ISSUE BRIEF

BSR

3-D Printing

Sustainability Opportunities and Challenges

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3-D printing—a technology known as "additive manufacturing," which builds objects by adding successive layers of materials—is having a tremendous impact on many industries. In the private sector, industries ranging from aerospace and automotive to healthcare and consumer products are using the technology to do things like print tools on demand and create custom products, which can reduce costs related to time, resources, and inventory. In the nonprofit sector, organizations are finding applications in disaster relief and wildlife conservation by printing humanitarian supplies in the field or creating replicas of animal products to reduce the poaching of endangered species. It's clear that this technology has the potential to transform manufacturing supply chains, distribution channels, business models, and the use of resources across a range of sectors.

But when it comes to sustainability, the impacts of 3-D printing are not yet well-known. As the use of this technology grows, it is important to understand 3-D printing's social and environmental consequences, as well as the opportunities for its applications.

This brief is intended to contribute to that discussion: What are the sustainability opportunities and challenges related to 3-D printing, and what recommendations can we offer to help companies enhance the opportunities while minimizing the risks?

3-D printing's main potential environmental impacts are linked to greenhouse gas (GHG) emissions, energy consumption, and resource efficiency, which the technology can affect in both positive and negative ways, depending on its use.

3-D printing also has notable economic and social implications. In terms of work opportunities, it offers the potential for job creation and enhanced entrepreneurship, as well as increased efficiencies in manufacturing. There is a risk, however, that the technology will result in job loss and/or the relocation of jobs due to automation and localized production. Other opportunities related to social impacts include improved access to products and services, increased opportunities for social inclusion, and reductions in

workplace accidents. Key social risks include health concerns from exposure to toxic substances used in printing, and increased access to 3-D-printed weapons.

This paper proposes a framework that will help companies using 3-D printing understand these environmental and social impacts. Our framework, described in the "Recommendations" section of this brief, focuses on the importance of carrying out lifecycle assessments, considering the sustainability impacts of 3-D printing during the company's materiality review and strategic planning, and adopting a precautionary approach to 3-D printing that allows the company to account for the technology's potential risks and limitations. We encourage company leaders who are exploring the applications of 3-D printing to consider how it might affect environmental, economic, and social issues, and incorporate those risks and opportunities into their planning.

To prepare this brief, we undertook a literature review and interviewed a sample of BSR member companies and subject matter experts. We hope this paper provides useful guidance on the potential issues and how to evaluate 3-D printing vis-à-vis sustainability. We welcome feedback from BSR members and others who are using this technology. Please email us at jmorris@bsr.org.

Introduction

3-D printing is often described as “revolutionary,” “game-changing,” or “disruptive,” and there’s no doubt it has the potential to profoundly affect the way we design, produce, buy, and distribute goods.

One of 3-D printing’s biggest “disruptive” qualities is based on how it works: It builds an object by adding thin layers of material, one at a time. This practice, known as “additive manufacturing,” differs from most traditional forms of production, which are “subtractive,” meaning they begin with a large piece of material that is whittled down to make the final part. 3-D printing is also unique because it is based on a digital blueprint, which is easier to refine.

According to PwC, 67 percent of manufacturers are already using 3-D printing[1] in their production systems. Today, the three most common uses are for prototyping, product development, and innovation.[2] The table below lists several examples of how various industries are applying 3-D printing (read the appendix for more details on how this technology is applied by different sectors).

Table 1: Current Applications of 3-D Printing

Sector	Application
Aerospace	-Lockheed Martin uses 3-D printing to produce satellite parts, achieving cost reductions of 48 percent and cycle time reductions of 43 percent.[3] -Made in Space Inc. manufactures 3-D printers for use in the international space station. -GE uses the technology to produce fuel nozzles for its jet engines, reducing costs and time.
Automotive	-Ford creates complex molds in a fraction of the cost and time. -BMW makes ergonomic and lighter tools for its assembly line.
Medical and Healthcare	-Stratasys has partnered with medical institutes to print accurate replicas of patients' hearts to assist doctors in surgery preparation. -The nonprofit E-Nable facilitates access to low-cost prosthetics.
Logistics	-Maersk has explored installing a 3-D printer aboard ships to manufacture spare engine parts on demand. -UPS is creating small factories in its warehouses to deliver parts as customers need them, reducing the need for large inventories.
Consumer Products	-L’Oréal uses the technology to produce living skin for product testing. -Nike uses 3-D printing in its FlyKnit shoes, reducing waste by 80 percent.[4]
Disaster Relief	-The nonprofit Field Ready uses the technology to print humanitarian supplies in the field.
Wildlife Conservation	-Biotech start-up Pembient produces and sells artificial rhinoceros horns, seeking to curb poaching.

[1] PwC, 2015.

[2] Forbes, 2015.

[3] Quinn, 2014.

[4] ThinkLAB, 2014.

While many of the applications of 3-D printing are for niche purposes and rapid prototyping, forecasts point to strong growth in the future.[5] According to the 3-D printing consultancy Wohlers Associates, the industry is likely to grow from US$3.07 billion in worldwide revenue in 2013 to US$21 billion by 2021. Currently, the potential for 3-D printing's use in large-scale manufacturing is limited by cost, speed, quantity, and quality, but analysts believe these barriers will soon be overcome.[6,7]

As 3-D printing grows, its social and environmental impacts will also grow, making this a critical time to identify this technology's potential challenges and opportunities. This brief is intended to help designers, manufacturers, regulators, sustainability professionals, and consumers understand the potential sustainability impacts of 3-D printing so that they can incorporate these considerations into their planning and decision-making. The sections that follow outline some of the key sustainability impacts of this technology, and provide our recommended framework for companies to maximize the sustainability opportunities and minimize the risks of 3-D printing.

[5] Forbes, 2015.

[6] PwC, 2014.

[7] D'Aveni, 2015.

