

3D printing and the new shape of industrial manufacturing

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Introduction: 3D printing's growth spurt

Surely, the potential of 3D printing (3DP) has captured the popular imagination. From jet engine parts to made-to-fit bikinis, the technology is being hailed as a revolution in how products are manufactured. According to estimates, the global 3DP printer market is poised to hit \$6 billion by 2017 from \$2.2 billion in 2012, with global shipments of printers costing less than \$100,000 expected to reach about 98,000 in 2014, roughly twice as many as in 2013.^{1,2} But in the heartland of US industrial manufacturing, 3DP appears more on an evolutionary track, as companies large and small shape 3DP programs—and as 3DP printers, software and materials science advance. What they're discovering is not just how the technology can build upon traditional manufacturing processes, but perhaps more important, how it can potentially produce products well beyond the scope of traditional manufacturing.

To help get a clearer picture, PwC surveyed over 100 industrial manufacturers, from small contract manufacturers to multinationals (referred to in this report as "PwC Innovations Survey").³ The overarching story is one of sprinters and sideliners. Two-thirds of manufacturers surveyed are currently implementing 3DP in some way (either experimenting on how to use the technology, or already using it for prototypes or final products). One in four said they plan to adopt 3DP some time in the future.

Based on this survey, interviews with industry leaders and a PwC analysis

surrounding the economics of 3DP, we explore how and why companies are bringing this technology closer to an effectual tipping point of adoption.

There are signs that the technology is on the cusp of being mainstreamed and thus there are glimpses of the disruptions and opportunities that it could create, including:

- Companies investing in the 3DP hardware and the talent to run it are seeing gains in speed and flexibility in research and development, enabling quicker launching of new products and product customization (the "lot of one" model).
- Early adopters are crossing the critical threshold from tinkerer and prototyper to producers of the final product.
- Companies are re-imagining supply chains: a world of networked printers where logistics may be more about delivering digital design files—from one continent to printer farms in another—than about containers, ships and cargo planes. In fact, 70% of manufacturers we surveyed in the PwC Innovations Survey believe that, in the next three–five years, 3DP will be used to produce obsolete parts; 57% believe it will be used for after-market parts. Some 30% of survey respondents believe that 3DP's greatest potential disruption will be exerted on supply chains.
- Companies are anticipating 3DP-driven savings in materials, labor and transportation costs, when compared to traditional subtractive manufacturing processes. A PwC analysis of 3DP adoption by the global aerospace industry's MRO (maintenance, repair and operations) parts market, estimates a \$3.4 billion annual savings in material and transportation costs alone, assuming a scenario in which half of that industry's MRO parts are 3DP-manufactured. And, even at a more conservative 20% 3DP adoption, savings could easily exceed \$1 billion, according to the analysis.

What is 3DP?

3D printing, also known as additive manufacturing, is the process through which hundreds or even thousands of layers of material are "printed," layer upon layer, using a range of materials, or "inks," most commonly plastic polymers and metals. The additive process, which manufacturers have been using for prototyping since the 1980s, contrasts with traditional subtractive manufacturing processes based on the removal of material to create products. But recent advancements in speed, capabilities and lowering prices in printers and feedstock have broadened the use and popularity of the technology. 3D printers range from small personal hobbyist machines (under \$200) to industrial printers (hundreds of thousands of dollars and more). Digital files (i.e., Computer Aided Design (CAD) files), which are either drawn up by a designer or are created by a 3D scan, communicate to the printer the dimensions of each required layer or "horizontal slice" to complete the object. 3DP technologies include:

Binder Jetting: Also called "inkjet head" or "powder bed" 3D printing, this technology is used to print with sand, powders or metal, employing inkjet-like printer heads that jet layers of material and a binder to fuse the layers of material together. Commonly used to produce sand castings printed from sand.

Stereolithography: Uses an ultraviolet beam to harden liquid resin, bonding each successive layer.

Fused Deposition Modeling (FDM): Originally developed by Stratasys, a stream of melted thermoplastic material is extruded from an extrusion nozzle to create layers, with each layer bonding to the previous layer. Common inks include ABS (acrylonitrile butadiene styrene) and polyactic acid polymers.

Selective Laser Sintering (SLS): Using powdered materials (e.g., nylon, titanium, aluminum, polystyrene, glass) instead of liquid polymers used in FDM, SLS employs a laser, which sinters or fuses the powder, layer by layer.

Selective Laser Melting (SLM): Similar to SLS, but rather than fusing the powdered material, the powder is melted at very high temperatures.

Electron Beam Melting (EBM): Similar to SLS, but employs an electron beam as its power source.

Laminated Object Manufacturing (LOM): Additive process involving the layering of laminates of materials (e.g., metal, plastics or paper) bonded in successive layers, then cut into shapes and, in some cases, worked on further (e.g., through machining or drilling) to finalize the product.

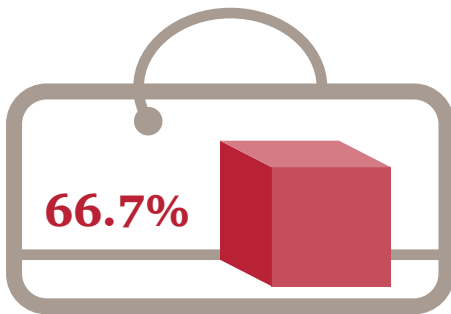
1 "Wohlers Report 2013 Reveals Continued Growth in 3D Printing and Additive Manufacturing," Wohler company press release, May 23, 2013.

2 "Gartner Says Worldwide Shipments of 3D Printers to Grow 49 Percent in 2013," Gartner press release, October 2, 2013.

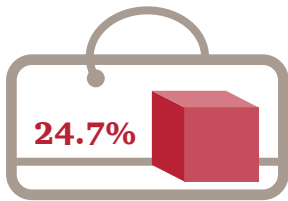
3 PwC and Zpryme conducted a survey of 145 US manufacturers in February 2014, titled "2014 Disruptive Manufacturing Innovations Survey."

3DP-powered research and development

3DP adoption: Now...or when?



66.7% of manufacturers are adopting 3DP in some way (Experimenting to determine how they might apply it, or using it to prototype products or producing final products.)



24.7% of manufacturers plan to adopt 3DP in the future in some way

- 5.2% within the next year
- 10.3% within 3 years
- 9.2% some time beyond 3 years



8.6% of manufacturers do not plan to adopt 3DP ever

Number of respondents: 114

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

Applying 3DP for rapid prototyping is nothing new for many manufacturers. It enables them (and their suppliers) to sidestep the often laborious, costly and expensive traditional processes—the production of casts, molds and dies, the milling and lathing and other machine work, and finally, the shipping of the object from a supplier (which could be in China). There are signs 3DP can give R&D a redoubled shot in the arm and accelerate new product development cycles which could translate into getting new products to market quicker and more frequently. This is especially the case with prototyping complex parts—or a product that has a system of complex parts. The PwC Innovations Survey found that 25% of manufacturers are currently implementing 3DP technology for prototyping only, that 10% are using 3DP for both prototyping and the production of final parts; only 1% is using the technology expressly for final product production. As companies wade into 3DP—either through implementing or at least through experimenting and/or assessing a potential application—the technology at present is still limited in the size, strength and complexity of products it can produce, even as it picks up steam as a powerful R&D tool.

Mainstreaming 3DP rapid prototyping

Large manufacturers with talent and capital resources already have embedded 3DP into their R&D cultures. General Electric Co., a leader in the technology for two decades, has a global network of 600 engineers involved in 3DP technology.⁴ GE, which raised its commitment to the technology through its 2012 acquisition of Morris Technologies, a 3DP specialist, estimates that currently less than 10% of its products are “touched” by 3DP (either through prototyping or final production), but that percentage will increase to 50% by 2020.⁵ Or, take Ford Motor Co., which is taking 3DP’s accelerated prototyping path for parts including brake rotors, rear axles and cylinder heads for its EcoBoost engines. Printing the prototypes (using 3DP binder jetting technology) for the cylinder heads—which have complex configurations including ducts and valves—enables the auto giant to skip the steps of designing a sand mold and a tool to cut castings from those molds. Ford said the technology saved up to two months.⁶ Ford announced at the 2014 North American International Auto Show that it had printed its 500,000th part—a prototype engine cover for its new Mustang model.⁷

4 GE website <https://www.ge.com/stories/additive-manufacturing> retrieved March 9, 2014.

5 “GE: 3D Printers To ‘Touch’ Half of Its Manufacturing,” *Investors Business Daily*, October 7, 2013.

