A Survey of Greenhouse Gas Emissions from 3D Printing

Stephen Kelly

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Farmingdale State College

Abstract

In this paper the greenhouse gas emissions associated with 3D printing are surveyed. The greenhouse gas emissions are explored as immediate offsets due to smaller supply chains, bioplastics, and material reuse. Similarly, 3D printing allows for complex and specialized components that provide further greenhouse gas reduction. Both upstream offsets and downstream optimizations allow for the reduction of greenhouse gas emissions. Similarly, the possibilities for improved recycling and the associated greenhouse gas reductions are discussed. Finally, possible economic effects and the net greenhouse gas emissions are explored in relation to consumption of goods derived from 3D printing.

Introduction

3D printing is a decades old technology that has recently come into the public consciousness as a new method of manufacturing. Early 3D Printers began in the early 1980's with nearly simultaneous invention in Japan by Hideo Kodama of the Nagoya Municipal Industrial Research Institute and the United States by Chuck Hull.[1] These early printers used Stereolithography, which is a techniques of layer-by-layer manufacturing using a photopolymerized fluid and light to cure each layer.[2] Later in the early 1990's, Scott Crump created the now widely used method of filament deposition manufacturing (FDM).[3] In contrast to earlier methods, this method used more robust thermoplastics, rather than thermosetting materials, improving the viability of 3D printing for mechanical components. Research has been intensive in this industry, and now most materials may be 3D printed, including metals, ceramics, plastics, and composites therein.[4] In the past, 3D Printing was commonly referred to as "rapid prototyping".[5] A popular term for 3D Printing is also "Additive Manufacturing", but throughout this paper we will stick to the 3D printing term for uniformity.

The modern consciousness of 3D Printing grew out of an open source project known as "RepRap", short for "REPlicating RAPid Prototyper". This project was started out of the University of Bath in the United Kingdom by Professor Adrian Bowyer in 2004.[6] The stated objective of the project was to develop low-cost 3D Printers that had the ability to self-replicate to some extent. Early iterations of the project use components that were widely available in hardware stores, which only a few specialty components such as electronics and motors. The rest of the machines were able to be printed by other machines.[7] In the early days of the projects the cost of components fell rapidly as machines propagated exponentially. It was not uncommon for one machine to print the components for hundreds more.[8] Similarly, commercial ventures such as Makerbot and Ultimaker were able to build off the techniques in the RepRap project to make consumer-grade 3D printers.[9] Coupled with expiring patents and new technology, by 2010 the benchmark price for 3D printing had fallen from tens of thousands of United States dollars to under 500 in a few short years.[10] This set the stage for 3D printing to be widely accessible to educators, hobbyists, and engineers.

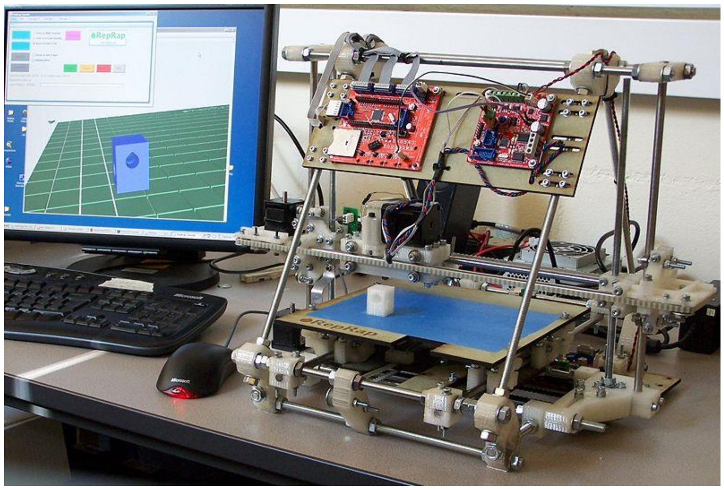
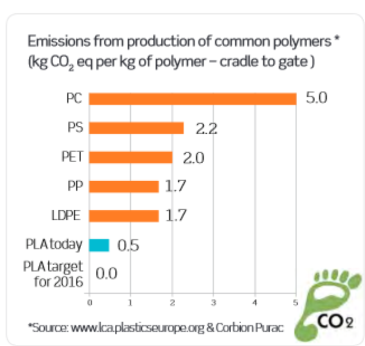