Environmental Implications

3-D printing's main potential environmental impacts are linked to GHG emissions, energy consumption, and resource efficiency. Few studies have quantified the potential for 3-D printing to reduce energy use and GHG emissions. A 2014 study published in the *Energy Policy Journal* suggests that through improvements such as using resources more efficiently and producing lighter parts, 3-D printing could reduce energy use by between 2.54 and 9.30 exajoules by 2025, and it could reduce GHG emissions by between 130.5 and 525.5 megatons by 2025.[8] Cutting 525 megatons of GHG emissions is the equivalent of taking about 105 million passenger vehicles off the road.[9] These forecasts vary greatly because the technology is still nascent.

The table below highlights the opportunities and challenges related to 3-D printing and energy use and emissions, and the sections that follow outline the opportunities in more detail and provide a discussion on some of the challenges.

Environmental Implications of 3-D Printing

Opportunities

- Energy and GHG emissions reductions due to:
  - Capacity to produce lighter parts
  - Distributed and on-demand manufacturing
- Resource efficiency due to:
  - Use of only the amount of material needed
  - Increasing opportunities for recycling 3-D-printed material
  - Reduction of inventory levels
  - Reduced need for support materials in manufacturing

Challenges

- Increased waste due to simplicity of printing
- Higher energy consumption and GHG emissions due to 3-D printing's supporting infrastructure
- Increased e-waste
- Higher use of non-renewable materials, such as certain plastics

LIGHTER PARTS, LESS ENERGY

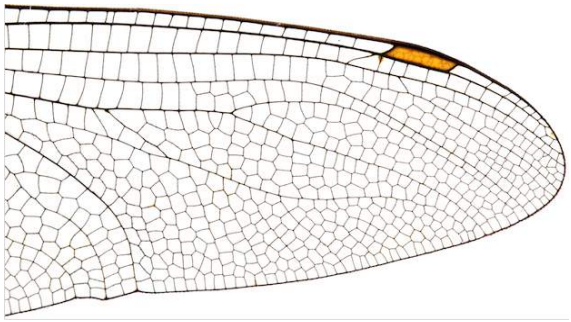
One of 3-D printing's unique characteristics is the ability to create parts with a lattice structure, or a configuration of points, particles, or objects throughout a space. Many experts we interviewed for this brief identified this technology, which results in lighter products, as among the most important when it comes to reducing GHG emissions. According to the *Energy Policy Journal* study, about two-thirds of 3-D printing's GHG-saving potential can be attributed to the creation of lightweight designs, which reduce emissions during the products' use phase.

[8] Gebler et al, 2014.

[9] EPA, 2015.

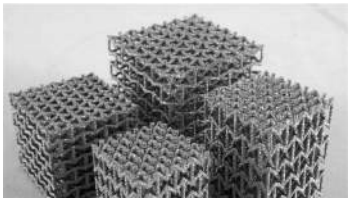
Found in crystals, insect wings, honeycombs, and bones, lattice structures are common in nature, and 3-D printing's use of lattice is a notable example of how biomimicry can support sustainability.

Lattice structure in the human skull. Source: Wang, 2005.



Lattice structure in an insect's wing. Source: Kratochvil, 2015.

The geometry of lattice allows for the creation of lighter parts that are as strong as or stronger than those produced with traditional manufacturing techniques. While engineers have long known about these advantages, it is difficult to create lattice structures using traditional manufacturing techniques.[10]



3D printed lattice structures. Source: Rochester Institute of Technology.

Some industries, like aerospace and automotive, have invested in 3-D printing in order to design lighter parts that have more potential to increase fuel efficiency. Matthew Swibel, Lockheed Martin's director of corporate sustainability, believes 3-D printing could have a large impact on the sector. "In the aerospace industry, the possibilities that 3-D printing allows for weight reduction are huge,"[11] he said in an interview for this paper. Swibel pointed to the example of 3-D printing for satellite parts, which result in a lighter satellite and lower fuel requirements for launch. According to one 2012 study of an aircraft component, the 3-D printing design resulted in a 63 percent reduction of energy and carbon-dioxide emissions throughout the product's lifecycle.[12]

GE also has used 3-D printing to produce lighter parts. Using the technology to produce a fuel nozzle for one of its best-selling jet engines achieved weight reductions of 25 percent[13] (see more details in the appendix).

The advantages of lighter parts apply to many industries: When parts weigh less, it requires less energy to move them around the assembly line and transport them, which also generates cost savings.[14] The reduction of GHG emissions specifically depends on the source of energy. However, given that the bulk of our energy needs are still supplied by fossil fuels, this technology has the potential to reduce climate impacts across these products' lifecycles.

[10] Rochester Institute of Technology, 2015.

[11] Swibel, 2015.

[12] Reeves, 2012.

[13] Forbes, 2015.

[14] Rehnberg, 2015.

DISTRIBUTED AND ON-DEMAND MANUFACTURING

DareDisrupt 3-D printing expert Märtha Rehnberg said that in manufacturing, this technology increases flexibility "in terms of both space and time," which is key to sustainability. In terms of space, 3-D printing allows manufacturing to become decentralized so that it can be done closer to where parts are needed. In terms of time, the technology allows for real-time production, which can adapt as customers' needs change.

The biggest sustainability implications of this "space and time flexibility" occur during transport and logistics, and during production. Transportation is responsible for approximately 22 percent of energy-related GHG emissions globally,[15] so reducing the need for transport can help reduce overall emissions. In the same way, localized manufacturing allows companies to place facilities much closer to their customers. Through localized production, a company can send the design of a needed part to a global hub, and then have the parts printed much closer to the facility.[16]One example of localized production is actually happening *in* space: California-based Made in Space, Inc., manufactures 3-D printers used to develop products on the International Space Station.[17]

3-D printing's flexibility also comes into play through on-demand production. Under current manufacturing conditions, many goods are produced in large volumes to ensure availability. By producing smaller lots, 3-D printing can reduce wasteful production and eliminate the need for large, energy-intensive warehouses to store inventory.