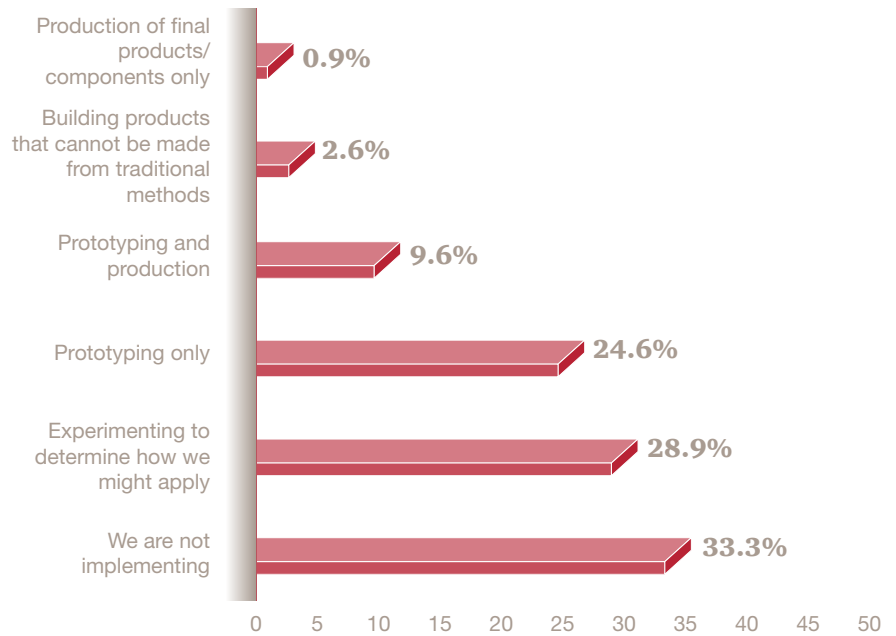
6 “Printing Out Barbies and Ford Cylinders,” *Wall Street Journal*, June 5, 2013.

7 “Why 3-D Printing Is Crucial to Ford Motor Company’s Survival,” *The Motley Fool*, January 19, 2014, retrieved on March 20, 2014. <http://www.fool.com/investing/general/2014/01/19/why-3-d-printing-is-crucial-to-ford-motor-companys.aspx>

It's often not the part itself where 3DP plays a role, but rather the 3DP-created dies and molds that are printed (for traditional manufacturing, such as injection molding). This yields cost and time benefits, an approach already underway in the aerospace and automotive industries. Increasing potential is seen in 3DP-produced molds for large parts—such as composite panels for automobiles—which could abbreviate the speed-to-market for new automobile models, for example.

3DP chiefly used for prototyping by industrial manufacturers

Q. How is your company currently using 3DP technology?



Number of respondents: 114

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

The longest mile: From prototyping to final product

“I see manufacturing taking a profound turn with additive technologies in the next five years. We’ll see elite job shops grow, and new start-ups grow. We’ll also see blue-collar employees learn the technology and adapt and start wearing white shirts. This growth will in turn help develop the localization and regionalization of manufacturing, where the traditional barriers of economies of scale are lifted. We’re seeing customers that are more interested in delivery time than they are about price.”

—S. Kent Rockwell
chief executive officer and chairman of
The ExOne Company, a global provider of
3D printing machinery and printed
products to industrial customers

Crossing the threshold from 3DP-produced prototype to final product has largely been confined to specialized, low-volume and customized products. Half of manufacturers said that it is “likely” or “very likely” that 3DP will be used mostly for low-volume, highly specialized product over the next three to five years; 20% believed the technology would be used for high-volume production, according to the PwC Innovations Survey. Adopters are finding that it reduces wasted material in parts that are difficult and complex to make through traditional processes, especially for parts with internal structures that add strength, reduce weight and increase functionality. A burning question is how much of a future 3DP has for production of final parts.

3DP printer maker Stratasys, whose Redeye division, which operates as a sort of contract manufacturer for manufacturers and entrepreneurs, has already seen a dramatic shift in the last several years as its orders go from “virtually” all being prototype product to “about 65%” being manufactured product (final, end-use product or a final mold or fixture), according to the Stratasys executive vice president for corporate affairs, Jon Cobb.

The technology has gained adherents in the medical devices industry for uses that include advanced prosthetics, and, potentially, even printed living tissue. Hearing aid makers, such as Denmark’s Widex, have been printing final product for decades, and are continuing to use more advanced printers to make ever-smaller hearing aids.⁸ An estimated 10 million “in-the-ear” hearing aids (where the ear canal is scanned and hearing aid shells are

printed) are currently in use.⁹ Meanwhile, Nike printed football cleats (the Nike Vapor Carbon) for players in Super Bowl 48 incorporating a new shape for improved traction. The development time, which would typically take two or three years, reportedly took about six months, according to the company.¹⁰ And fine mesh, printed from polymers, is closing in on the fashion industry. Even 3DP bikinis, made from threads 0.7 mm thick from Nylon 12, have arrived.¹¹

3DP’s consolidating effect The technology is also simplifying design. It’s enabling designers to print products that might otherwise be created via the assembly of numerous parts, thereby consolidating them in a product that has fewer parts. Take GE for example, which is printing fuel nozzles in one piece—rather than assembled in 20 parts through traditional means—for its LEAP engines. It has plans to print as many as 45,000 annually with cost-savings of up to 75%.^{12, 13} The company is developing a “micro-factory” to roll out the printed parts, adding to one already in use devoted to 3DP rapid prototyping. Boeing already makes about 300 different smaller aircraft parts using 3DP, including ducts that carry cool air to electronic equipment. Some of these ducts have complicated shapes and formerly had to be assembled from numerous pieces,

9 “Additive Manufacturing and 3D Printing,” *INGENIA Magazine*, Issue 55, June 2013, Royal Academy of Engineering.

10 “For Super Bowl, Nike Uses 3-D Printing to Create a Faster Football Cleat,” *WIRED*, January 10, 2014.

11 Continuum Fashion website, retrieved from <http://continuumfashion.com/N12.php>

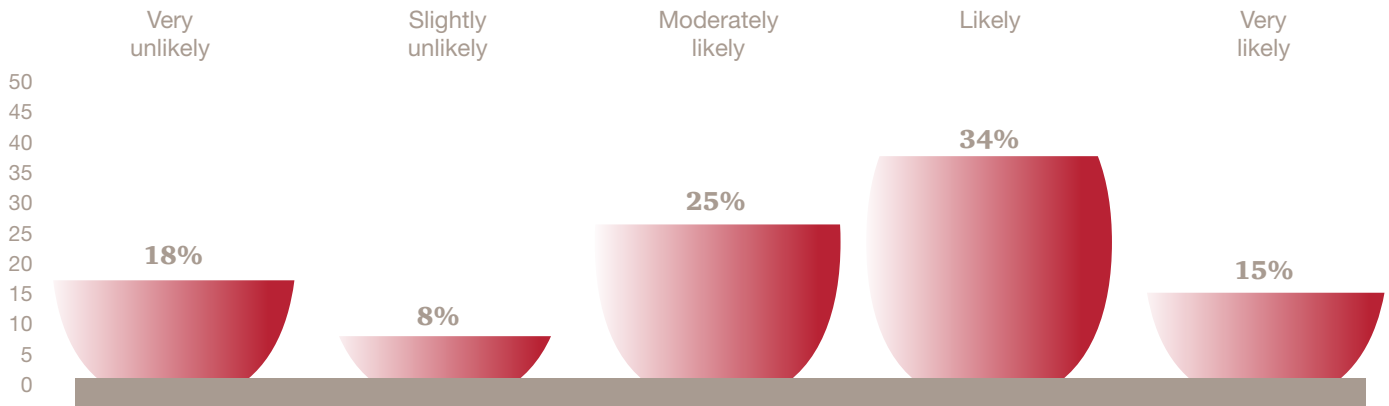
12 “GE Printing Engine Fuel Nozzles Propels \$6 Billion Market,” *Bloomberg*, November 12, 2013.