Figure 1: An early RepRap machine (Mendel). Note that all beige components were printed on another 3D Printer with PLA.[1]

Bioplastics in 3D Printing

The RepRap project, aside from being an interesting project in the application of open source hardware and distributed manufacturing, has its roots in environmentalism.[11] The team saw local production as a mechanism for reducing dependence of supply chains and industrial manufacturing. Early in the project the team evaluated several different materials for 3D printing such as ABS, Polypropylene (PP), Polycaprolactone, and Poly Lactic Acid (PLA). It was discovered by the RepRap project that PLA was an ideal material for printing dimensionally accurate objects and met the environmental objectives of the project as well. In particular, PLA is synthesized from food starch and without the use of any fossil fuels.[12] This allowed the team to explore local synthesis PLA from locally-sourced agricultural by-products, furthering the objective of distributed production. Similarly, it has been discovered in 2009 by a team at the Korean Advanced Institute of Science and Technology that PLA can be synthesized using genetically engineered bacteria, further reducing the dependence on industrial manufacturing processes.[13] In 2016 it was announced that the French company CARBIOS is bringing this process to commercial production to address the 15% annual increase in demand for PLA.[14] In the graph below, we can see that the carbon emissions associated with PLA are roughly 1/3 to 1/10 of the comparable emissions of traditional plastics.[15] For all bioplastics the demand has grown form 0.9 million tons in 2009 to 5.3 million tons in 2019.[16]



[1] https://reprap.org/wiki/Mendel

Trends in 3D Printing

It has been nearly a decade since the RepRap project kicked off low-cost 3D Printing. Since then there have been millions of 3D Printers sold and the industry has grown as a tremendous pace. Over the last decade the industry has sustained an 18% growth rate. As of 2019 the industry is estimated to be 14 billion USD worldwide and is projected to grow to 23 billion by 2022.[17] Large companies such as Hewlett Packard, Alcoa, and General Electric have made billion-dollar investments into the technology through R&D and acquisitions. [18]–[20]

Gartner’s hype cycle is a proposed framework for understanding the underlying psychology of emerging technologies.[21] It is proposed that emerging technologies go through five phases: technology trigger, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and plateau of productivity.[22] In the phases of “technology trigger”, research and development will lead to commercial viability and the public will be able to participate in either purchasing the technology or investing in future production. Later it is proposed that this leads to widespread optimism of the impact of the technology, and speculation and tremendous interest gathers around this emerging technology. However, by the third phase it is realized that more development must occur for the technology to have the expected impact, and interest begins to wane. However, by the fourth phase of “enlightenment” the technology begins to see real application and becomes understood in the context of technological problems. By the fifth phase, it is proposed that the emerging technology is no longer emerging and has become a productive technology and is used in real applications. The hype of 3D printing has several categories which fit into this framework. In 2019, the firm published an exposition of the hype cycle for 3D printing including different aspects of the technology, seen in Figure 2.[23] We can see from this graph that it is likely in the next decade 3D printing will begin to see use in manufacturing operations, supply chains, retail, biomedical/surgical, and aerospace applications.