RESOURCE EFFICIENCY AND WASTE REDUCTION

In addition to being lighter, lattice structures require less material for fabrication. Traditional manufacturing begins with a solid piece of material that is whittled down to create the final product, leaving the rest as waste. Because 3-D printing uses an additive approach, most of the material used in production ends up in the part. In this way, 3-D printing requires less raw materials—and hence less natural resources to produce a product. The technology also requires less support materials such as lubricants and coolants, which have environmental footprints of their own.[18]

Certain applications of 3-D printing have already demonstrated high resource-efficiency potential. A case study on aerospace manufacturing indicated that 3-D printing reduced up to 40 percent of the waste from raw materials. The same case noted that 95 to 98 percent of the unused raw material could be used again.[19] In the consumer products industry, Nike has demonstrated the possibilities of waste reduction. By using 3-D printing in company's FlyKnit shoes, Nike has reported an 80 percent decrease in waste, while producing a lighter shoe.[20]

The opportunity to reuse or recycle 3-D-printed products is also intriguing. DareDisrupt's Rehnberg described a futuristic scenario: Picture a family with small children whose growing feet require new shoes a few times a year. Now imagine if that family had access to a 3-D printer and a machine that could crush

[15] WRI, 2014.

[16] Smith, 2014.

[17] Made in Space, 2015.

[18] Petrovic et al, 2011

[19] Petrovic et al, 2011.

[20] ThinkLAB, 2014.

the old shoes to be used as feedstock for new ones. The same concept could be applied to toys and other consumer products.

The scenario is not without drawbacks. While many families throw away outgrown shoes and toys, many others hand them down to younger siblings or give them to charity. 3-D printing and recycling could affect this second-hand market. It could also affect today's overall economic model, which is based on industrial production—a large employer in many parts of the world.

Nonetheless, there are also flaws in the traditional system of recycling, which may be resolved through technologies associated with 3-D printing. Asheen Phansey of Dassault Systems has written about the advantages of reusing input materials:

> This gets to one of the biggest sustainability challenges with plastic products today: their end-of-life treatment. Putting plastics into curbside recycling bins seems like an environmentally sound idea (and it's still better than throwing them into a landfill), but once they're trucked, sorted, cleaned, and usually commingled with lower-value resins, there's usually not much economic margin to squeeze out of these recycled plastics—one reason why their rates of recycling are so low.[21]

This section has provided an overview of what we believe are 3-D printing's biggest opportunities for positive environmental impact: GHG emission reductions and resource efficiency. In the appendix, we briefly outline ways the technology could contribute to biodiversity protection (also see the case study on using 3-D printing to combat rhino poaching).

In the next section, we outline some of 3-D printing's potential environmental risks and challenges.

RISKS AND CHALLENGES

Despite the potential for positive impacts on the environment, 3-D printing also presents some risks and challenges related to energy use, GHG emissions, and waste.

Although certain 3-D printing processes may reduce energy impacts when compared to traditional manufacturing, energy consumption will still be the leading cause of the technology's carbon footprint due to its supporting infrastructure, such as data servers.[22]

And despite encouraging examples of reduced waste, some experts are concerned 3-D printing will create more waste. Jeremy Faludi, who has been studying the environmental impacts of 3-D printing at the University of California, Berkeley, wrote in GreenBiz that "3D printing does not mean zero waste."[23] In his research, he found that certain 3-D printing processes can waste up to 40 percent of the material, which he said cannot always be recycled. For instance, while thermoplastics can be melted and reused, their chemical structure eventually breaks down.[24] Faludi's studies did confirm, however, that other 3-D printing processes, such as "fused deposition modeling," or FDM, produce negligible waste.

Other experts have expressed concern that 3-D printing could also contribute to waste given how easy it will become to produce useless knickknacks. This risk, however, applies only to small-scale, consumer-centric production, not to mass production at an industrial scale.

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[21] Phansey, 2014.

[22] Faludi, 2013.

[23] Faludi, 2013.

[24] Phansey, 2014.

Interviewees also noted that the household use of 3-D printing could create additional waste, since household printers tend to produce more defective parts than conventional manufacturing. More households with 3-D printers could also generate more e-waste, which must be disposed of properly.

Materials Innovation

3-D printing materials. Source: 3Dprint.com, 2015.

A lot of discussions about 3-D printing revolve around the printers, but innovation in materials is just as important for sustainability.

Two commonly used plastics in 3-D printing are polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). ABS is oil-derived and therefore not renewable, while PLA is developed from renewable sources such as sugar and corn.

In part because of the sustainability impacts of the plastics used in 3-D printing, 3D Systems, which manufactures 3-D printers, focuses on material development. “We spend as much time working on our materials as we do on our print engines,” said 3D Systems Chief Marketing Officer Cathy Lewis. “Material science is growing dramatically. One of the things we find very important is finding new types of materials that reduce waste further, or are recycled to start with.” The company has developed a printing material made from 27 percent recycled polyethylene terephthalate (PET) bottles.

Eight years ago, the catalogue of materials available for 3D Systems consisted of only about 50 alternatives. “Today, we have more than 125 different options to choose from, and that number is over 300 across the whole industry,” said Hugh Evans, head of corporate development. “What’s often missed is that this is as much a materials science breakthrough as anything else.”

Economic and Social Implications

3-D printing has notable economic and social implications. It offers the potential for job creation and enhanced entrepreneurship, as well as increased efficiencies in manufacturing. There is also a risk, however, that the technology will result in job loss and/or the relocation of jobs due to automation and localized production. Other opportunities related to social impacts include improved access to products and services, increased opportunities for social inclusion, and reductions in workplace accidents. Key social risks include health concerns from exposure to toxic substances used in the printing, and increased access to 3-D-printed weapons.

The table below provides a summary of the economic and social impacts of 3-D printing, and the sections that follow provide more detail on issues related to manufacturing cost and time reductions, consumer access to products and services, social inclusion, jobs and development, and occupational health and safety.

