BUSINESS MODELS FOR ADDITIVE MANUFACTURING

BY RICHARD A. D’AVENI
A new era in additive manufacturing, or “3-D printing,” is at hand, with major implications for adoption of the technology and for business models that companies can use in taking the plunge. In the three years since I last wrote about the field for HBR (“The 3-D Printing Revolution,” May 2015), additive’s growing capabilities, together with expansion in both the materials available and the supplier ecosystem, have made it possible to affordably produce a much broader range of things—from the soles of running shoes to turbine blades—often in much higher volumes. The technology provides an unprecedented ability to customize products and respond quickly to shifts in market demand. As a result, it is moving from limited applications, such as prototyping and making conventional machine tools, to a central role in manufacturing for a growing number of industries.

Strategically, that means additive is becoming a full-fledged competitive weapon: It can be used to hold on to market leadership, to dethrone a dominant player, or to diversify by exploiting a printer’s capability to make products for different industries. Consequently, leaders need to understand additive’s range and potential and the possibilities that will open up in the near future. This article offers a playbook.

**RECENT ADVANCES**

Let’s start by examining the breakthroughs propelling additive manufacturing’s spread. Technological advances have led to dramatic gains in efficiency and expanded applications in a wide range of areas. The new machines put out products much faster and at lower cost, and the items that emerge from them require less finish work than they did with earlier 3-D printers. Some of these advances are:

**Faster, more precise printer heads.** Used mainly for plastic products, they can deposit material at 12 to 25 times the speed that was possible three years ago, making them competitive with injection-molding processes for many if not most of those products.

**Faster powder deposition.** New powder-jetting systems that use binding agents and adhesives can build up complex parts for metal and plastic goods 80 to 100 times as fast as laser-based printers can. These parts cost on average only $4 versus $40 and are made in minutes, not hours.

**Continuous liquid interface production (CLIP).** Plastic objects are pulled continuously from a vat of resin instead of being built up layer by layer. While not quite as fast or as inexpensive as layer-based additive, CLIP is still economical for mass production, and it offers advantages in finishing, the making of complex parts, and the materials it can use.

**Electronics-embedding technologies.** New machines can print electronic circuitry and components such as antennae and sensors directly onto the walls of objects. This lessens the need for assembly, frees up space within products, and improves the electronic integration of the entire product, reducing manufacturing waste and enhancing quality. The increasing precision of the machines means that they can be used, for instance, to produce OLED (organic light-emitting diode) display screens.

The benefits of these advances are amplified by breakthroughs in materials.
Manufacturers can choose from a much wider range of them, including high-tech alloys for jet-engine parts and other products with demanding performance requirements. Composites, such as very strong plastics infused with glass fiber, carbon fiber, and carbon nanotubes, can replace metals in many cases. Most of these materials are available from multiple sellers, so manufacturers aren’t forced to buy proprietary materials from the printer makers at higher prices.

Vast expansion in the additive ecosystem makes it much easier for companies to adopt the new technologies. The ecosystem now includes an array of contract printers, consultants, and suppliers of software and quality-control scanning systems along with makers of printers and materials. Participants range from start-ups to giants such as Siemens, Dassault Systèmes, and DowDuPont. The field has entered a virtuous cycle: A larger ecosystem leads to more applications and lower costs, inducing more manufacturers to adopt the technology, which attracts even more players to the ecosystem.

Additive is fulfilling its promise. It is now competitive with conventional manufacturing in its ability to make tens and even hundreds of thousands of units a year. Factories can use optimizing software to adjust production (changing the number of units or switching between items made) or upgrade products on the fly, at low cost, rather than having to shut down while expanding, retooling, or altering the expensive assembly lines used in conventional plants. Additive also allows companies to make intricate products that can’t be made with the subtractive (CNC cutting and drilling) or formative (injection molding) techniques at the heart of conventional manufacturing. And finally, additive is much less capital-intensive than conventional mass-manufacturing equipment: A printer costing less than $1 million can replace a $20 million machine, making it feasible to have many smaller production sites and locate them close to customers.