13 “From teeth aligners to jet engine parts: 3-D printing’s booming business,” *CNBC.com*, August 17, 2013.

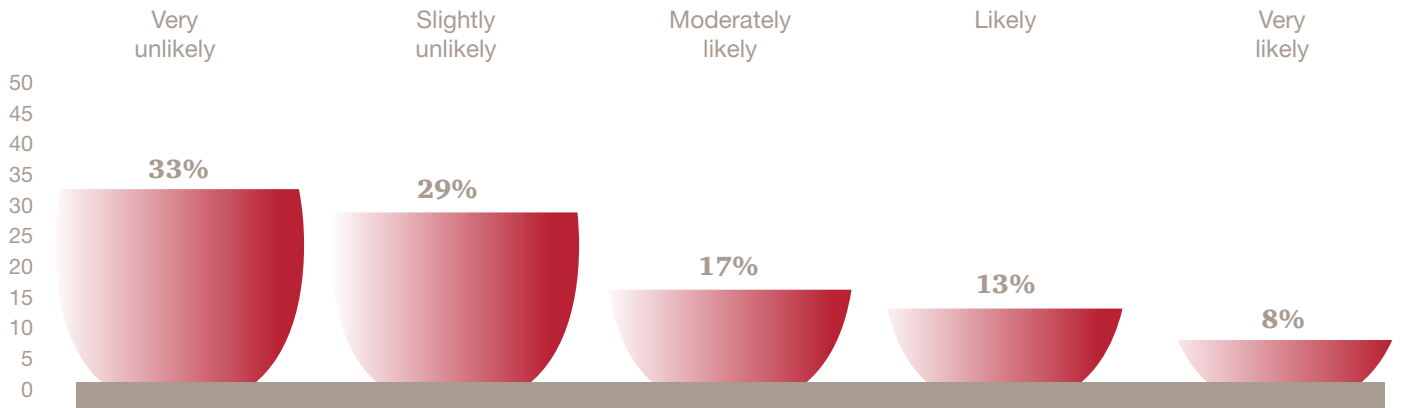
8 “Hearing Aid Manufacturer Widex A/S Purchases Multiple Viper SLA Systems,” 3D Systems press release, June 10, 2003.

Sweet spot in 3D-printing is in low-volume, highly specialized products

Q. Over the next 3–5 years, rate the likelihood that 3-D applications will be used mostly for low-volume, specialized products.



Q. Over the next 3–5 years, rate the likelihood that 3-D applications will be used for high-volume production.



Number of respondents: 110

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

boosting labor costs. The company notes that it can save up to 30% through printing compared to traditional manufacturing.¹⁴

Lonnie Love, a robotics and 3DP researcher at Oak Ridge National Laboratory, has firsthand experience of 3DP's consolidating effect. He is redesigning a robotic arm for the US Army that had 238 distinct parts, and had the hydraulics printed into the structure obviating the need for conventional hoses. "With 3DP, we're now down to 28 parts. We did this by combining and integrating parts that had previously been separate," Love said in an interview with PwC.

Next-gen materials to next-gen products

On the materials science front, research is unveiling new possibilities—adding to a growing list of “inks” which include now-conventional ones such as polymers, ceramics, metals and glass. Take, for example, the entrance of graphene, the carbon-based material, on to the 3DP stage. Touted as a supermaterial, graphene holds promise in electronics, communications and energy storage. Graphene 3D Labs, a company founded in 2013 to research new 3DP inks, has produced a graphene-based “nano-composite” which CEO Elena Polyakova said the company expects to make available commercially by 2015. Graphene, when added in small quantities to material, such as polymers, adds mechanical strength and significantly improves the thermal and electrical conductivity properties of the material to which it is mixed. Polyakova believes the “inks” are just beginning to evolve and that, potentially, a greater variety will spur wider adoption of 3DP by consumers and manufacturers. “Yet, prices for the inks have a way to go for wider adoption to take hold,” she said in a PwC interview. She noted that material scientists ought to be developing the 3DP industry in greater cooperation with mechanical and software engineers, who are developing the printers and 3DP software. “As next-generation printers start accepting new materials—and when multiple-material printers become common—we’ll see more entrants come into the 3DP ink market,” Polyakova said. She added that the company is seeing interest in printing with graphene-based materials “from all fronts—from artists to the US military, which is interested in

using graphene to develop smart devices like helmets and vests with built-in electronics.”

The fourth dimension Pushing inks to still another level, there's the prospect of 4-D printing—which incorporates “shape memory” fibers into inks which assume different forms (by folding, curling, stretching or twisting) under certain thermal or mechanical forces or other conditions. The 4-D technology could usher in a new era of building functionality into products (e.g., pipes that expand at a certain temperature or material that “reassembles” into a new shape when in contact with water). Alternatively, it could be used to produce hard-to-manufacture shapes, such as a helicopter blade that morphs into a desired shape that's costly and time consuming to achieve through conventional means. “I think we're about five years away from seeing 4-D printing yield critical applications,” noted H. Jerry Qi, associate professor, *mechanics of materials* at Georgia Institute of Technology, a researcher of shape memory fibers, in a PwC interview. “For example, producing an aircraft part made from composite materials is a highly laborious, time-consuming and expensive process. If we could 3D print these composite parts—using multiple materials to build strength—that would be a real game changer,” Qi added.

Printing an “intelligent system”

As printers advance to multiple materials that are distinctly different (such as ceramics, composites, polymers, and metals), possibilities for wider applications are likely to grow significantly. This is especially the case for products comprising a system of parts and incorporating intelligent functionality—such as sensors, electronics, communications, and microprocessors—making possible the printing of electrical circuits and transistors, for example, into a product. “With current technology, one can add sensors and electronic elements such as wires or induction coils with most of the complex elements produced by traditional means and then added to 3D-printed objects. However, actually printing electronic elements on the inside of the object takes design and production to an altogether different level,” said Elena Polyakova, Ph.D., CEO of Graphene 3D Labs.

“The important thing now is to advance 3D printing with two distinctly different materials—say, polymers and metals or polymers and ceramics. That will be a game changer. For example, if we could print polymer with copper wires within the part, that would expand applications. This is the design and 3D printing of systems, as opposed to parts. For example, one could eventually build a helicopter with an energy storage printed into the inside to allow for wireless recharge over a telephone line. It's hard to do this conventionally with all the parts—and even all the fasteners which add so much weight.”

—Dr. Lonnie Love
group leader—manufacturing systems,
Oak Ridge National Laboratory

¹⁴ “Next 3-D Frontier: Printed Plane Parts,”
Wall Street Journal, July 14, 2012.