Economic and Social Implications of 3-D Printing

Opportunities	Challenges
• Cost and time savings in manufacturing • Increased consumer access to products and services • Greater opportunities for social inclusion • Job creation and opportunities for entrepreneurship • Reduction in workplace accidents	• Loss of jobs due to increased automation • Transfer of jobs due to localized manufacturing • New health concerns such as toxic fumes from the technology • Access to 3-D-printed weapons • Need to update technical skills

COST AND TIME SAVINGS

Although prices for 3-D printing materials are currently higher than those commonly used in conventional manufacturing processes, the technology's efficiencies can make up for the higher costs.[25] 3-D printing gives engineers the flexibility to make designs and test them without having to invest a lot in tools. With the additive process, there is no need to produce molds, which makes it much easier and less expensive to make adjustments in the design.

According to figures from Lockheed Martin, which uses 3-D printing to produce satellite parts made out of titanium, this process has reduced the time cycle by 43 percent and has reduced costs by 48 percent. Although the company currently uses 3-D printing for only certain parts of the satellite, it is likely that the final product can be produced using the technology.[26]

Shorter lead times, reduced handling, and shorter production times contribute to time savings, which John Fleming, Ford's head of global manufacturing, calls the technology's "ultimate game-changer." "We're

[25] Gebler et al, 2014.

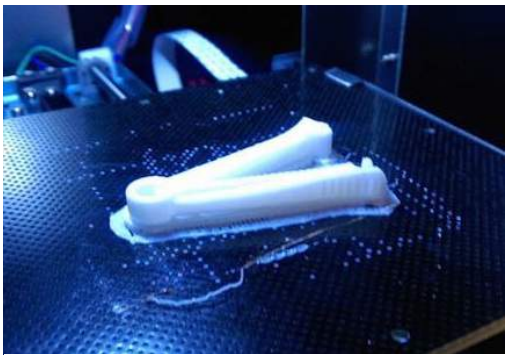
[26] Swibel, 2015.

able to get production-level parts in a matter of days, compared with months using traditional methods," he said.[27]

3-D printing's costs reductions also apply to consumer use. In a report for PwC, Michigan Technological University's Joshua M. Pearce wrote about his work developing the RecycleBot, which can recycle household plastic waste such as milk jugs to be used as feedstock for a 3-D printer. Using recycled plastic containers and the RecycleBot, the cost of plastic filament costs roughly 10 cents per kilogram, compared to US$35 per kilogram for commercially available filament. "A typical household can easily recover the cost of a printer in less than a year and also have a positive impact on the environment,"[28] Pearce wrote.

FACILITATING ACCESS

3-D printing's localized manufacturing can help make products available for underserved markets. Field Ready, an NGO that uses the technology for disaster relief and humanitarian aid, has been working with medical staff in Haiti to increase access to basic healthcare solutions such as sterile tools. For instance, in isolated villages where newborn babies sometimes suffer from infections and umbilical sepsis, the NGO was able to print a sterile umbilical cord clamp to reduce these risks.



3-D printed umbilical cord clamp. Source: Core77.

In the healthcare sector, the power of 3-D printing to increase access also has been useful in the development of prosthetics. Significant reductions in cost and the ability to produce these products almost anywhere have made it possible for many more people to acquire the prosthetics they need[29] (read more about 3-D printer applications for the healthcare industry in the appendix).

Although this increased access to products creates many social gains, it also generates security threats. Open-source blueprints for 3-D-printed weapons are already circulating online, and in 2013, the U.S.-based Defense Distributed made headlines when it developed the first usable 3-D-printed gun.[30] Although the U.S. Department of State demanded the plans be surrendered, the blueprint is still available on other sites. In 2014, a man in Japan became the first person to be arrested for possession of a 3-D-printed gun.[31]

SOCIAL INCLUSION

Because 3-D printing permits customization, this may allow for innovations that create more opportunities for social inclusion in consumer products. The British toy company Makies illustrates these possibilities with its customizable dolls. Parents and children are able to go on the company's website and choose characteristics such as skin color and hair type—as well as more "inclusive accessories" such as hearing aids, walking canes, and wheel chairs—to design their own dolls. The idea is to increase the

[27] Hessman, 2013.

[28] PwC, 2014.

[29] Dunham, 2015.

[30] Nosowitz, 2013.

[31] BBC, 2014.

representation of people with disabilities in toys, and allow children to see dolls that more accurately reflect their own appearance.

JOBS AND LOCAL DEVELOPMENT

Experts' opinions vary when it comes to how 3-D printing will affect jobs and development. This is described in the BSR brief "Good Jobs in the Age of Automation": "The pace, nature, and ubiquity of technological change will have significant impacts on job availability, access, and quality. Some jobs will be replaced by machines, while new jobs are created and existing jobs take on new and different tasks."[32]

3-D printing is likely to affect jobs in a few ways. First, because of localized production or what some call "nearsourcing," it's possible the technology will lead to shifts in job locations, as production facilities move closer to their final markets. A common concern is that this shift will lead to more job-creation in the developed world as opposed to the developing world.[33]

In an interview with one 3-D printer manufacturer, we discussed the issue of job-creation. "We hear from many companies that they are bringing jobs back to the U.S. in part due to 3-D printing," this source told us. "I see it as a job creator for the U.S. We think it's a net add, bringing jobs home, and manufacturing closer to your end market."

However, this opportunity may present challenges in some countries, where jobs could be lost. To address that challenge, countries and businesses should invest in capacity-building to help employees retain jobs.[34]

In its May 2015 edition, *Harvard Business Review* published an article on the "3-D Printing Revolution" that echoed these concerns about job availability: "Imagine how new, highly capable printers might replace highly skilled workers, shifting entire companies and even manufacturing-based countries into people-less production," the author wrote. "In 'machine organizations,' humans might work only to service the printers."[35]

Despite these concerns, 3-D printing expert Rehnberg thinks the overall impact on jobs will be positive. For instance, in the case of Maersk printing spare parts on ships, economic activity would move from China to Denmark (since Maersk's vessels are under Danish flags). However, she said she is not too concerned about losing jobs at a global scale because the design, pre-processing, and post-processing phases will still require skilled human labor.

