David Hayes on Thinking Big

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3-D Printing: A Boon or a Bane?

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A Boon or a Bane?

3-D printers can produce parts or products wherever and whenever wanted. But their ability to revolutionize manufacturing, including environmental and energy benefits, is a long way from being proven, leaving regulators so far standing on the sidelines as the technology matures

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President Obama highlighted 3-D printing in his last State of the Union address as having "the potential to revolutionize the way we make almost everything," while reviving U.S. manufacturing and increasing high-tech jobs. Stories regularly appear in the press about the new things that 3-D printers are making: guitars, aircraft wings, tracheal implants, a fully functional camera, heart valves constructed of living tissue, guns, even gourmet foods. Some printers are industrial, replacing factory equipment. But increasingly 3-D printers are available for the home, and their prices are cheap and falling rapidly.

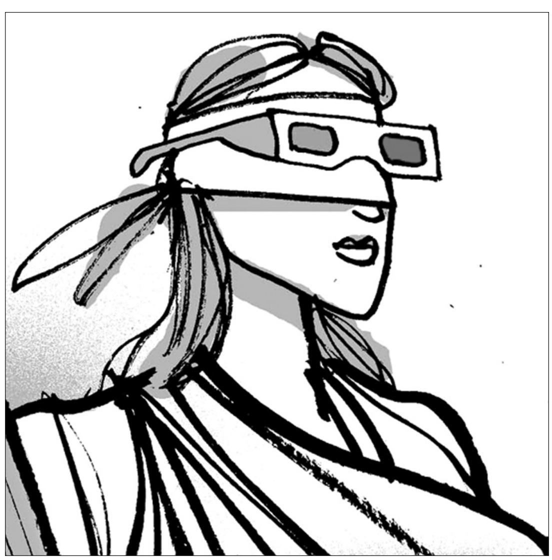
Bold claims are also being made about the environmental benefits of 3-D printing. Some enthusiasts believe it can be at the heart of a new model of sustainable production and consumption. More important from the regulator's point of view is the fact that 3-D printing will change not only how we manufacture many items in the future, but where we manufacture them. As yet, however, little research has been done to assess 3-D printing's environmental impacts. The assessments need to begin by asking fundamental questions. What technologies are involved in 3-D printing? How efficient are these technologies in the use of materials and energy? What materials are used and what are the worker exposure and environmental impacts? Does the design of printed objects reduce end-of-life options? Does more localized production reduce the carbon footprint? And will simplicity and ubiquity cause us to overprint things, just as we do with paper?

Questions like this need answers to help us shape our evolving production technologies toward a sustainable future. To address them, we need to be clear at the outset about what 3-D printing actually is. There are actually many different technologies for 3-D printing, but they all make solid objects using an additive process, where successive layers of material are laid down in different shapes, as opposed to traditional subtractive machining techniques, which rely on the removal of material by methods such as cutting, grinding, or drilling. The 3-D printing process begins with a three-dimensional model of the object to be printed created by computer-aided design software or a scan of an object. This digital representation is then sliced into hundreds of thin layers, creating a computer file to guide the action of the printer as it builds up the object by selectively placing layer after layer of material.

As to those materials, 3-D printers use substances as varied as thermoplastics, epoxy resins, nylon, ceramics, titanium, aluminum, and a wide range of stainless steel and chromium alloys. Some even print food products like chocolate, frosting, and dough. Because such widely different methods and materials are involved, it is highly misleading to make sweeping statements about the environmental impacts.

The technology is not exactly new. 3-D printers have been used since the 1980s to rapidly create prototypes of parts or products. Prototyping allows designers and engineers to quickly "bring objects to life," assess their functionality, show potential customers what they would be like, and check the fit of different parts long before committing to costly production. In this low visibility role they have already had a high impact, speeding product innovation.