Reaching the 99%: Small and medium manufacturers

Beyond the headway that large manufacturers—and hobbyists—are making around 3DP adoption, it is likely that the technology’s penetration will be dictated by the extent to which small and medium sized enterprises embrace it. How quickly and innovatively this swath of companies, comprising the vast network of suppliers, advance 3DP manufacturing could have profound effects on the large clients they supply in sectors such as automotive, aerospace and defense, energy, and medical devices. Consider that 63% of manufacturers surveyed believe that at least half of all manufactures will adopt 3DP in the next three to five years, according to the PwC Innovations Survey. It’s interesting to note, for example, that small manufacturing firms (under 500 employees) comprised 99% of the 284,941 firms in the US in 2013.¹⁵ “We’ve had about 500 companies

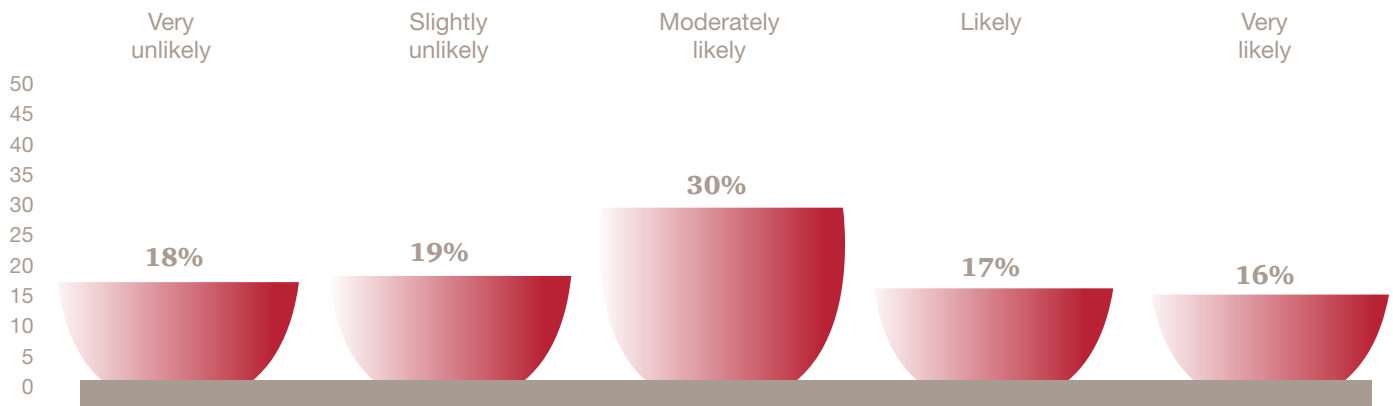
through our lab [at Oak Ridge National Laboratory] and about 2,000 people checking out our research. It’s a constant rush,” said Lonnie Love, a researcher at Oak Ridge National Laboratory. “Companies like FedEx and UPS see a revolution coming, and they want to get out in front of it. But we get interest from companies in the tooling industry, too. The work they do can be very expensive and slow, and much of it has been offshored. With 3D printing, metal parts can take days instead of months and a few thousand dollars versus hundreds of thousands,” added Love.

Small, but keeping pace According to our survey, 59% of enterprises with fewer than 500 employees are implementing 3DP in some way, compared to 75% among

larger firms (more than 500 employees). Another big difference between small and big manufacturers lies in the number that have no plans whatsoever to use 3DP—15% of smaller firms say they have no plans compared to 2% among larger firms. Scott Paul, president of the Alliance for American Manufacturing, believes raising the 3DP adoption rate is key to the future of small manufacturers, especially tool and die shops that can diversify into printing. “As we see the possibilities of new materials expand and the cost of industrial printers go down, and the print speeds rise, you’ll see adoption not only by larger companies, but also by the smaller companies. Take for example all the smaller tool and die companies that do have capital expenditure capability to invest in additive manufacturing, which will be able to take

Most survey respondents believe 3DP will be adopted by more than 50% of US manufacturers in the next 3–5 years

Q. Over the next 3–5 years, rate the likelihood that 3D applications will be adopted by more than 50% of manufacturers.



Number of respondents: 110

Source: PwC and Zpryme survey and analysis, “2014 Disruptive Manufacturing Innovations Survey,” conducted in February 2014.

¹⁵ “Facts About Manufacturing,” The Manufacturing Institute, the Manufacturers Alliance for Productivity and Innovation, and the National Association of Manufacturers, (retrieved from NAM website, http://www.manufacturingfacts.org/single-project_10.html)

3DP Adoption: Small firms keeping pace with larger firms

3DP adoption among **small** companies
(under 500 employees)

3DP adoption among **large** companies
(500+ employees)



59% of companies are adopting 3DP in **some way** (Experimenting to determine how they might apply it, or using it to prototype products or producing final products.)

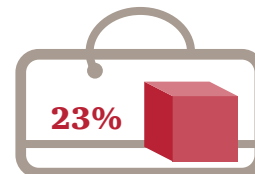


75% of companies are adopting 3DP in **some way** (Experimenting to determine how they might apply it, or using it to prototype products or producing final products.)



26% of companies plan to adopt 3DP in the future in some way

- 7% within the next year
- 14% within 3 years
- 5% some time beyond 3 years



23% of companies plan to adopt 3DP in the future in some way

- 4% within the next year
- 7% within 3 years
- 12% some time beyond 3 years



15% of companies do not plan to adopt 3DP ever



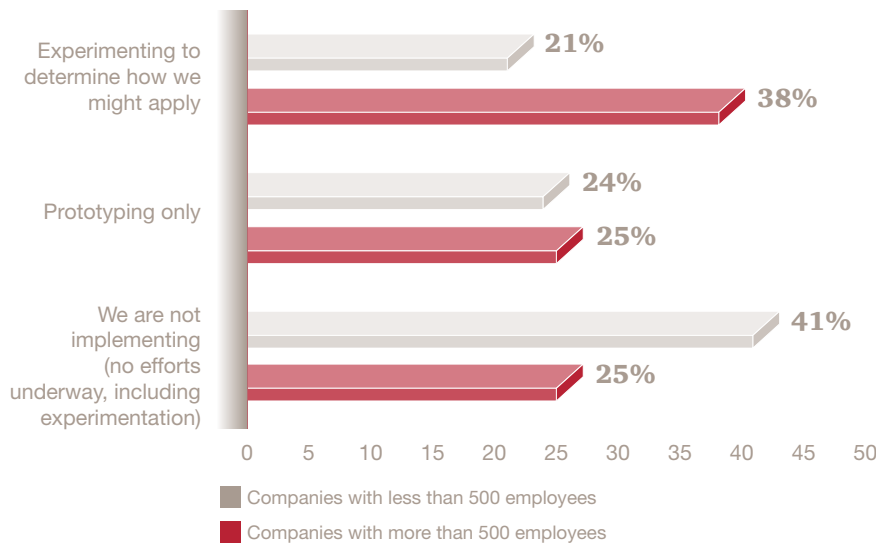
2% of companies do not plan to adopt 3DP ever

Number of respondents: 116

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

Wider 3DP adoption and more tinkering among large companies

Q. How is your company currently adopting 3DP technology?



Number of respondents: 114

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

on more jobs and grow into larger-scale job shops or even tech shops and evolve from the traditional tool-and-die firms. So, we'll see evolution, but some companies which do not evolve may not hold strong growth prospects," said Paul in a PwC interview.

Fourteen men and a printer....and 300 orders later Consider the experience of a second-generation Toolmaker with three generations of family working at his company in Hutchinson, Minnesota. Two years ago, Jon Baklund purchased a \$165,000 Stratasys 400m industrial printer for his machine shop, Baklund R&D LLC. Since then, Baklund has filled some 300 orders for a total of about 2,000 3DP-produced parts for clients, with roughly 80% of those parts being prototypes and the rest final products. Baklund recently produced very complex fixtures for a large medical device company using a combination of computer numeric control (CNC) machining processes, and that order was followed by an order for 300 of the fixtures produced through 3DP. "3D printing is definitely great for prototyping and can create things that would be virtually impossible to create through traditional machining. We often machine complex metal parts and attach them to a printed part—or do traditional machining to a 3DP part—so we're literally mating the technologies. Our primary tools sometimes become secondary to 3D printing," Baklund said in a PwC interview. "Additive manufacturing is by no means a replacement for traditional manufacturing—it is truly an additive process in our shop in many ways, and it allows us to have much flexibility in serving our clients," he added.

Can 3DP shrink the supply chain?

“If I were a manufacturer, I would buy a mid-sized printer in the \$20,000–\$30,000 range, hand it over to my engineers and have them use it, and learn it for their purposes...learn the advantages and disadvantages. This approach is as valid for a small machine shop as it is right up to the huge diversified manufacturer.”