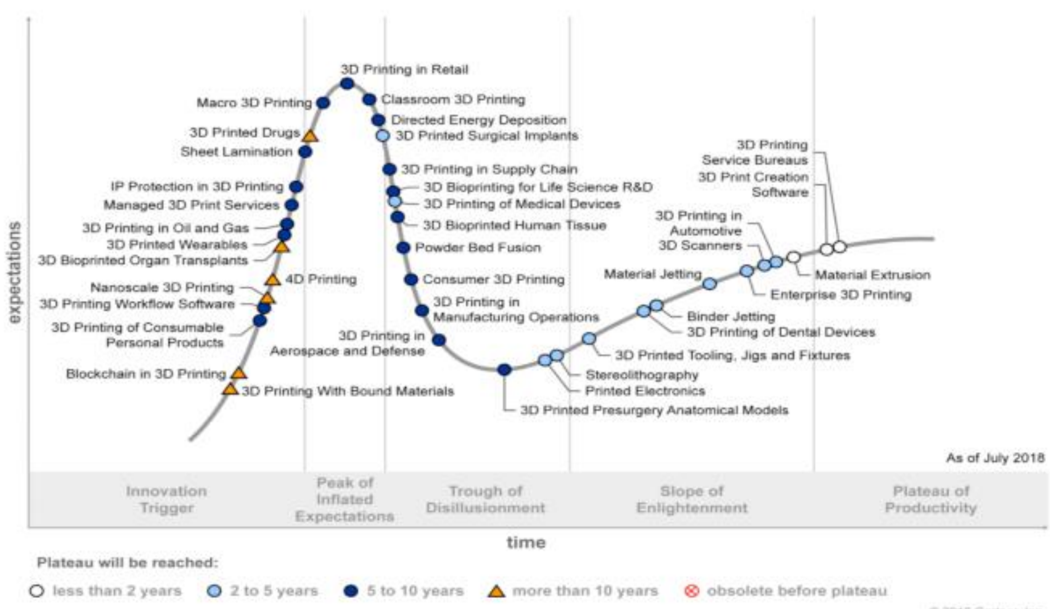


Figure 2: Gartner's Hype cycle for 3D Printing disciplines.

Principles of 3D Printing

The core operating principle of 3D printing is layer-by-layer deposition or fusing of material. In contrast to other forms of manufacturing, the starting form of a component is not defined by any of the tooling or fixtures in the machine. In contrast, the primary limiting factor of a 3D printer is the build volume and geometry of the device. This contrast greatly with traditional manufacturing methods that require extensive setup or costly tooling in order to produce a component. For example, in CNC milling, one may start with a piece of metal billet material which must be held in a vice or fixture, or in injection molding one will start with a mold and cavity. The low-cost setup of 3D printing has made it appealing for prototyping purposes. A 2019 survey by 3D Hubs showed that the predominant use of 3D printing is for prototyping purposes and for some small run manufacturing.[24], [25]

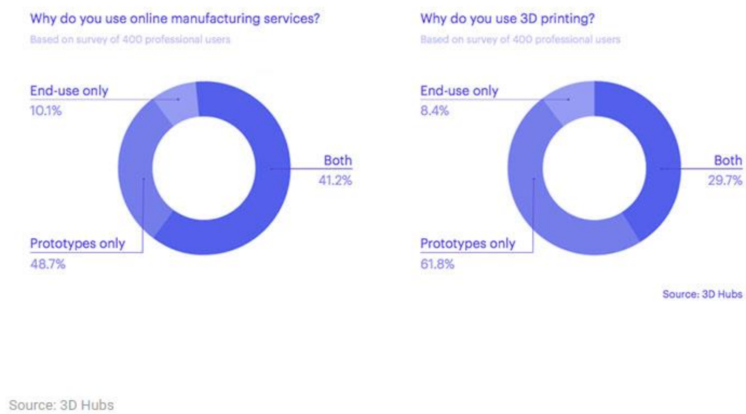


Figure 3: Surveyed use of 3D Printing by 3D Hubs (2019)