3-D printing also has the potential to reduce barriers to market entry for small businesses. With this technology, an entrepreneur can design and produce locally, avoiding the need to produce hundreds of thousands of units to justify the tooling costs of producing an injection-molding rod, for instance. Similarly, entrepreneurs can benefit from shorter product-development cycles because 3-D printing allows for less expensive design and prototype phases.[36] With these advantages, smaller businesses may be able to compete on a more level playing field with established industrial players.

Given the opportunities for entrepreneurship, 3-D printing may open opportunities for new or enhanced sources of employment. In India, the company Protoprint, which calls itself a social enterprise, gives

[32] BSR, 2015.

[33] Gebler et al, 2014.

[34] Rehnberg, 2015.

[35] D'Aveni, 2015.

[36] Interview with Christoph Meinrenken, 2015.

waste collectors access to the technology to produce feedstock for 3-D printers. According to Protoprint, plastic waste collectors can earn more than 15 times what they normally would make by recycling the materials themselves.[37] Formalizing this marketplace could also help ensure better labor conditions and reduce child labor. And it could reduce the overall use of virgin plastic, which currently comprises the majority of the market.

While 3-D printing will clearly replace some jobs and create others,[38] its overall impact on workforce numbers remains to be seen.

OCCUPATIONAL HEALTH AND SAFETY

In addition to the environmental benefits of the lighter parts produced by 3-D printing, this change may help improve health and safety conditions for workers. The ability to work with lighter tools or finished parts can reduce workplace injuries.[39] Injuries may also be reduced because workers will not interact with as much heavy machinery, since at least some of these processes can be automated.

On the other hand, 3-D printing may present new risks related to exposure to toxic substances and fumes. The material ABS can produce carcinogenic fumes when heated,[40] and a study on the health impacts of desktop 3-D printers noted the potential toxicity of vapors in areas that were not properly ventilated.[41]

[37] Gilpin, 2014.

[38] BSR, 2015.

[39] Rehnberg, 2015.

[40] Autodesk Spark Blog, 2015.

[41] Stephens et al, 2013.

Recommendations

Our research has revealed that 3-D printing has the potential to create both opportunities and challenges related to environmental, social, and economic issues. In this section, we provide preliminary recommendations designed to help companies enhance the opportunities while addressing challenges and minimizing risks. Our recommendations focus on three main areas: the importance of carrying out lifecycle assessments, considering the sustainability impacts of 3-D printing during the company's strategic planning, and adopting a precautionary approach to 3-D printing that allows the company to account for the technology's potential risks and limitations.

LIFECYCLE ASSESSMENTS

It is critical for companies using 3-D printing or considering the technology to carry out thorough lifecycle assessments to identify sustainability impacts at different points. These holistic assessments should cover both environmental and social issues, including GHG emissions, energy, water use, and waste, as well as impacts on health, accessibility, and job creation. What follows are some important points to consider in conducting lifecycle assessments for 3-D printing:

- **Use the right baseline**. In an interview with BSR, Columbia University industrial ecology expert Christoph Meinrenken said it can be difficult to evaluate what would have happened if 3-D printing did not exist, which makes creating a baseline challenging. As you carry out assessments, consider different baselines, including the possibility that 3-D printing could be replacing a technology that is more environmentally friendly.
- **Incorporate sustainability criteria in materials selection.** When choosing the input materials to be used for 3-D printing applications, it's important for companies to analyze factors such as recyclability, water use, and carbon footprint, as well as traditional features such as strength, cost, heat resistance, and flexibility. As discussed in this paper, the type of material used can affect the overall sustainability impacts of 3-D printing.
- **Consider applications in other sectors**. For companies that are directly involved in 3-D printer manufacturing and related products such as software development, assessments should consider how their products will be used, and establish strategies to mitigate the potential that 3-D printing is misused for nefarious purposes, such as to manufacture illegal weapons.
- **Evaluate social impacts.** While lifecycle assessments generally focus on the environmental issues, it is also important for companies to consider social issues such as the creation and transfer of jobs. Companies should also learn how 3-D technologies they are using affect worker health and safety. For instance, if a company is using 3-D printing to replace a process that does not require abundant ventilation, it might be necessary to install more ventilation when setting up the 3-D printing facility.

SUSTAINABILITY STRATEGY

Sustainability strategies should be forward-looking, which means the potentially transformative impacts of 3-D printing over the coming decades should be integrated into company strategic-planning processes. There are a number of potential considerations and opportunities related to sustainability strategy:

- **Be prepared to move quickly.** There are still many uncertainties surrounding 3-D printing, and the field is changing rapidly, so it is important for companies to build systems into their strategies that

allow for the evolving impacts of 3-D printing. Case in point: The U.S. hearing-aid industry completely shifted to 3-D printing manufacturing in less than 500 days.[42]

- **Shift the design mindset to focus on sustainability.** 3-D printing provides a much higher level of freedom and flexibility in design, allowing designers to focus less on the manufacturing process and more on design for function. Companies can encourage their designers to apply this new thinking to sustainability attributes as well, to design using less materials and less energy. **"**With additive methods, you are unconstrained," said 3D Systems' Evans. "Complexity is free. You can focus on designing a part that accomplishes the function with the least amount of material and the least amount of energy."[43]
- **Take advantage of localized manufacturing**. Companies can analyze production to determine which parts could be 3-D-printed and would provide the most benefit from being moved to local facilities.
- **Foster cooperation with small suppliers**. With the advent of 3-D printing, larger companies can incorporate into their supply chains smaller businesses that can apply these technologies in new ways.
- **Prepare the workforce.** Companies need to ensure that their workers have the skills required for 3-D printing, not only with regard to manufacturing applications but also in design abilities such as digital 3-D modeling.
- **Invest in research and development.** We are only now becoming aware of the sustainability implications of 3-D printing, and investments in research and development will help companies, and this field, push the sustainability agenda forward.
- **Look for opportunities to collaborate.** Many companies are shaping the sustainability impacts of 3-D printing, including both the makers and the users of the technology. We see numerous opportunities for companies across the 3-D printing value chain to share lessons learned, develop common approaches, and raise awareness among sustainability professionals of the need to proactively manage the sustainability impacts of 3-D printing.