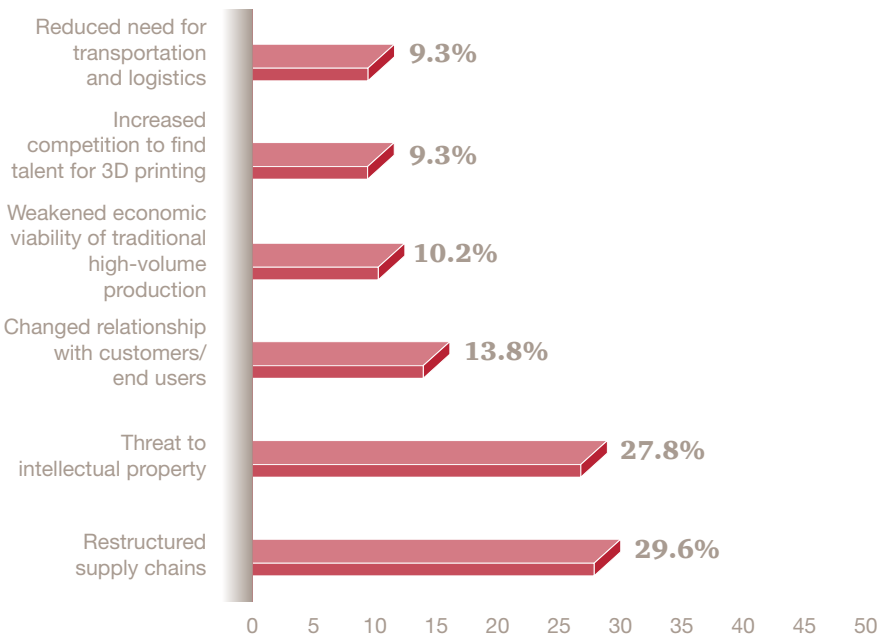
—Dr. Lonnie Love,
group leader—manufacturing systems,
Oak Ridge National Laboratory

The allure of “on-demand” For some industries and some products, the concept of “on-demand” manufacturing could radically change business models and supply chains. Consider the homeowner needing a spare part for a dishwasher. He orders the part online from the manufacturer, receives a bar code for the part and gets it printed at a local 3DP center, perhaps at a library, post office or a big box retailer. Or an airline carrier that needs a spare part for a jet in Singapore prints it on a printer installed at the airport for such needs.

These scenarios shrink the supply chain to almost one link—eliminating those connecting development, prototyping, production, delivery, and warehousing of parts. According to our survey, about 30% of manufacturers believe that, potentially, the greatest disruption to emerge from widespread adoption will be “restructured supply chains (followed closely by “threat to intellectual property”). Logistics companies see this coming. UPS is testing 3D printing services aimed at start-ups, small businesses and retail customers at six test locations including San Diego and New York City.¹⁶ Retailers may well be close to following suit. Staples and Mcor Technologies, a maker of paper and 3D printers, recently launched its first 3D printing “experience center” in the Netherlands to introduce 3D printing technology and services to its customers.¹⁷

How could 3DP disrupt? Supply chain restructuring, intellectual property threats top list

Q. If and when 3D printing is widely adopted, what will be the most disruptive effect on US manufacturing?



Number of respondents: 108

Source: PwC and Zpryme survey and analysis, “2014 Disruptive Manufacturing Innovations Survey,” conducted in February 2014.

Opening the door to customization, testing new products Companies could also avoid producing products that are unpopular—and only print those products that are. This is the “lot of one” model, which opens the door to customization of popular products, especially in the case of retail consumer goods. Toys “R” Us has offered customized rubber ducks in a store in Hong Kong.¹⁸ Manufacturers of consumer products, for example, could

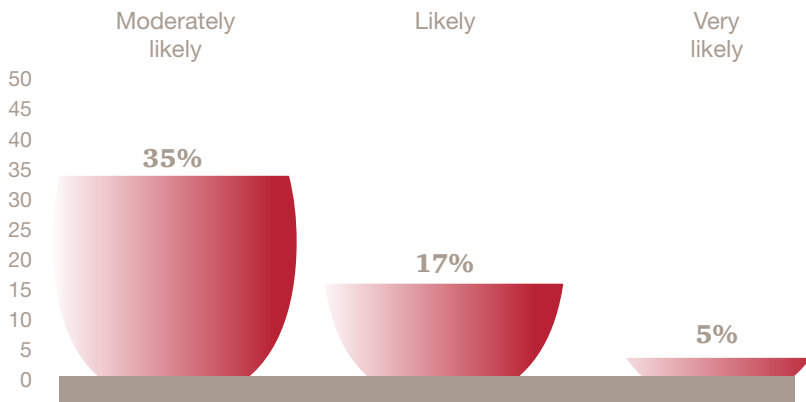
¹⁶ UPS company website, <http://www.theupsstore.com/small-business-solutions/Pages/3D-printing.aspx>, retrieved on March 14, 2014.

¹⁷ “Staples’ First 3D Printing ‘Experience Centre’ goes live, powered by Mcor Technologies,” Staples press release, April 29, 2014.

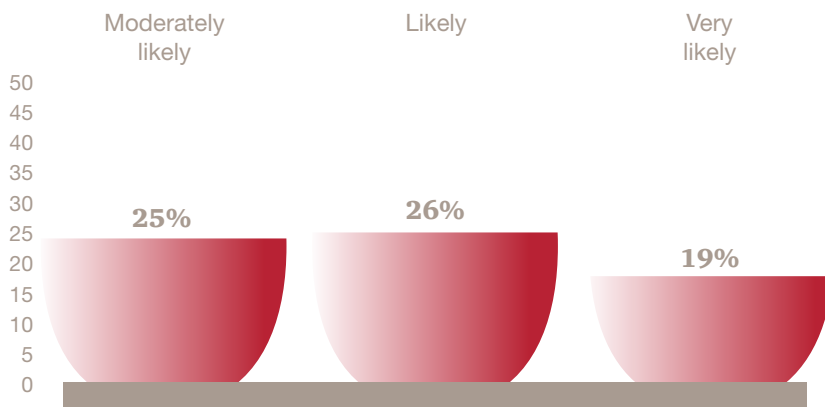
¹⁸ “3D printed mini yellow ducks debut in Hong Kong,” www.3ders.com, June 6, 2013.

Fertile 3DP ground seen in after-market and obsolete parts production

Q. Over the next 3–5 years, rate the likelihood that 3DP applications will be more useful in producing after-market products.



Q. Over the next 3–5 years, rate the likelihood that 3DP applications will be useful to replace obsolete parts.



Note: Not all responses were included and therefore do not add up to 100%.

Number of respondents: 110

Source: PwC and Zpryme survey and analysis, “2014 Disruptive Manufacturing Innovations Survey,” conducted in February 2014.

even test the market first with 3DP, and turn to traditional high-volume manufacturing for those products that do attract orders, thus avoiding holding inventory for products with little or no demand.

New era for entrepreneurs Companies in a first wave of serving entrepreneurs—and even small manufacturers—with 3DP services (i.e., 3DP designs, or actual printing), include RedEye (owned by 3DP developer Stratasys), Middler, Shapeways, Thingiverse, and MakerBot’s digital store, to name a few. This ushers in an age for designers and entrepreneurs that focus on design and marketing, and less on production and even distribution and inventory management.

The after-market: adding speed, easing logistical logjams Looking ahead, 3DP could potentially make significant inroads in the after-market of products, particularly for manufacturers of products with long lives and a high demand for parts replacement and repair and even for obsolete parts. Beneficiaries of this model could include industries such as aerospace, consumer appliances, electronics, transportation, power and utilities, and energy. According to manufacturers we surveyed, 70% believe that, in the next 3–5 years, 3DP would be used for obsolete parts, while 59% said that it was likely that the technology would be used for the production of after-market products. Assuming an availability of local industrial printers, companies could have spare parts printed as needed, obviating the need for a complex supply chain and expensive inventory and delivery system. In the same vein, in an effort to lighten the logistical burdens for soldiers in the field, the US Army is using mobile, deployable printing stations for troops in Afghanistan.¹⁹

¹⁹ Reardon, Sara, “US Military Gets Into the 3D Printing Business,” *New Scientist*, October 18, 2012.