Distributed Manufacturing Greenhouse Gas Emissions

Modern manufacturing relies immensely upon specialized tooling. This specialization means that only certain goods can be produced by a given factory. 3D Printing does not require this specialization and allows for more versatile production processes. By far the largest application of 3D printing is for prototyping. This saves immense time and resources and de-risks traditional prototyping methods. In the case of an injection molded design, an engineer will be able to use 3D printing to understand the design characteristics in a similar material to the finished component, such as ABS or PLA. Prior mechanisms for prototyping which do not involve 3D printing may require the development of prototype molds in a temporary material such as aluminum.[26] This requires CNC mills and energy intensive injection molds for only a few parts. The Center for Climate and Security cited the ability rapid prototype as one of the initial benefits, however the long term benefit would ostensible be supply chain security and off-grid production through the use of solar panels.[27]

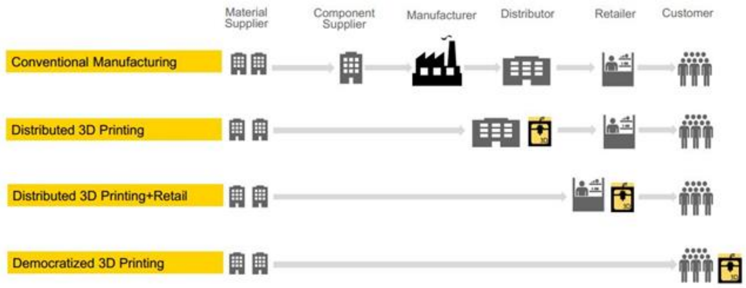
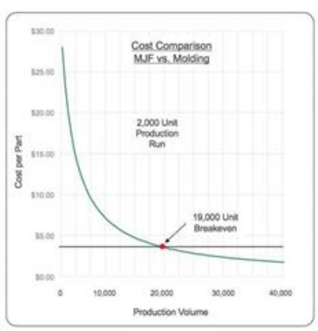


Figure 4: Examples of conventional supply chains and 3D Printing supply chains integrated at varying scales.

However, prototyping is the initial application of 3D printing in the current marketplace. Several manufacturers and vendors are looking towards 3D printing as a more cost-effective solution for their manufacturing and distribution requirements. DHL cited the growth of 3D printing as a future risk to the shipping industry in a 2016 research paper.[28] Hewlett Packard (HP), currently has one of the most cost effective 3D printing production methods and has begun to work closely with industrial manufacturers to save costs for part runs in the tens of thousands of units.[29] In figure 5, a case study by HP shows the breakeven point for a bracket being 19,000 units in comparison to injection molding. A study by the metal 3D printing company EOS, in partnership with Airbus, estimated that for a general bracket on their airplanes the initial CO2 emissions associated with the production were reduced 40%.[30] However, the major concern for these applications is the understanding of quality control, which has yet to been defined by the industry.[31] This makes integration into production of high-risk applications such as aerospace difficult. Companies such as Zeiss are actively working on specialized instrumentation and computer vision to address these concerns.[32]



Technology	MJF	Production Injection mold
Part material	Nylon	Nylon
Tool material	N/A	Steel
Part lead time	1 day	16 weeks
Tool cost	$0	$70,000
Part cost	**$3.75**	**$0.18**

Figure 5: Cost comparison by HP of 3D printing to injection molding. Advancements have made 3D printing cost effective for greater quantities of components.

One of the clear benefits of 3D printing is that the manufacturing process becomes more distributed. In contrast to traditional manufacturing technologies, a 3D printer does not require any specialized tooling or fixtures to make a component. It can make aerospace components one hour, and then switch to making computer components the next. One machine provides versatility that is currently not possible in traditional components.[29] This provides immense benefit for industries that require resource-intensive logistics in order to facilitate rapid repairs. Examples of industries that require rapid repairs are machinery, transportation, and appliances. Frequently the process for repairing a machine involves a site visit by a technician to diagnose a problem. If the problem is outside the routine scope of maintenance, frequently components may not be available, and they must be overnight shipped from a remote warehouse in order to fix the machine. Industries such as consumer appliances, and industrial machinery are looking toward 3D printing to try to alleviate the logistics of overnight shipping, but also to save the associated cost.[28] This is a future application of 3D printing that is just beginning to see testing and development within the industry.