All this explains why a growing number of diversified, well-established companies—from BMW to Boeing to the Japanese conglomerate Sumitomo—are buying up 3-D printers in quantity, or even printer manufacturers. General Electric, which aims not only to use 3-D printers but to sell them to others, has moved very aggressively into the field: It has acquired three printer makers and has developed software to talk to the machines.

As with any emerging technology, current applications will evolve as learning occurs and may morph into something quite different. Some failures and modifications are inevitable, but the breadth of investment and the multitude of business models now being commercialized demonstrate that players in almost all manufacturing industries should be considering additive.

**EMERGING BUSINESS MODELS**

In light of these developments, where should a mass manufacturer start? The most important decision is the business model. So far six have emerged. The first three exploit additive’s superiority in product variation relative to traditional manufacturing; the fourth and fifth maximize its benefits in making complex products; and the sixth takes advantage of efficiencies the technology offers. These models can be used by both B2B and B2C businesses. Some of them are further along in practice than others, but together they show the range of possibilities additive currently provides.

**MASS CUSTOMIZATION**

This model takes product variation to the extreme. It entails creating one-off products that are precisely adjusted to the needs or whims of individual buyers—adjustments that can be carried out by simply uploading each customer’s digital file into a 3-D printer. Thanks to the efficiency and precision of digital technology, these products cost less than conventionally manufactured items but fit individuals’ specifications more exactly.

Mass customization is suitable for any large market in which customers are dissatisfied with standardized, conventionally produced offerings and it’s easy to collect customer information. Among the many examples are hearing aids, orthodontic braces, prostheses, sunglasses, car and motorcycle accessories, and Christmas tree decorations.

In the case of hearing aids, a laser scan of a patient’s ear is automatically converted into a production file, and a printer forms the shell. The electronics are still added separately, but that could soon change, given that it’s now possible to print them directly into the shell.

This model can rapidly and significantly affect an entire industry. With hearing aids the shift happened in a year and a half, forcing some manufacturers into bankruptcy.

The main competitive challenge is to reduce the cost of acquiring individual customers’ information. Hearing-aid companies first needed a scanning device that audiologists could easily use. In this case, customers were willing to go to an audiologist to be measured. In contrast, buyers of custom orthotics and insoles didn’t want to visit an expensive podiatrist to be measured. That’s why SOLS Systems, which innovated in this area, couldn’t make it on its own; it was acquired in 2017 by another footwear company, Aetrex Worldwide. But the development of smartphone apps that allow people to measure their own feet is overcoming the information-collection obstacle. And HP Inc. has devised a 3-D scanning solution, FitStation, that can be placed in stores. The market is poised to take off.

**MASS VARIETY**

This model targets customers who have strong and varying preferences but don’t need products adjusted to their personal specifications. Manufacturers can skip the process of collecting personal information and offer a wide variety of options at affordable prices. As with mass customization, units are one-offs.

Some jewelry manufacturers, for example, take a few basic designs and make hundreds or even thousands of variations, which they can show online or display in stores. The display versions are hollow and made with faux gold or silver. Instead of maintaining a large and costly inventory of pieces that might not sell, retailers can wait for actual demand. With orders in hand, they can have a contract additive manufacturer
such as Shapeways produce the items with solid precious metals, order a desired piece from the designer, or acquire a 3-D printer to make the products in-house.

With mass variety, the main competitive challenge is managing choice. Offering a broad selection will expand the market, but presenting buyers with a huge number of possibilities may overwhelm them. And even with additive, each choice adds some design costs. Manufacturers will have to watch the market carefully or use machine learning to continually sense and respond to what consumers want. They must be ready to develop new designs immediately and purge old ones that aren’t selling—an approach that’s much easier with additive than with conventional manufacturing.

### MASS SEGMENTATION

This model greatly limits variety, offering only a few dozen versions of a product to customers whose needs are less variable and easier to predict than with the previous two models. It works well for highly segmented markets, such as components designed specifically for popular B2B products. Each version serves a single segment and differs from the others enough that conventional manufacturers would need costly new machine tools to make all of them. Thus additive companies can make them at a lower cost.

