA	Lifecycle assessments look at the environmental impacts of the various stages in the lifecycle of a product.
PA	Polyamide, nylon semi-crystalline plastic.
PEEK	Polyether ether ketone, an organic polymer thermoplastic.
PLA	Polylactic acid or polylactide, a thermoplastic aliphatic polyester derived from renewable sources, such as corn starch.
PS	Polystyrene, a synthetic aromatic polymer made from the monomer styrene, a liquid petrochemical.
ROHS	EC legislation on Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment.
SEAD	The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, a voluntary multinational collaboration with the objective transforming global markets toward energy efficient products.
SLA	Stereo-lithography is a printing process that uses lasers to produce a solid part from a liquid.
SLS	Selective laser sintering, see DMLS.
UFP	Ultra fine particle, less than 100 nm in diameter, a variable and heterogeneous component of environmental air pollution derived from primary combustion sources.
UV	Ultraviolet, the range of invisible radiation wavelengths from around 4 nanometers (border of the x-ray region of the spectrum), to around 380 nanometers (just beyond the violet in the visible spectrum).
WEEE	Waste Electrical and Electronic Equipment Directive, EC legislation addressing the environmental impacts of unwanted electrical and electronic equipment at the end of its life.

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1. Royalty Free images: Courtesy of freedigitalphotos.net. Image creators: dream designs (heart), potowizard (construction), lamnee (guitar), olovedog (car engine), nokhoog_buchachon (house model), akeeris (spare parts), Piyachok Thawornmat, (pills), Maggie Smith (shoes), thaikrit, (airplanes), Apolonia, (cake icing). 3-D printed model boat courtesy of John and Les Geddes, Edinburgh, 2014.
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