A 2013 study by Michigan Technical University by Pearce, et. al. showed the environmental lifecycle of 3D printing at the small scale.[33] In this study they compared injection molding with a sub $1000 RepRap 3D printer. In this study the team evaluated a baseline solid block, waterspout, and fruit juicer for overall energy demands of production and transportation in the case of injection molding over 3000 miles. The team showed that for low-complexity components, the RepRap 3D printer was an inferior manufacturing method regarding emissions, unless the fill density of the component was reduced. However, for a high complexity component, such as the waterspout, the emissions from 3D printing were a fraction of those found in conventional manufacturing. In this way, complexity in 3D printing is low-cost and allows for efficient manufacturing. The team also noted that localized manufacturing allows for the control of energy sources, and it is much easier to run a local 3D printing operation off a solar panel than it is to run an industrial scale injection molding facility and supporting logistics system off green energy. In the case of using 3D printing with photovoltaics, the emissions were roughly 29% less in the case of the block and 84% less in the waterspout. In Figure 7 we can see the varying fill rates of the block. In Figure 6 and 8 the energy demands of the block and waterspout, respectively, are compared to injection molding with varied infill rates and energy sources.

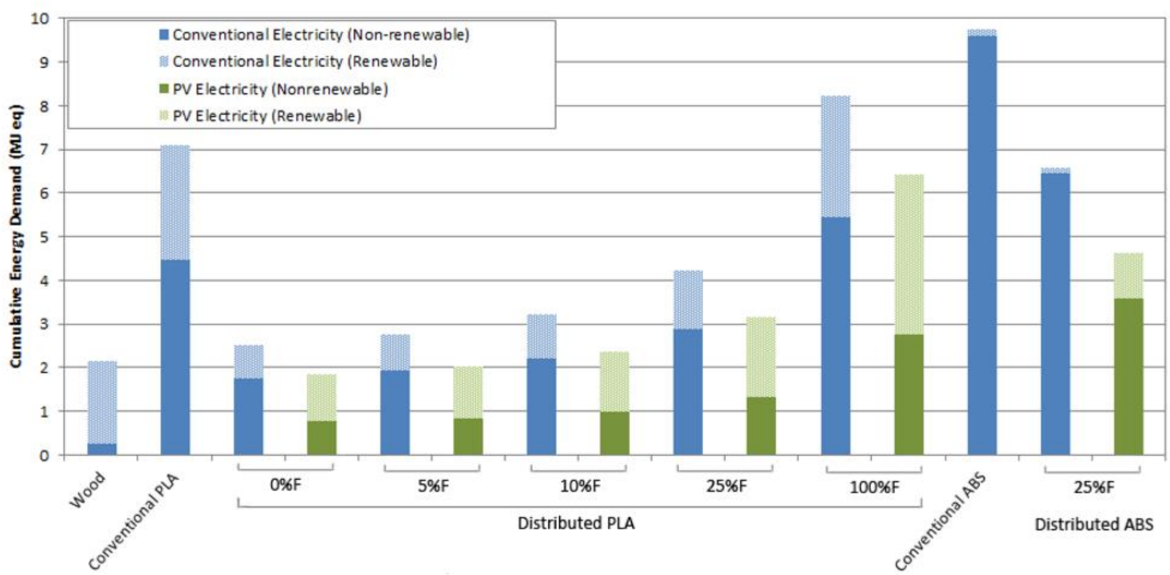


Figure 6: Comparison of overall electricity demand of a low complexity part (block) in PLA and ABS for 3D printing and injection molding. Pearce, et. al.

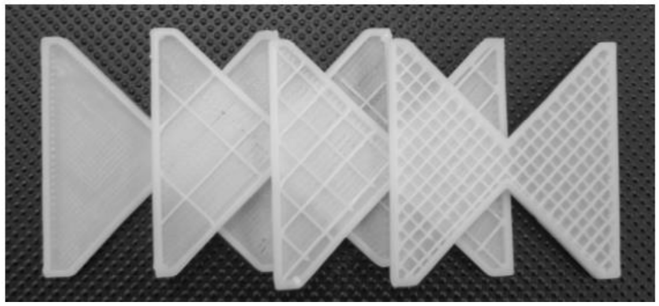


Figure 7: Comparison of infill hatching. From left, 100% 5%, 10%, and 20%. Pearce, et. al.