Rapid prototyping is still their most common use. What is new is that high-end industrial printers are increasingly used to create final products. Boeing uses 3-D printing to produce environmental control ducting for its 787 aircraft. The ducting traditionally requires the production and assembly of up to 20 different parts but can be printed in a single piece that is both lighter and stronger.



Printers are taking over several areas of manufacturing that involve making small variations on a basic design. There are already more than 10 million In-The-Ear hearing aids in circulation worldwide with individually fitted shells made by 3-D printers. Printers are also increasingly used to make temporary crowns, retainers, and other dental products. Printing can also be cost-effective for short-run manufacturing. Freedom of Creation, for example, prints limited runs of designer products such as lighting and jewelry. Printers are often the most economical approach for creating one-of-a-kind objects. Earlier this year, a 3-D printer extended the life of Kaibi Gionfriddo, a three-month old boy whose airway kept collapsing, by allowing doctors to quickly form and implant an artificial airway splint. The Mayo Clinic recently produced the first 3-D printed, precisely fitted hip replacement.

One of the best applications is producing parts when and where needed. NASA provides the most dramatic example with its plans to send a 3-D printer to the International Space Station. An estimated 30 percent of the parts on the ISS can be replicated by printing. Back on Earth, online design libraries like Thingiverse carry designs for a wide range of commonly used objects, such as replacement parts for many Ikea products.

Capabilities like these combined with continuing progress in printing technology are driving rapid growth in the 3-D printing market. The Wohlers Report 2013 forecasts the global market will grow from $1.7 billion in 2011 to $6 billion by 2017 and $10.8 billion by 2021.

In no time at all, 3-D printing has become a media sensation. There were about 1,600 articles published on 3-D printing in 2011 and over 16,000 in 2012 — a ten-fold increase in one year. Many of the articles in the popular press compare 3-D printing to the personalization of computing, which moved large computers out of universities and businesses and onto our desktops. Enthusiasts are quoted predicting that 3-D printing will make conventional factories and warehouses obsolete and empower people everywhere to become inventors, entrepreneurs, and manufacturers.

Disappointment is sure to set in before long. The slow speed of 3-D printers is a major constraint on their use in mass production. Most items take hours or sometimes even days to print. Speeds will increase, but unlike desktop paper printers, which have become faster, the speed of 3-D printers is limited by physical constraints such as how long it takes a layer of melted plastic to harden. 3-D printers are also constrained by volume. Carl Bass, president and CEO of Autodesk, a major provider of computer-aided design software, describes this limitation in terms of a "third power law" of 3-D printing: "If we want something twice as big, it will cost eight times as much and take eight times as long to print. If we want something three times as big, it will cost about 27 times more and take 27 times longer to print. And so on." Further, printers can only print with one material at a time, or materials with very similar melting points. The melting temperatures of plastics and metals are hundreds of degrees apart. Problems with the precision, surface texture, and structural strength of printed parts have not been fully resolved.

Staples has begun to sell The Cube 3-D printer for $1,299, and the least expensive printer, the Makibox, lists for $200. The fact that printers for hobbyists and do-it-yourselfers are now available at such low prices has contributed to the perception that 3-D printing is inexpensive, but that is not the case with industrial printers. The list price for one of Concept Laser's X line 1000R metal additive manufacturing machines is more than $1 million.

The hype about 3-D printing extends to its environmental impacts. Articles portray 3-D printing as environmentally superior to conventional manufacturing despite the fact that there have been no comprehensive studies to demonstrate that superiority. The broadest study to date is a life cycle analysis recently done in the University of California at Berkeley's mechanical engineering department. It compares one model that dispenses plastic through a heated nozzle and an inkjet printer that lays down polymeric ink and UV-cures it layer by layer. For a broader comparison, the authors also looked at a computer-controlled mill that creates objects by cutting away material, although they acknowledge that plastic is not usually milled, it is injection molded. The analysis includes the materials and manufacturing of the machines themselves, transportation, energy use, material in the final parts, material wasted, and end-of-life disposal of the machines.