3DP-generated savings in the after-market: a glimpse at how they could be captured

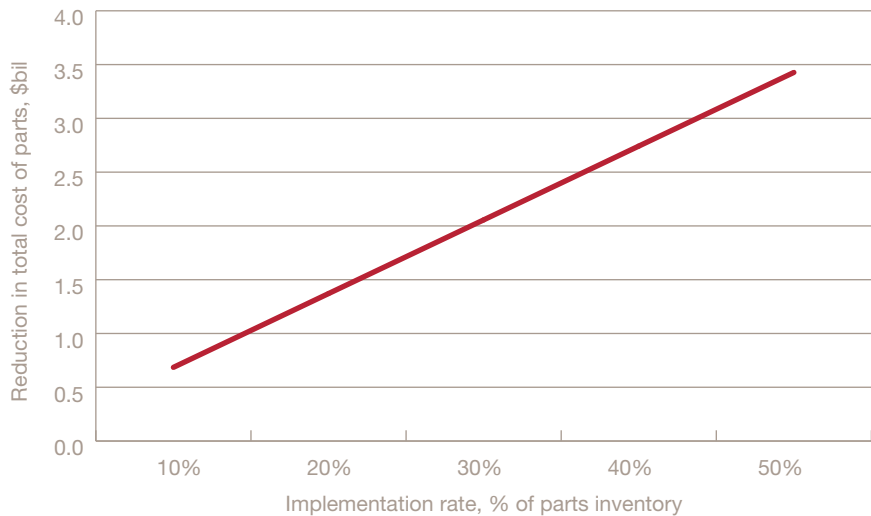
Apart from the speed and agility that 3DP could usher in for the after-market side of businesses, what could 3DP bring in bottom-line benefits? Clearly, that would vary drastically industry-by-industry. We honed in on two industries—aerospace and airlines—to see how 3DP could translate into savings.

A PwC analysis, conducted for this report, of the benefits of potential 3DP adoption in the aerospace MRO market found that global aerospace MRO costs could be reduced by up to \$3.4 billion, assuming that 50% of parts are printed. Even if 15% of aerospace replacement parts could be printed, we could expect over \$1 billion

of materials and transportation-related savings. Another PwC analysis, conducted for this report, looks at the potential benefits 3DP could usher in for the airline industry. Assuming that half of MRO materials are 3D printed, our analysis finds that the global airline industry could realize about \$1.8 billion in additional pre-tax profits annually as a result of the printing technology savings. Incremental pre-tax profits could top \$1 billion for the global industry, even at a more conservative 3DP penetration rate. A third analysis, also conducted for this report, suggests that the airline industry could benefit from 3D printing through lower global airline industry inventory costs. This analysis estimates additional liquidity of between \$50 million and \$250 million for the industry, depending on 3DP penetration rate. The figures below detail these three analyses:

Aerospace + 3DP

How 3DP could save the global aerospace industry up to \$3.4 billion in MRO savings.



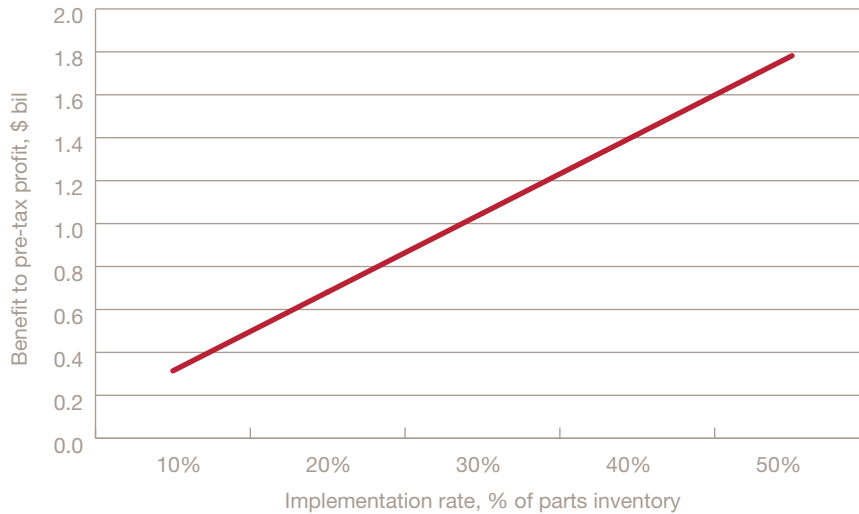
Source: PwC analysis conducted for this report

Note: Part cost savings were calculated using market size and a cost savings estimate across scenarios of various penetration rates. Transportation costs savings were derived from applying a benchmark of supply chain cost percentage to addressable market at these same penetration rates.

Airlines + 3DP

How 3DP could generate as much as \$1.8 bil in incremental pre-tax profit in the global airline industry.

Global airline industry pre-tax profit benefit from 3D printing implementation, \$ bil

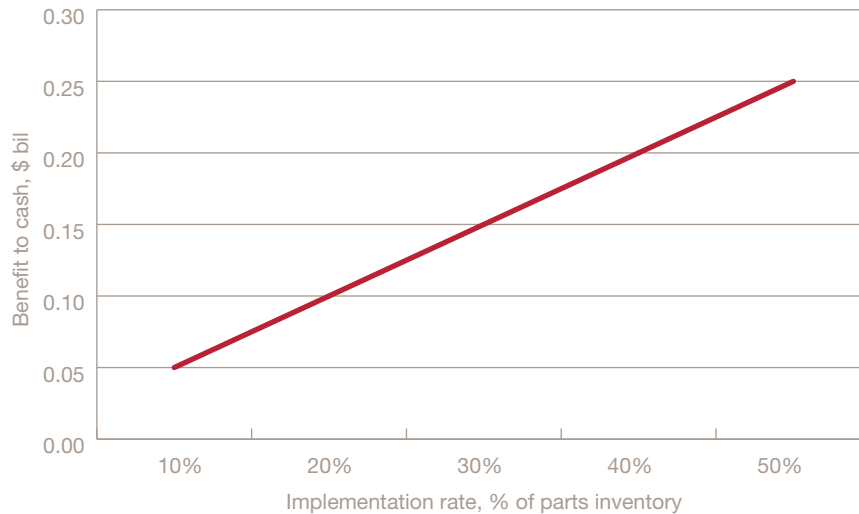


Source: Company reports and PwC analysis conducted for this report.

Note: The profitability model uses a benchmark of parts-related inventory cost, and applies a cost savings estimate across a range of penetration rates, while netting out incremental depreciation expense.

How 3DP could benefit global airline inventory liquidity by as much as \$250 mil.

Global airline industry liquidity benefit from 3D printing implementation, \$ bil



Source: Company reports and PwC analysis conducted for this report.

Note: The liquidity model adjusts a benchmark of parts inventory downward due to estimated cost savings, while taking into account the likely required increase in raw material inventory. The net cash benefit as a percent of sales for the airline sample was then applied to the level of global airline industry sales.

3DP's beneficiaries?

Manufacturers poised to benefit through 3DP adoption

Near-term:

Original equipment/parts manufacturers of

- **Low-volume and/or new designs** not economically attractive through subtractive production methods (e.g., **aerospace**) and/or more customized products such as hearing aids or knee replacements (e.g., **medical devices**), goods and products that are frequently **updated and re-designed**.
- **After-market goods production**, including aerospace **MRO firms** that can limit or eliminate buffer inventory with on-demand production at local maintenance facilities.
- **Complex and older generation products with many parts**, and **obsolete parts** that are still in demand (e.g., **heavy machinery, energy, agricultural equipment makers**).
- **Products that incur high fuel and/or other operating costs** 3DP can make possible new, and potentially more efficient, product designs.

Longer term:

Possibly, 3DP could break more into other sectors such as **auto manufacturing** for some higher-end/low-volume equipment, as well as after-market sales for older vehicles. **White goods/appliances** also could benefit in the after-market. Additionally, companies offering **3DP inks/feedstock**, such as plastics, polymers, metals and ceramics, cement, carbon composites, graphene (e.g., **chemicals** and **metals** sectors) could also benefit. **Retailers that offer 3DP services** (big box, large online retailers) particularly those with wide geographical networks of printers or "printer farms."