A PRECAUTIONARY APPROACH

The precautionary principle, as set out in the Rio Declaration on Environment and Development, refers to an approach that should be taken to address potential environmental impacts. The principle states that where there are threats of serious or irreversible damage, a precautionary approach should be taken. Specifically, in order to protect the environment, the lack of full scientific certainty shouldn't be used as reason for postponing cost-effective measures to prevent environmental degradation.

As we have described in this paper, there are still many uncertainties when it comes to the sustainability impacts of 3-D printing. For this reason, we recommend that even as they pursue the clear sustainability opportunities associated with 3-D printing, companies should inject an element of caution into their approach.

Several of the experts we interviewed warned that companies perceive 3-D printing as a silver bullet to solve all sustainability challenges. But to foster sustainable development, manufacturers and users must also be aware of 3-D printing's negative impacts. "As with any game-changing technology, it doesn't

[42] *Harvard Business Review*, 2015.

[43] Evans, 2015.

mean you can't lose," warned Lockheed Martin's Swibel. "It's not a panacea. It's important to think about the entire lifecycle." When approaching 3-D printing, it's important to have a clear and balanced understanding of the risks and opportunities, as well as the scale of those risks and opportunities.

LOOKING FORWARD

This brief provides a general overview of the sustainability implications of 3-D printing. But looking forward, it will be essential to continue exploring how the technology will affect environmental, social, and economic well-being.

We believe there are two main priorities to explore going forward: examining how 3-D printing can help us manage climate change, and considering how it can help foster an inclusive economy. We would like to see future researchers ask some of the following questions related to both themes.

To foster an inclusive economy:

- How can 3-D printing help create new jobs and improve the conditions of existing ones?
- How can 3-D printing improve access to essential goods and services?
- How can 3-D printing enhance investments to create prosperous and sustainable communities?

To mitigate climate change:

- How can 3-D printing contribute to reducing GHG emissions and holding temperatures below 2°C above pre-industrial levels?
- How can we use 3-D printing to build resilience in the face of inevitable climate impacts?

At BSR, we look forward to helping companies increase their understanding of this technology and how 3-D printing can be used to support a just and sustainable world.

BSR'S CORE THEMES

An inclusive economy is one in which all individuals and communities participate in, benefit from, and contribute to global and local economies. BSR's "**Business Leadership for an Inclusive Economy**" strategy leverages traditional business resources to support three core pillars—good jobs, access to critical goods and services, and sustainable communities—creating short and long-term benefits to business and society alike. For more information about BSR's inclusive economy initiative, visit http://www.bsr.org/en/topics/allchannels/Inclusive-Economy.

BSR's "**Business in a Climate-Constrained World**" strategy catalyzes private-sector action on climate resilience in two ways: by helping reduce greenhouse gas emissions consistent with holding global mean temperature rises to less than 2˚C above pre-industrial levels, and enhancing adaptive capacity in the face of inevitable climate impacts. For more information about BSR's climate change initiative, visit http://www.bsr.org/en/topics/all-channels/Climate-Change.

Appendix: Applications by Key Sectors

This appendix provides more information about the applications of 3-D printing in key sectors: aerospace, automotive, medical and healthcare, and transport and logistics.

AEROSPACE

By some expert accounts,[44] aerospace, whose characteristics like long time horizons and low-production volumes, is the industry best suited to benefit from 3-D printing. Aerospace manufacturers are quickly adopting the technology in order to simplify production and reduce costs.[45]

REDUCING THE BUY-TO-FLY RATIO

In aerospace, the buy-to-fly ratio refers to the total raw materials needed to create the final product, versus the quantity of material in the final product. With traditional manufacturing technology, buy-to-fly ratios of 20:1 are common,[46] but certain uses of 3-D printing allow for ratios of almost 1:1, resulting in reductions in waste and resource demands.

According to Joel Smith of Stratasys, a leading manufacturer of 3-D printing equipment, there are three main ways the aerospace industry is using this technology:

1. **Testing designs and reducing tooling costs**: Making changes is a simple matter of updating the design in the digital file and printing the adjusted part. In aerospace, a high source of costs comes from tooling, and 3-D printing provides a means to reduce those costs.
2. **Manufacturing lighter parts:** Reducing aircraft weight is a priority because this can reduce fuel costs and improve aerodynamics. 3-D printing facilitates the creation of parts with weight-optimized geometries that are not possible to produce with more traditional manufacturing technologies.
3. **Addressing inventory issues:** Managing inventory for aftermarket parts is a key challenge for the industry. Traditionally, companies have had to maintain stock for parts that sometimes go unused for years. But 3-D printing allows these companies to print parts on demand.

[44] Hessman, 2013.

[45] Smith, 2014.

[46] Gebler, 2014.

Company Applications of 3-D Printing in Aerospace

GE's 3-D-printed fuel nozzle. Source: GE.