All versions of a product can collectively total hundreds of thousands of units or more. So production is in batches rather than one-off. (Even with additive, uploading files, changing materials, and so on entail small switchover costs.) But because it’s still easy to switch printers to other products, a company limits batches to the number it is confident it can sell.

This model is also suitable for seasonal, cyclical, or short-term fad markets, which are tough for traditional manufacturers to serve because they must bet on what consumers will want several months in the future to set up an efficient production line. Additive manufacturers, with their much lower setup time and costs, can commit to production closer to when demand actually

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**ADVANCES THAT ARE TAKING 3-D PRINTING MAINSTREAM**

Here are just some of the technology improvements that are making additive manufacturing competitive with or even superior to conventional factories in a wide range of applications.

<table>
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<tr>
<th>TECHNOLOGY</th>
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<tr>
<td><strong>MULTIJET FUSION</strong></td>
<td>Thousands of print heads precisely and quickly lay binding agents on plastic powder to build up an object.</td>
<td>12 times as fast and half as expensive as previous plastic additive processes and competitive with injection-molding production for manufacturing up to 110,000 units of an average plastic part</td>
<td>Custom shoe insoles; customized dolls for LookReal; exoskeletons for military and defense drones</td>
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<td><strong>CONTINUOUS LIGHT INTERFACE PRODUCTION (CLIP)</strong></td>
<td>Objects are pulled from a vat of resin that solidifies when exposed to light; oxygen is used to speed up the process.</td>
<td>25 times as fast as (but not significantly cheaper than) conventional stereolithography, especially for making complex nonlinear shapes</td>
<td>Nozzles for Vita-Mix’s commercial mixers; mounts for Oracle servers</td>
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<td><strong>AEROSOL JETTING AND NANO-PARTICLE INK JETTING</strong></td>
<td>Conductive metal inks, dielectric pastes, and semiconductor material are precisely deposited to print electronic components and chips.</td>
<td>Allows electronic circuits and components to be embedded in the product, saving space and assembly costs</td>
<td>Embedded antennae for mobile phones (LTE-ON); high-efficiency solar cells</td>
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<td><strong>INKJET SCREEN PRINTING</strong></td>
<td>Specialized nozzles spray soluble inks in a nitrogen chamber to print flexible and large OLED screens.</td>
<td>20% to 40% lower production costs, fewer defects, and higher quality (screens last two or three times as long) compared with conventional manufacturing: almost zero waste</td>
<td>Flexible OLEDs for wearables and mobile displays; LG and Samsung large OLED TV screens</td>
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<td><strong>AUTOMATED PARALLEL PRINTING</strong></td>
<td>A series of printers combined with a robotic arm and a finishing function create ready-to-sell plastic products.</td>
<td>First fully automated, “lights-out” system using additive and automation to reduce labor in unloading and moving products to a separate finishing area</td>
<td>Surgical guides for the healthcare industry; dental molds and crown and bridge models</td>
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<tr>
<td><strong>SINGLE-PASS JETTING</strong></td>
<td>The high-speed jetting of metal powder is combined with binding agents in a continuous bidirectional process.</td>
<td>100 times as fast as laser-based metal additive manufacturing and 1/20th as expensive</td>
<td>Water impellers (for pumps); drill bits; gears</td>
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<td><strong>CAROUSEL CONVEYOR PRINTING</strong></td>
<td>A moving platform rapidly rotates the product being printed among numerous printheads and finishing functions.</td>
<td>10 times as fast as stationary printing</td>
<td>Customized footwear; spare parts for automotive and transportation industries (in development)</td>
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occurs, offer more choices, and avoid the risk of being stuck with unwanted goods that must be heavily discounted to sell.

RaceWare Direct, a UK firm that makes accessories for serious cyclists, has adopted the mass segmentation model. It sells a variety of handlebar mounts and other durable, lightweight parts. Each version of its mount for GPS devices, for example, sells only a few hundred or a few thousand units. A conventional manufacturer might need to achieve economies of scale by making just one mount for all such devices.