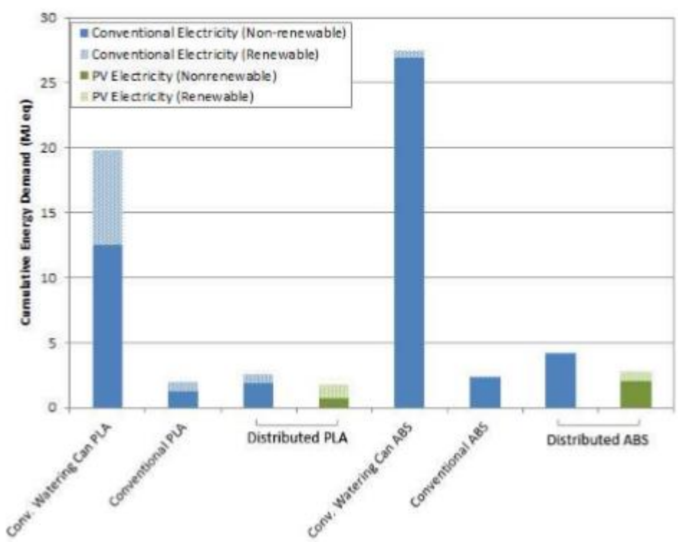


Figure 8: Comparison of overall electricity demand of a high complexity part (waterspout) in PLA and ABS for 3D printing and injection molding. Pearce, et. al.

Recycling with 3D Printing

Recycling is a critical are where 3D printing can help mitigate greenhouse gas emissions. Traditionally, recycled plastic is difficult to sort at large volumes. This leads to most of the plastic collected by municipalities for the purpose of recycling being sent to landfills and incinerators. A study at the University of Georgia estimated that only 9% of global plastic production is recycled, 14% incinerated, and 79% landfilled or littered.[16], [34] In the same study, this problem is attributed to the relatively short service life of plastic goods used from things such as disposable cutlery, packaging, and electronics. However, one of the benefits of thermoplastic, is that it may be reformed several times. Similarly, plastic production is growing rapidly. Despite this tremendous growth, the Royal Society of London estimates that only 4% of global petroleum demand is used for the production of plastics.[35] A study of greenhouse gas emissions in the production of plastic drain covers showed that the emissions are 36% lower when using recycled material.[36]

One of the most common concerns of recycled plastic is that it no longer retains its material properties. Since plastic is a polymer, it is made of long chains of monomers which are attached together. Over several thermal cycles these polymer chains begin to break apart and degrade.[37] Several studies have shown that successive thermal cycles of plastic can degrade the tensile strength roughly 5-30%.[38], [39] This variation in recycled plastic properties makes it difficult to account for the final mechanical strength of a component. However, for bespoke manufacturing where the mechanical properties can be tested, this make recycling somewhat simpler.[40] Recycling provides somewhat marginal benefits in the overall greenhouse gas emissions associated with production and consumption. The most immediate concerns are more directly related to the pollution of the goods themselves, rather than the energy consumption of their production. However, 3D printing can provide a mechanism for alleviating some of the above by shortening supply chains and allocating materials by their required mechanical properties.