Manufacturers not poised to benefit immediately through 3DP adoption

Industrial machinery It is likely that 3DP will become a standard technology (in concert with their existing CNC extractive manufacturing technology) offered by industrial machinery companies in the near future. It may well help revive this industry and help regain business that has been offshored. Those that do not will likely lose a competitive edge to those that do adopt this technology.

Transportation and logistics As more parts and goods are printed locally, freight transportation volumes will be impacted. Express delivery firms that deliver replacement parts could be highly affected. There are already 3DP service pilots in retail locations for businesses and consumers, and, if this trend grows, it could potentially impact warehousing of replacement part inventories, and even **air cargo and ground transport** firms.

Patent-reliant industries with weak intellectual property protection IP protection is a major issue surrounding the growth of 3DP that has not yet been solved. Platforms through which customers can purchase a license to 3D-print product already exist and will likely proliferate, opening the gate to potential IP losses. Regulation and certification of 3DP industry will likely be a hot topic as 3DP adoption grows.

3DP and the industrial worker: Awkward bedfellows?

As manufacturers enter the 3DP playing field, a big part of their strategy will be retraining an existing workforce or drawing in new talent with the skills to create digital designs as well as oversee the printing production (and, in some cases, execute on additional post-printing work). Clearly, as there's no one 3DP production strategy, there's also no one 3DP talent strategy, either. It is telling, however, that 45.3% of manufacturers attributed their "lack of current expertise in our company to fully exploit the technology" as one of the top barriers they see in implementing 3DP in their business, according to the PwC Innovations Survey.

More printer farms, fewer (human) workers? But, a future of "printer farms" with dozens of printers humming away overseen by only a handful of workers, certainly raises the spectre of losing manufacturing jobs (yet again) to laborsaving technology. While it may be too early to discern how 3DP will alter the industrial workforce, the arrival of 3D printers may well be a double-edged sword—cutting into the ranks of unskilled factory floor workers, but adding jobs for workers with technical know-how or those who can be trained to acquire it. Fears of lost jobs likewise emerged with the widespread adoption of computer numerically controlled equipment and greater automation, and advanced robotics. "With any kind of new automation technology, factories become more flexible, making more customized products, and that automation

can bring job losses," said Scott Paul, president of the Alliance for American Manufacturing in a PwC interview. "But with a technology such as 3D printing, it's about positioning companies so they can bid for more jobs not just in the US but also globally and gain market share. And with greater market share comes the need to hire more talent," Paul added.

Jon Cobb, Stratasys' executive vice president for corporate affairs, said that while there may be job losses for companies shifting a large part of the production to 3DP, he also notes that workers at some companies Stratasys consults are being retrained, and that some companies are interested in how 3DP can contribute to re-shoring jobs back to the US that were offshored 20 years ago. He added that he expects students entering the workforce may be attracted to 3DP's "cleaner" sort of manufacturing. "I think there's a generation that is genuinely attracted to making things you can hold in your hand, and this technology really attracts people who are creative. So with some job losses, the excitement around the technology will likely bring in a new type of worker to manufacturing," he added.

Add 3DP to core 21st-century skills

Lonnie Love, Ph.D., a researcher with Oak Ridge National Laboratory, sees 3DP as yet another core 21st-century discipline the public and private sectors need to promote to make US manufacturing more competitive. "We, as a country, need to

include 3D printing training in the same way we need STEM (science, technology, engineering and math) skills. We open our lab to students here at Oak Ridge to give them hands-on experience. These students also need to know how to use a lathe or a drill press, because often printing a part is only part of a job to finalize a product. The only way to learn is to get a printer and start using it. Having a printer in-house is essential to learn what you can and cannot do," said Love. Love is also involved in 3DP training and education initiatives. One plan is for Oak Ridge to distribute 28,000 3D printers to schools nationwide, with about 4,000 distributed in 2014.²⁰

If widespread adoption does materialize so, it could draw a new group of talent into manufacturing that might not have considered it a decade ago. "The evolution of the design software has really driven adoption and has created a culture of design freedom. And as the 3DP industry grows, we'll see a lot of talent needed in manufacturing that can carry out designs," said S. Kent Rockwell, chief executive officer and chairman of ExOne, a global provider of 3D printing machinery and printed products to industrial customers. "3D printing will give manufacturing a whole new world of opportunities, and there will be a new type of entrant into manufacturing—the free thinkers and the creative. Because of this, I think that Silicon Valley and its community of entrepreneurs will play a larger role in its adoption, and, by doing that, help bring back manufacturing in the US," added Rockwell.

Jon Cobb, Stratasys' executive vice president for corporate affairs, said that while there may be job losses for companies shifting a large part of the production to 3DP, he also notes that workers at some companies Stratasys consults are being retrained, and that some companies are interested in how 3DP can contribute to re-shoring jobs back to the US that were offshored 20 years ago.

²⁰ "3-D Printing and the Skilled Workforce of the Future," *Industry Week*, November 11, 2013.

Shaping your 3DP strategy

“Some adopters will learn the technology and apply it in-house, while others are just as happy to focus on the design aspect and leave the actual printing to us. But working with a company through a developmental contract to get them on a path of adoption could take 12 months—from initial consultation, to having a product ready for final use. Initially companies are using it for low-batch production, but over the next five to seven years, we’ll see larger runs being printed. For example, some of our customers wanted just five to 10 parts, now they’re asking for 25 to 50. We find that speed and cost savings, in addition to optimization of existing parts impress our clients about 3D printing.”

—S. Kent Rockwell
chief executive officer and chairman of
The ExOne Company, a global provider of
3D printing machinery and printed
products to industrial customers

As 3DP takes root in the US industrial manufacturing sector, there are early adopters, the sprinters, the innovators, and those who have yet to even consider how they may use the technology. If, as the PwC Innovations Survey suggests, half of manufacturers will have adopted 3DP to some degree in the next five years, it could indeed change the face of manufacturing—not only the original equipment manufacturers, but also, perhaps more importantly, the vast network of smaller suppliers they rely on as vendors.

The sideliners: What barriers are keeping some companies away? But, what of the manufacturers sitting on the sidelines with

no plans to adopt 3DP? What will it take for them to enter? Our survey provided some suggestions of which barriers seem to be the steepest. Topping the list of barriers to implementing a 3DP strategy is uncertainty of a 3D-printed products’ quality, followed by lack of talent to exploit the technology and the price of printers. “What we often see is that the companies that get into 3DP may only have one engineer or one champion who is the prime mover and convinces the organization to buy a printer, said Jon Cobb, Strataysys executive vice president for corporate affairs. “And if you don’t have that champion, the technology simply is not taken up. Or, companies which are high-volume producers look at the price per piece and feel 3DP is simply not economically viable—but there are other costs they can save, such as warehousing, materials cost, labor. So, these savings can also be overlooked when only looking at the price of one part [in assessing 3DP versus traditional manufacturing],” Cobb added.

Other future limitations

IP protection Apart from the more typical barriers to entry posed by new technology adoption, there are other potentially nettlesome hindrances to widespread adoption of 3DP. Intellectual property protection looms as a potential concern, in which a world of CAD-files, 3D scanners and printers could open the door wider to patent infringement. Take, for example, the simple act of 3D scanning a complex part and producing a mold, which could be used for mass production. Or a hacker gaining access to CAD files that are “printer-friendly.” Gartner’s analyst group forecasts that annual IP losses due to 3DP could reach \$100 billion globally by 2018.²¹ “There is no question that IP issues will become more and more complex. Who

owns the designs? How do companies protect from breaches of intellectual property? In a way, CAD files are like music, and you can see how that industry has struggled with the protection of its IP rights. So, we need to stay ahead of that by continuing to advance our know-how and expertise,” said ExOne’s CEO S. Kent Rockwell.