Daimler has moved toward mass segmentation in stages. It initially used additive to make spare parts for older trucks. After it became proficient with the technology, it started producing specialized parts for some current low-volume truck models. As the number of segments served grows and the number of units sold per segment increases, this process will generate enough parts to become a profitable aspect of the business.

The main competitive challenge here lies in deciding on the size of each segment and the number of segments to serve. Smaller segments will better satisfy some customers but can add design and switchover costs—especially if they require different materials or performance specifications.

### MASS MODULARIZATION

Rather than offering customers different versions of a product, this model involves selling a 3-D-printed body with interchangeable modules for insertion. It applies mainly to electronic devices, which can mean everything from cars to fighter jets and drones. So far this approach has been used only for military hardware and some niche automobiles, but it has significant potential—which Facebook, for one, has realized. It bought Nascent Objects, an additive start-up, to create modular versions of its virtual reality headsets and other hardware.

Here's another application: a smartphone that allows customers to buy a base unit and then snap in modules. The base unit's exoskeleton is printed in customized ergonomic shapes or with flashy designs, and users choose which modules to insert over time as their needs and preferences change or as technology advances, negating the need to buy an entirely new phone. Google gave up on such a phone a few years ago, but Moduware, an Australian company, has developed software to help smartphone manufacturers design the base units. Moduware could profit from making the modules used in products designed with its software.

Traditional manufacturers in a range of areas already offer modular products. But 3-D-printed products have two advantages. First, additive allows customization of the base unit. Second, and more important, that unit can be made in a completely new way, with antennae, wiring, and circuits printed directly onto it or into its body. This reduces assembly costs, increases opportunities for miniaturization, and creates space for additional electronic components to be integrated into the product in ways that conventional modular production methods cannot manage.

### MASS COMPLEXITY

The first four models take advantage of additive’s flexibility to make a variety of product versions at low cost. This model exploits its ability to make products with intricate designs that conventional manufacturing can’t achieve and to produce unusual shapes and embed sensors and other elements. That ability reduces production costs while improving the product’s reliability—as Vita-Mix found when it used the CLIP printer to make a nozzle for its commercial mixers. It’s now making tens of thousands of those nozzles.

Boeing is using additive to build supports shaped like a honeycomb for airplane fuselages. The intricate structure of the supports makes these load-bearing parts just as strong as the conventional equivalents but with much less material—thereby significantly reducing weight and fuel consumption. Adidas uses CLIP printers to make strong, supple, lightweight lattice structures for the midsoles of running shoes, which are too complex to be made with conventional technology. It expects to print 100,000 pairs in 2018; 500,000 in 2019; and eventually millions a year. These midsoles will absorb the impact of running better than conventional ones do.

With new design software emerging, additive manufacturing can now restructure materials at the micro level to improve properties such as porosity, strength, durability, elasticity, and rigidity. It can even improve a product’s resistance to water, chemicals, and bacteria.

The main challenge here is simply the human imagination. Can product developers escape the conventional mindset to design products that take full advantage of additive’s potential? If so, mass complexity may expand far beyond high-performance products. And new software from Autodesk, Dassault, and others means that product developers may not even have to do the thinking. This software allows developers to specify certain attributes and then leave it to the computer to generate a design that will optimize performance and cost, overcoming trade-offs that have stymied human designers. Automobiles, for example, could be made both safer and lighter. Such “generative design” may become the killer app that persuades many companies to jump into additive, lest their rivals offer desirable new products that are simply unachievable with conventional techniques.

### MASS STANDARDIZATION

This last model attacks traditional manufacturing’s home turf. It proves—contrary to naysayers’ dismissal of additive as a niche technology that is useful only for small-scale production—that high-volume standard products can be churned out at a low
cost in certain circumstances. The technology is still emerging in this area, but it could become a game changer.

Take video screens. Conventional manufacturing processes for OLED screens waste a lot of expensive light-emitting electrochemical materials. Printers now on the market handle these materials more precisely and thereby produce lower-cost, higher-performance screens. Additive-made OLED screens for cell phones and other handheld devices are everywhere; television manufacturers, interested in joining in, are conducting pilot projects for mass-producing TV screens with these printers.