When all three machines were run at a high production rate, the first printer (using the heated nozzles) had the lowest environmental impacts — good news for people using hobbyist-level printers. The mill was next best, and the inkjet printer had the highest impacts. Picking the winner was tricky, however, because the study found that "it's more about how you use the tools than about the tools themselves." The best way to minimize environmental impacts is to "have the fewest number of machines running the most jobs each. . . . Job shops legitimately can argue that they provide both economic and environmental advantage to their customers."

A number of narrower studies help give a clearer picture of 3-D printing's impacts. The most common environmental claim is that they produce less waste. That claim appears valid, at least for some 3-D printing technologies. The UC study found that printers using heated nozzles can be nearly waste-free. However, users of these printers often run several copies to get the best print and then discard the less satisfactory ones. Further waste is generated when support materials are needed to shore up parts of the object being printed. The UC study found that inkjet 3-D printers are less efficient, wasting 40 to 45 percent of their ink.

At the industrial scale, 3-D printers that use powdered or molten polymers leave behind a substantial amount of raw material in the print bed. This unused material is typically not reused because its properties have been corrupted. Commonly used selective laser sintering machines also use only part of the metal in their powder beds. Good prints require a ratio of 20–50 percent virgin material to previously used powder to avoid problems, so a significant amount of waste is generated with each build.

Another common claim is that 3-D printers are more energy-efficient than other manufacturing technologies. This claim is highly questionable because 3-D printers vary so dramatically in their energy use. A 2011 study measured the electricity use per kilogram of material deposited using several different 3-D printing methods and found that some printers used up to 80 times more energy than others. In a 2009 study, Tim Gutowski, who heads MIT's Environmentally Benign Manufacturing Laboratory, measured the energy consumption of common industrial printers where metal powder is deposited and then fused by a high-energy beam. He found these printers use hundreds of times the electricity per unit of metal produced than traditional methods like casting or machining.

A 2012 study compared the energy efficiency of selective laser sintering with conventional injection molding to create nylon parts. On the one hand, SLS is energy intensive, but on the other hand injection molding requires a fabricated mold and the accompanying energy and material investments. The researchers concluded that SLS is more energy efficient than injection molding for very small production volumes. The crossover point, where SLS and injection molding consume the same amount of energy, was in the range of 150 to 300 parts. Beyond that, injection molding became increasingly more efficient.

3-D printers also use energy-intensive materials. David Dornfeld, who leads UC Berkeley's Laboratory for Manufacturing and Sustainability, explains: "Additive processes usually use very highly refined materials (in powder or rod form) with large 'embedded energies,' meaning the energy it takes to mine, process, and convert the materials into the final form used."

The other most common environmental claim is that distributed 3-D printing can reduce energy use and associated emissions in transportation compared to providing the same product through conventional manufacturing. While energy is used in moving raw materials in both cases, the final products move no further when they are made on-site.

But the calculation is not that simple. For example, shipments of materials to larger manufacturing sites are made in bulk quantities. Many more shipments are involved in distributing materials in small quantities to many thousands of stores and homes, not to mention the energy required to ship the printers themselves. This is an area where 3-D printing could offer an environmental advantage, but no careful studies have been done to demonstrate it.

Recycling is an area where the performance of 3-D printing depends largely on users. The most commonly used plastic in personal printers, ABS, is easily recycled (the other common feedstock, PLA, is biodegradable), so a high rate of recycling is possible — if users do it. Companies like Cubify and 3DSystems are making it easier by offering recycling services. Smaller start-up projects like Filabot and RecycleBot are emerging to allow people to recycle plastic on their own. At the industrial level, companies like Stratasys have programs for customers to recycle their used feedstock cartridges, canisters, spools, and the printers themselves. Many of the materials used by industrial printers are recyclable, but the additives, stabilizers, finishes, and binders used in some techniques can irreversibly change the composition so the final product itself is not.