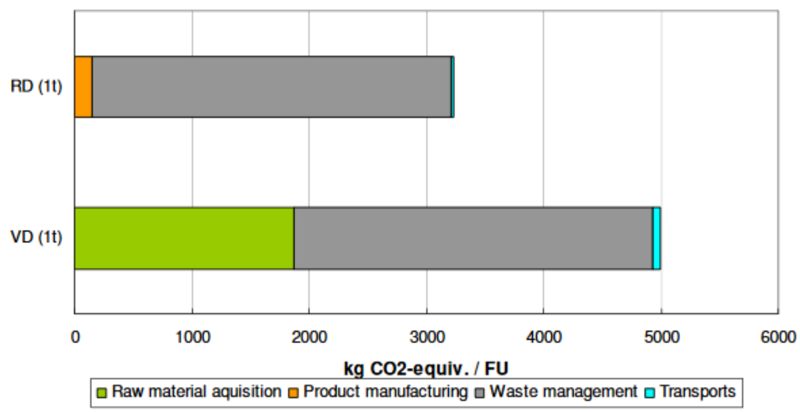


Figure 9: Greenhouse gas emissions estimated by Hiltunen, et. al. from Recycled material (RD) compared to new (VD) for plastic drain covers.

Design/Process Complexity and Greenhouse Gas Emissions

Currently, several manufacturers such as General Motors and Airbus are investigating the use of 3D printing in their production lines.[19] The immediate benefits of these techniques are the furtherance of the objectives set forth in the lean production system. Lean production is a type of manufacturing process popularized by Toyota where materials and components are not stored or warehoused along a production line, but rather the components are pulled and pushed into a queue as required.[41] This prevents ancillary processes to route components and costly buildup of components. General Motors and Airbus view 3D printing to further these objectives. In their future model they envision a system where 3D printers are perpendicular to the assembly line, and produce components as needed. This cuts out transportation and logistical requirements to the extreme.

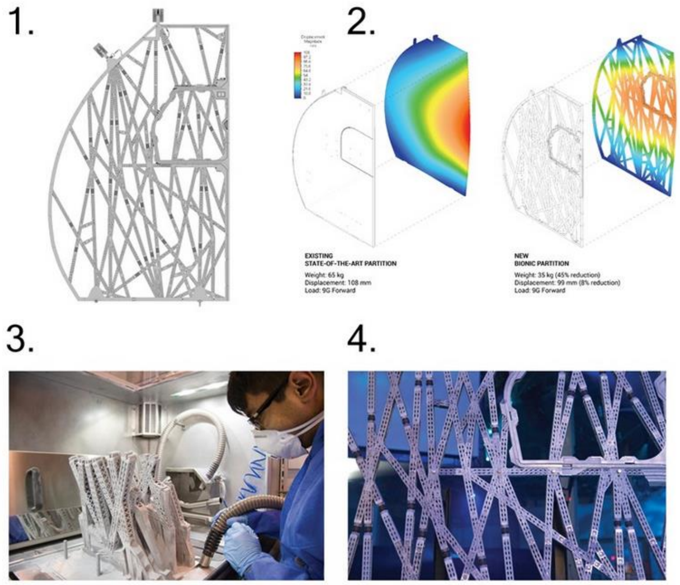


Figure 10: A study of topology optimization to create airplane dividers by Airbus and Autodesk. The final component was 45% lighter and had 8% less displacement.

However, logistics and transportation are not the only areas where 3D printing provides benefit. One of the key benefits of 3D printing in place of conventional manufacturing techniques is that complexity of the design does not add additional costs to the process as shown by the study by Pearce, et. al.[33] Rather, the production of complex components is the optimal use of the technology. The key area of current interest is the use of novel design shapes to reduce weight and enhance strength. It was shown in the study by Pearce that highly complex parts ultimately allow for lower emissions in the 3D printing process.[33] However, the introduction of complex designs helps to improve the performance and reduce the weight of components used in transportation. One of the most common techniques for achieving this are techniques known as topology optimization. In this process simulation techniques such as Finite Element Methods or Finite Difference Methods are used to determine the shape of a component.[42] This is in contrast to widespread methods such as parametric design where dimensions may be iterated upon to determine optimal outcomes within a constrained design space. In contrast, topology optimization methods allow for arbitrary and unconstrained complexity based upon the regions or stresses or deformation within the component.[43] Topology optimization is a key benefit for several sectors, but transportation as a sector has one of the highest emissions of greenhouse gases and stands to benefit from this immensely to improve performance of the finished vehicles.