Making the grade A potential bottleneck for widespread adoption of 3DP may be in how well printed parts or components can perform, and whether they will gain certification or approval for use by regulating bodies. Despite current limitations in materials and speed, companies are dipping their toes in. Take BAE Systems, which gained EASA (European Aviation Safety Association) Form 1 approval for use of a plastic window breather pipe in its BAE 146 regional jet. With the original tooling for the part no longer available, the company turned to 3DP. Printing the parts saved the company 60% compared to what it would have cost to make them with injection (not counting the costs from new tooling).²² Or Solid Concepts, a California-based contract manufacturer, which specializes in additive manufacturing for the automotive, aerospace, and other industries, which gained an FAA Form 8130 approval for a printed air duct for use on the Orbis DC-10.²³

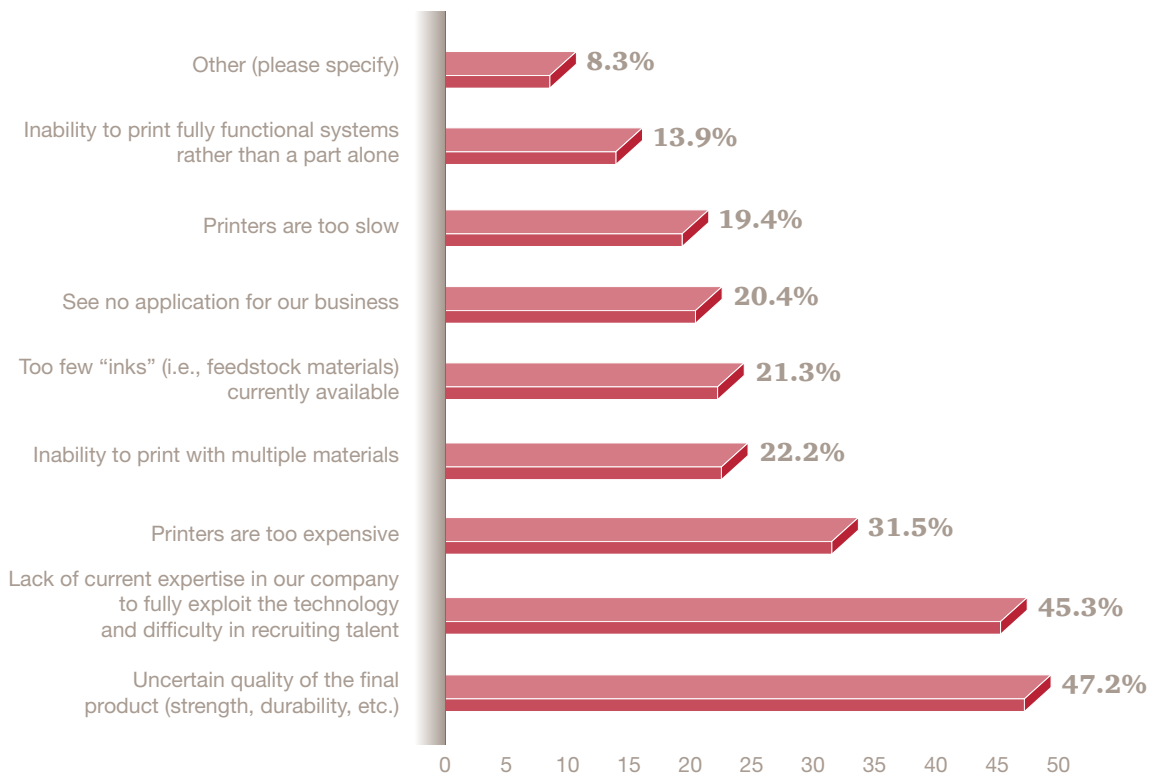
²² “BAE Systems Produces 3D Printed Part for Use on BAE 146,” AeroNewsNetwork.com, January 22, 2014.

²³ “Solid Concepts 3-D Printed Components Take Flight,” AINonline.com, October 20, 2013.

²¹ “Gartner: 3D printing to result in \$100 billion IP losses per year,” www.3ders.com, October 13, 2013.

Print quality and talent are top barriers to 3DP adoption

Q. What are the barriers to your company's in-house adoption of 3DP?



Number of respondents: 108

Source: PwC and Zpryme survey and analysis, "2014 Disruptive Manufacturing Innovations Survey," conducted in February 2014.

A 3DP self-assessment

Is 3DP for us? And, if not now, could it be in the future? Given both 3DP's potential opportunities—and real barriers—manufacturers of all stripes are, indeed, left with much to consider when assessing a 3DP strategy and considering their own “3DP tipping point.” As with any disruptive technology adoption, companies take different directions and wade in at different speeds. In any case, there are core questions all manufacturers ought to be asking themselves—and actions they ought to be mulling—to exploit 3DP in ways that expands their business and makes them more competitive. Some questions surrounding such a “3DP self-assessment” include:

- How can 3DP be integrated into your research and development (e.g., through rapid prototyping) and can it help get new products released to market faster?
- Do your product lines lend themselves to 3D printing? And which 3DP technology would you need?
- Would it be economically viable now? Could it be if the costs of 3DP go down? What other barriers exist that, if dropped, would make it easier to use 3DP?
- Should your company invest in industrial 3DP technology (buy industrial 3D printers) and recruit talent with the skills to innovate with 3DP technology? Or, does it make sense to partner with a supplier(s) that already has established itself in the technology?
- Can 3DP be used to help your business customize products, or does it make sense to print products on demand in the “lot of one” model?
- Could 3DP present opportunities for your company to diversify into new products and bid on jobs that presently you cannot?
- At what point does it become economically attractive to use 3DP over traditional manufacturing (i.e., injection molding, casting, subtractive manufacturing, machining, milling, and turning), and in which parts of the business (e.g., R&D, testing and custom production)? When does its benefits outweigh the economies of scale that traditional manufacturing has built itself upon over the last century?
- If your business does not find it worthwhile to purchase a 3D printer or to invest in the talent, does your business have access to industrial printers to start experimenting with how it might be applied to your prototyping needs or final product mix?
- What opportunities do you see to “hybridize”? That is, combine 3DP and traditional subtractive processes?
- Could your business take advantage of the growing global network of 3D printers in ways that could simplify your supply chain?
- Will your company be prepared to swiftly exploit the new technology when or if it becomes available?
- Have you assessed the barriers of 3DP for your company (e.g., limited ability to use multiple materials printing one object, process quality and speed, feedstock availability and price, the right talent and skill sets)? Does your company have a plan to adopt 3DP when or if those barriers drop?
- Would it make sense to “buy into” 3DP through an acquisition, joint venture or other business combination in order to have the expertise instead of developing it internally?
- Has your company identified the best vendors/suppliers that could help you wade into 3DP adoption?

Methodology

About PwC's analysis

The aerospace MRO material cost savings model uses the size of the MRO parts market and applies a 25 percent cost savings—which is toward the low end of public estimates from various aerospace companies—across scenarios of 3D printing penetration rates ranging from 10 to 50 percent. Transportation costs savings were calculated by applying a median supply chain cost as a percent of sales to the addressable MRO part market at various 3D printing penetration rates.

The airline pre-tax profitability model uses a benchmark of cost of revenue attributable to parts, and applies the aforementioned cost savings estimate and range of 3D printing penetration rates. These savings were netted against estimated incremental depreciation expense resulting from 3D printer-related capital expenditures.

The airline liquidity model uses a median of parts-related inventory from a sample of publicly available airline financials, and adjusts the level of parts inventory downward based upon the previous 3D printing cost savings estimate for the range of penetration rates applied elsewhere in this analysis. This was partially offset by an estimate of the required increase in raw material inventory (i.e., “inks”). The estimated net reduction in inventory was then calculated as a percent of sales and applied it to an estimate of total global airline industry sales in order to derive the industry-wide reduction in inventory and commensurate benefit to cash.

About Zpryme Research Survey

The survey findings in this report were generated by Zpryme, which conducted an online survey of 120 U.S. manufacturing professionals in February of 2014.

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Elena Polyakova, Ph.D., CEO of Graphene 3D Labs

H. Jerry Qi, associate professor, mechanics of materials, Georgia Institute of Technology

S. Kent Rockwell, chief executive officer and chairman of ExOne

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