A unique issue posed by 3-D printing is the ability to create solid, multi-material designs. While today's printers cannot combine materials as different as plastics and metals, some can combine plastics with different characteristics into the same object. Tim Gutowski at MIT says, "It is very easy to combine mixtures and customize 3-D products but it becomes much more difficult to break up such a product for recycling."

Since desktop 3-D printers will be widely used in homes and other unregulated environments, toxicity issues are important. A first of its kind study by researchers at the Illinois Institute of Technology examines the ultrafine particle concentrations resulting from the operation of two types of commercially available desktop printers inside a commercial office space. The printers used both PLA and ABS feedstock to create small plastic items. The study found that emission rates of total ultrafine particles were approximately an order of magnitude higher for printers utilizing ABS feedstock relative to PLA feedstock, and that printers using both can be characterized as "high emitters."

The authors compare the use of the machines to smoking cigarettes indoors and warn that operating some commercially available printers in poorly ventilated indoor environments poses health risks. Tom Campbell at Virginia Tech's Institute for Critical Technology and Applied Science reports that some 3-D printing hobbyists have complained of headaches, light-headedness, nausea, and other health effects.

Industrial 3-D printing uses many materials besides plastics. Health safety data sheets, as used by the Occupational Safety and Health Administration, are available for some of the "older generation" materials such as epoxy resins and indicate that severe eye and skin irritation and possible allergic reactions can occur as a result of handling or inhaling vapor. Little information is available on the health and environmental effects of newer materials like the fine metal powders used in selective laser sintering. Bert Bras at the Georgia Institute of Engineering stresses that using these materials requires care because "whenever you deal with fine powders, you can get dust explosions and/or respiratory problems."

There is considerable uncertainty about where most things will be made using 3-D printers. Current forecasts anticipate that industrial printing will be by far the largest area of dollar value growth. It is possible, however, that personal printers could be the biggest market. There is also an in-between area that may prove important. Carl Bass says, "Think about the Kinko's model, which didn't replace desktop printers or production-scale printing houses, but still played an important role in the reproduction ecosystem." Companies like Shapeways, Kraftworx, and iMaterialize are already emerging to provide both 3-D printing services and a marketplace for designs.

Bert Bras makes a comparison to home photo printers. They're convenient and you can save gas not driving to the drug store to get your prints. But you can also waste paper and ink when your photos come out poorly and you start over. There are advantages, he argues, to having things run off on high-quality machines. The UC life cycle assessment indicates that this "job shop" approach with fewer printers working steadily has major environmental advantages.

Personal printers raise the issue of overprinting. Will people print out multiple variations on a design to get it just the way they want it, like printing draft after draft of a term paper? Will personal printers be used mainly to produce trivial knick-knacks? James Goodman states the issue clearly: "It [3-D printing] could herald the apotheosis of consumerism, instant gratification, the throwaway society. Or it could be at the heart of a new model of sustainable consumption. Which of these comes to pass will be determined in large part by how we apply the technology."

Thomas Princen at the University of Michigan stresses that product use is a major determinant of consumption. 3-D printers can be used deliberately to foster sustainability. Parts can be printed only when needed, for example, avoiding excess or unsold production and the energy and economic costs of storage. 3-D printers can make replacement parts that extend product lifetimes and "upcycle" some old products into new ones. Products customized to meet personal needs or preferences would be less likely to be thrown out.

Unfortunately, a look at the major digital design sharing site, Thingiverse, shows that so far personal 3-D printing is leaning more toward overproduction of throwaway goods than toward a new model of sustainable consumption. Whether we overprint or not will depend on whether we, as a culture, are able to move from what Princen calls "misconsumption," consumption that does not improve our quality of life.

As with other rapidly emerging technologies, 3-D printing will likely challenge existing governance frameworks, but it also offers some unique opportunities for early engagement by government and other stakeholders with the goals of minimizing any risks and supporting innovation.