GE is incorporating 3-D printing across many of its businesses. GE Power & Water has been working on identifying parts that can be manufactured with 3-D printing, and GE's healthcare division has been developing transducers, the costly ceramic probes that are used for ultrasounds.[47]

One of the most attention-grabbing uses the company has found has been implemented by GE Aviation, which uses 3-D printing to produce a fuel nozzle for its LEAP jet engine. The additive process can produce the nozzle with less material, resulting in cost reductions of 75 percent.[48] The final product is also up to 25 percent lighter,[49] which contributes to the aircraft's fuel efficiency. 3-D printing has also allowed GE to manufacture the nozzle in a single piece, while previous manufacturing processes required the assembly of 20 different parts. Fewer requirements for assembly simplifies manufacturing, requiring less energy and time, while lowering the possibility of errors and defects. The 3-D-printed nozzle is also five times stronger.[50] The technology has been so successful that GE Aviation is planning to 3-D-print 25,000 fuel nozzles for the LEAP engine.[51]

3-D PRINTING AND LIFECYCLE ASSESSMENTS

EOS, Airbus Group Collaborate on Lifecycle Assessment[52]

Working with Airbus, the German 3-D-printer-systems manufacturer EOS carried out a lifecycle assessment to analyze the environmental impacts of the 3-D-printing technology "direct metal laser sintering," which was being used to manufacture a nacelle hinge bracket for the Airbus A320.

The assessment compared 3-D printing to the more traditional steel-casting method, looking at the entire life of the part, including the supply of the raw materials, the manufacturing process, and the end use.

Key conclusions from the study:

- In terms of carbon-dioxide emissions and energy use, the use phase had the highest impact.
- The 3-D-printed hinge generated 40 percent less carbon-dioxide emissions due to weight reduction.
- The 3-D-printed hinge reduced the aircraft weight by 10 kilograms.
- The 3-D-printed hinge enabled a reduction in waste of 25 percent.

[47] *MIT Technology Review*, 2013.

[48] *Harvard Business Review*, 2015.

[49] GE Aviation, 2015.

[50] *Fortune*, 2015.

[51] *Forbes*, 2015.

[52] EOS, 2014.

AUTOMOTIVE

In the automotive sector, 3-D printing is used to create tools for production, produce spare parts, and consolidate many pieces into a single piece. These applications reduce the time in product development, mainly through rapid prototyping.[53]

Ford has been using 3-D printing (specifically, sand printing) to produce complicated molds, which saves the company millions of dollars annually.[54] When an auto manufacturer is working on a new engine, engineers are continuously experimenting with new ideas and variations for parts. With traditional manufacturing technologies, it is necessary to create an entirely new mold for each part; 3-D printing allows this to happen much more quickly and inexpensively.[55]

BMW also uses 3-D printing for vehicle-design prototyping and to produce tools for auto assembly, among other uses. One of the tools BMW has manufactured—ergonomic hand-held devices used in the assembly line—are 72 percent lighter.[56] According to BMW engineer Günter Schmid, the 3-D-printing process known as "fused deposition modeling" provides a viable alternative to conventional metal-cutting production methods like turning and milling.[57]

The lighter parts some auto manufacturers are developing from 3-D printing may also help reduce cars' carbon footprint—not in end use but in the manufacturing process. Kevin Czinger of Divergent Microfactories said that a great percentage of a car's total emissions come from the materials and energy used in production.[58] "How we make cars is actually a much bigger problem than how we fuel our cars," he said. Divergent Microfactories uses 3-D printing for its new Blade car, whose carbon fiber and aluminum chassis weighs about 90 percent less than traditional cars of its size and requires far less material for manufacturing.

[53] PwC, 2015.

[54] Hessman, 2013.

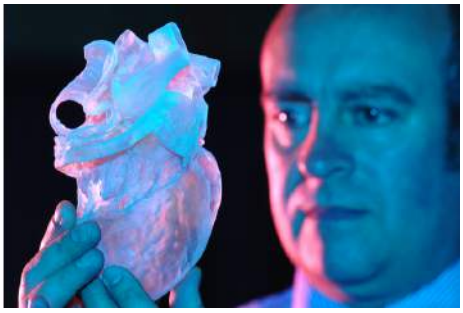
[55] Hessman, 2013.

[56] Stratasys, 2015.

[57] Stratasys, 2015.

[58] Weiss, 2015.

MEDICAL AND HEALTHCARE



3-D-printed model of a heart. Source: Open Biomedical Initiative.

The medical and healthcare sector has used 3-D printing for custom body part implants and prosthetics, medical tools prototypes, surgery-planning models, and even the production of live tissue for drug testing. Each human body is unique, and 3-D printing allows medical practitioners to produce products that suit patients' specific needs.

3-D-printer manufacturer Stratasys has partnered with doctors at the Texas Cardiac Arrhythmia Institute to create true-to-life models of patients´ hearts that surgeons can use to understand the hearts' characteristics before performing the operations.[59] This technology helped save the life of a 2-year-old girl with a heart defect in January 2015.[60]

Applications like this have helped reduce risks of mistakes, reduce surgery time, cut costs, and improve treatment results.

3-D printing also has great implications for the development of prosthetics. Historically, it has been challenging for medical parts producers to develop prosthetics at scale because the total market value is not cost-effective.[61] This also makes prices prohibitive for many patients. A prosthetic hand, for example, can cost between US$6,000 and US$10,000 in material costs alone, and these costs add up even more for children, whose devices must be replaced as they grow. 3-D printing can produce a prosthetic arm for less than US$50.[62] To help more people access this application, the nonprofit E-Nable has set up a network of volunteers who design prosthetics, give advice, upload digital blueprints, and match patients with local 3-D printers.

3-D-printed hand prosthetic. Source: E-Nable, 2015.

There are many other examples of 3-D printing use for personalized patient care. Companies such as Siemens and EnvisionTEC have been applying the technology to rapidly produce hearing aids, which are customized to fit each patient's ear canal.[63] Similarly, the dental industry has created models that follow precise scans of patient's dental impressions.

The drug industry could also benefit from 3-D printing to develop one-off productions of compounds, and to establish facilities to serve places where large amounts of medications are needed, such as in disaster-struck areas.[64]

In an article for Live Science, Scott Dunham summarized the advantages this technology presents for healthcare:

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[59] Stratasys, 2015.