The two largest companies in the topology optimization industry have been working several industries to explore performance improvements coupled with 3D printing.[44], [45] In collaboration with Airbus, Autodesk has produced plane dividers and seat frames that reduce weight and increase strength. [46] Similarly, with General Motors the team has produced seat brackets that are 20% stronger and 40% lighter, both improving overall efficiency and improving the safety of the vehicles.[47] While the components themselves provide very marginal improvements to the overall performance of the vehicle, if this design philosophy is used throughout the construction, great improvements can be had to the efficiency of different forms of transportation.

Figure 11: As study of topology optimization for automotive seat brackets by GM and Autodesk. The final component was approximately 40% lighter and 20% stronger.

Total Demand Considerations on GHG Emissions

Jevons paradox is an economic theory proposed by William Stanley Jevons in 1865 in his paper *The Coal Question* upon analysis of the coal industry within England during the industrial revolution.[48], [49] In this paper he noted that as technology improved and coal was used more efficiently in industry, the demand for coal would increase. The underlying economic construct used to describe this phenomenon is the principle of elasticity of consumption. The conditions for Jevons Paradox to occur from 3D printing are open to debate. 3D printing reduces the cost of goods and reduces the corresponding time to obtain those goods. In this case, it is possible that 3D printing may cause an increase in consumption, which may make all the initial benefits and greenhouse gas offsets negligible. As with all new technologies, one must be cautiously optimistic to the benefits.

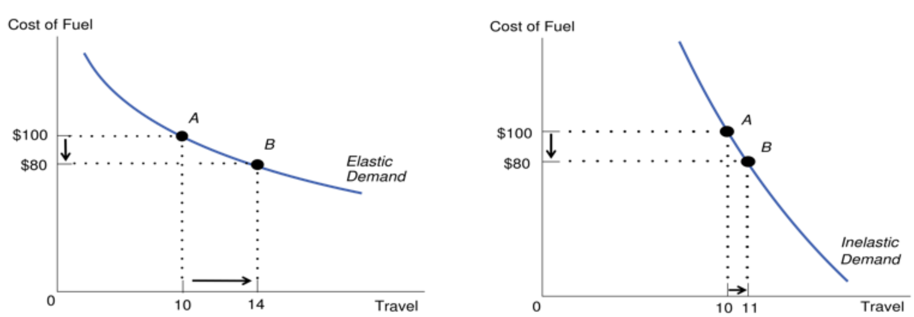


Figure 12: The conditions of Jevons paradox. On the left Jevons Paradox occurs due to elastic demand of fuel. On the right it does not occur because the demand is inelastic.[2]

[2] Source: Wikicommons user: Lawrencerkhoo

Conclusion

3D Printing is not necessarily a green technology. It however complementary to what we think of as true green technologies. Currently the processes for 3D printing are not amicable to mass consumption, and there are outstanding challenges in quantifying the output consentience of the components. However, the future of the technology is promising and can provide a pathway to reduced dependence on complex supply chains that entail large emissions from warehouses, transportation, and material waste. Several large companies are looking to 3D printing as a future component of their operations. Coupled with bioplastics and other environmentally friendly materials, the greenhouse gas emissions from 3D printing can be lower than traditional manufacturing processes. The ability to eliminate constraints on complexity has more than immediate benefits to supply chains and costs. Low-cost complexity allows for highly optimal design that reduces weight and improves performance of components in all sorts of industries. With the support of computational geometry and simulation techniques such as topology optimization, 3D printing can make vehicles, factories, and robots that operate far more efficiently than their traditionally manufactured counterparts. These down-stream benefits may be the most significant, and immediate, towards greenhouse gas reduction. 3D printing coupled with optimal design can make green technologies such as electric vehicles, planes, and pumps more efficient than fossil-fuel counterparts.

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