Industrial 3-D printing can expose operators to toxic substances like epoxy resins and metal powders, but many of these materials are likely to be covered by the material safety data sheets or other worker exposure regulations required by OSHA. However, history shows that information does not necessarily equal compliance in the workplace, and OSHA enforcement can be spotty, with only about 2,000 inspectors for seven million workplaces around the country.

The growing use of printing in the biomedical field raises other challenges. When printing with living tissue, cells, or bacteria is undertaken in industrial or university settings, the work should be overseen by trained biosafety officers and comply with NIH regulations. The emergence of "do-it-yourself bio" poses a unique challenge. One approach to safe bio-printing in the home or a community lab is the Ask-A-Biosafety Expert program, an on-line service that provides near-real time professional advice to amateur biologists.

The role of EPA in the 3-D printing world has yet to be defined. Any hazardous waste generated by industrial 3-D printing would fall under the Resource Conservation and Recovery Act, subtitle C, though there would be exclusions if the waste were to pass through a sewer system and be treated by publicly owned treatment facilities, which fall under the Clean Water Act. The scale of 3-D printing is not large enough to pose a solid waste problem, and 3-D printers are relatively efficient in terms of avoiding materials waste, but any solid waste output from printers would fall under the jurisdiction of state governments.

The most powerful tool EPA has at its disposal at this point is its Design for Environment Program. A wide framework could be especially useful if adopted early. The most powerful DfE tool is life cycle assessment, and better LCAs of 3-D printing are important. However, LCAs are data intensive, difficult to do, and only applicable at the end of the design process since they require a fully specified design to assess. Because decisions with the greatest environmental impacts are made during earlier design stages, what is needed most now is a widely accepted set of principles to influence those early stage decisions.

Drawing on the substantial DfE literature, here is a proposal for an initial Green Design Framework for 3-D Printing based on six green design principles. Suggestions for improving this initial proposal are welcome.

- First, ensure the sustainability of 3-D printer production. Develop manufacturing processes that use energy and materials efficiently, use renewable resources where possible, and treat waste as a design failure.
- Second, design 3-D printers for energy and resource efficiency. Strive for more energy-efficient operation, prevent waste, improve durability, and allow easy repair and upgrading.
- Third, use feedstocks that are renewable and biodegradable whenever technically and economically practicable. When that is not possible, use easily recyclable feedstocks and insure they are properly recycled.
- Fourth, design both 3-D printers and feedstocks for safe and healthy operation. Minimize dangers of exposure to toxic materials of any kind.
- Fifth, provide product take-back and recycling of 3-D printers, feedstock cartridges, etc., and recycling of discarded printer products.
- Sixth, provide easy-to-understand information on safe operation, minimizing particle exposure, using features that improve energy efficiency and minimize waste, and doing cleaning and other maintenance needed to minimize environmental impacts. Promote sustainable consumption over frivolous use.

Home applications of 3-D printing provide a special challenge in that those engaged can be designers, manufacturers, and end users. However, the DfE framework can shift the focus of home users upstream, so they are more likely to favor companies doing sustainable manufacturing, buy energy-efficient printers, choose feedstocks more carefully, take full advantage of recycling programs, minimize unhealthy exposures, and keep their printers in good operating condition.

Various routes can be taken to popularize a "Green Design Framework for 3-D Printing," including EPA, environmental and consumer groups, trade associations like the Association for 3-D Printing, and the National Additive Manufacturing Innovation Institute. Companies in the field can promote the principles to both their supply chains and their customers.

Contrary to the hype, 3-D printing is not an environmental panacea. But as David Dornfeld says, "3-D printing is an innovation that will change the way manufacturing is practiced in a wide range of applications. The challenge will be to insure that the environmental impacts of this new technology are fairly evaluated as we rush toward this 'next big thing.'"

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