[60] BBC, 2015.

[61] Dunham, 2015.

[62] E-Nable, 2015.

[63] Campbell et al, 2011.

[64] Manners-Bell et al, 2014.

> There is an unusually strong synergy among digital 3-D design, medical imaging, and 3-D printing for medical applications. The three form a trifecta of medical problem-solving power, where physicians can use patient-specific data to capture, manipulate, and ultimately apply physical solutions of all shapes and sizes through 3-D printing. Without such technology, personalized medicine would be difficult, as patients will need unique parts that can be rapidly and simply manufactured.[65]

TRANSPORT AND LOGISTICS

In a 2014 DHL poll of its business customers, only 8 percent of respondents said they believe 3-D printing plays an important role in their supply chain. However, 22 percent of those interviewed said they believe the technology will have an impact within three years.[66]

The research firm Transport Intelligence identified three main aspects of 3-D printing that will affect the transport and logistics sector:[67]

- The trend in "nearsourcing" products that were previously manufactured in developing countries will reduce cargo and shipping volumes.
- Mass customization could reduce inventory levels since goods can be made to order, reducing the need for warehouse and inventory.
- A new logistics sub-sector could develop to deal with storage and transport of input materials for 3-D printing.

In the industry, leaders such as DHL and UPS have already begun incorporating 3-D printing into their operations. A 2015 report published in *Harvard Business Review* noted that UPS is expanding its third-party logistics division, converting warehouses in airports into small production facilities.[68]

In an interview with BSR, Alexander Heil, chief economist at the Port Authority of New York and New Jersey and a Columbia University professor of economics of sustainable development, talked about the disruptive potential of 3-D printing. "If [the technology] takes hold, it will completely turn the logistics chain on its head," he said. According to Heil, localized manufacturing will be particularly important for high-value, customized products that are capital intensive.

Heil has given thought to the implications for his work. At the Port Authority, one of his responsibilities includes forecasting truck traffic to consider capital allocation for infrastructure such as new bridges and tunnels. Right now, he said, it is very difficult to quantify how 3-D printing will affect these forecasts, but it is important for people like him to watch the field and incorporate the implications of the technology into planning.

The shipping company Maersk has considered an innovative application of 3-D printing. Traditionally, when a vessel's engine breaks down and requires a replacement part, the procurement team must obtain the needed part and send a boat to deliver it. But according to Rehnberg, who led Maersk's research project, 3-D printing could provide a much simpler solution by allowing the crew to simply print the replacement part on the ship.

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[65] Dunham, 2015.

[66] Manners-Bell et al, 2014.

[67] Manners-Bell et al, 2014.

[68] *Harvard Business Review*, 2015.

Case Studies

The following two case studies demonstrate how 3-D printing can be used to support sustainability directly.

PRINTING SKIN

A common challenge for the cosmetics industry is how to test new products to evaluate effectiveness, toxicity, and allergic reactions. In the past, animal testing has been used for this purpose, but the practice is controversial and now outlawed in certain countries and regions, including in the European Union.

French cosmetics manufacturer L'Oréal has been working on applying 3-D printing to solve this problem. Through a partnership with Organovo, a bioprinting company, the company is trying to produce living skin through a completely synthesized process. L'Oréal currently produces skin in its labs, but this complicated, slow process requires donor tissue.

If Organovo and L'Oréal are successful, this technology could be used for other applications, such as to create skin grafts for burn victims.[69]

COMBATTING RHINO POACHING

Poaching can have a significant effect on wildlife populations, which has happened with the rhinoceros. A subspecies of the animal, the Western black rhino, was declared extinct in 2011, primarily due to poaching. Today, three of the five remaining subspecies are classified as "critically endangered" by the International Union for the Conservation of Nature.[70]

Poachers are killing the rhino for their horn, which is used in some traditional Asian cultures for medicinal purposes (although there is no scientific evidence of any curative effects).[71] According to the South African Department of Environmental Affairs, in 2014, poachers killed more than 1,200 rhinoceros in South Africa alone.

While prohibition, penalties, monitoring, and captive breeding have had only limited success in protecting rhinos, the biotech company Pembient has proposed a novel solution: using 3-D printing to manufacture artificial rhino horns that have the same biological characteristics as the real thing. Company leaders believe these artificial horns, available at an eighth of the price of the real horns, will diminish the market for poached horns.[72]

To manufacture the horn, Pembient combines real rhinoceros DNA with keratin (the basis for our nails and hair). According to the company, the artificial horn is similar genetically to authentic horns, and will have a similar feel and smell.

Some conservationists are concerned that the artificial horn could drive up the demand for the original product. They also worry that as the availability of rhino horn increases, the public could perceive an implicit acceptance of its use.[73]

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[69] Bloomberg Business, 2015.

[70] IUCN, 2015.

[71] Maxwell Braun, 2010.

[72] Unnikrishnan, 2015.

[73] Nuwer, 2015.

Others question whether consumers will accept the substitute. To address this question, Pembient surveyed rhino horn users, reporting that less than half of those surveyed would purchase a synthetic substitute.

While Pembient is approaching rhino conservation from a different angle, a lot of effort has gone into educating buyers and trying to reduce demand. Mathew Markus, Pembient CEO and co-founder, said he believes people should be able to enjoy the product without harming any animals. “There is room for better, bioidentical substitutes,” he said.[74]

Pembient is also planning to produce synthetic versions of other substances that are in high demand on the black market, such as ivory and tiger bones.

[74] Nuwer, 2015.

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ABOUT THIS REPORT

This report was written by Federico Sendel with contributions from Dunstan Allison-Hope and Jonathan Morris. This document analyzes the impacts 3-D printing can have on sustainability. With this research, we hope to raise awareness on emerging issues and share different perspectives on enhancing the sustainability opportunities and minimizing the risks. The findings of this brief are based on a review of existing literature, as well as interviews with experts, technology makers, and users of 3-D printing.

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