Mass standardization is possible even for low-tech products. Cosyflex, a 3-D printing system made by Tamicare, produces textiles by spraying various mixtures of polymers and natural fibers onto a moving platform. This fully automated system can produce finished goods at lower cost than conventional production can, even at scale. Tamicare is still commercializing its technology, but the results it has seen to date are promising.

Over time, as 3-D printers grow ever more efficient, they may become competitive for making standardized products even when they don’t save on direct costs. That’s because traditional manufacturing often involves a lot of indirect and overhead costs: an extended and risky supply chain, expensive capital equipment, the elaborate assembly of parts, and high inventory or transportation costs. Additive reduces all those. What’s more, the printers themselves are generally less expensive than conventional machines with tool-and-die elements.

The main competitive challenge here is likely to be how much to specialize 3-D printers for these products. Specialization can help achieve the efficiencies needed for mass standardization, but it may increase risk by restricting companies to certain industries.

**STRATEGIC MOVES**

These six business models are not mutually exclusive—a company might find value in both greater variation and greater complexity. GE’s fuel nozzles for jet engines combine mass complexity with mass segmentation. The nozzles are complex combinations of many parts, and each kind of jet engine needs a different shape of nozzle. So GE uses additive to make dozens of versions in medium quantities. Adidas’s additive midsoles follow the mass complexity model, but a separate line will use mass customization to satisfy high-level runners or those with special orthopedic challenges. To better understand the preferences of its customers, Adidas is considering moving its manufacturing closer to them and perhaps even locating some of it within retail stores.

Once you’ve gained capabilities in additive, you can apply it in a variety of competitive situations. Here are some ways it can be used against rivals that rely on conventional production:

**Blocking out potential competitors.** Suppose your company has a strong market position but is vulnerable to rivals’ targeting of specific segments. You could use additive to proactively expand your product line and prevent any openings. Hershey seems to be following this strategy with its recent investment in additive. Although it is the dominant player in the U.S. chocolate industry, it has been losing market share to premium foreign companies that might creep into the mass market. Creating its own conventional product line for fancy Italian or Belgian chocolate would be too costly, because the company couldn’t sell enough to cover its expensive equipment. But with additive it can economically make chocolate in a range of recipes by using many small printers, each dedicated to a specific country’s style—and thereby prevent the foreign rivals from expanding their foothold. Hershey is also hoping that its new chocolate printers become so easy to use that it can sell them to restaurants, bakeries, and pastry shops—thereby blocking rivals that might try to enter the American market through those channels.

**Dethroning the market leader.** Suppose your company is struggling to compete with the dominant player in your industry, which offers only a few standard products. Because it has the largest market share, the leader’s economies of scale enable it to invest more aggressively than your company can. The only way to compete is to change the game. With additive, your company can cheaply produce variations on the standard product and determine whether customers are interested in them. If you attract enough interest, you can adopt one of the variation-based business models. Even if your offerings aren’t cheaper than the leader’s, you will gain market share, because customers will be happy to benefit from an offering closer to their tastes or needs. As you add more variety to your offerings, you might draw so many customers away from the market leader that it will have to scale down, and its margins will collapse. Even if the leader sees the danger, it will struggle to respond, because the importance of achieving scale economies by making standard products is entrenched in its mindset.

**Coexisting with the market leader.** What if you find that customer demand for variety isn’t sufficient for your company to seize enough market share to dethrone the leader anytime soon? You might still decide to go with additive and focus on just a few segments—again with a variation-based business model. You might be able to restrict your rival to its current markets by preempting its growth opportunities. If not, your company could still profitably coexist with it by using your product variety and niches to avoid direct competition.

**Overcoming rivals that have strong supply or distribution chains.** A powerful value chain is hard to beat, but additive can change the game by creating an entirely
THE TEMPTATION OF INDUSTRY 4.0

For several years the German government and some consulting firms have promoted “Industry 4.0,” a broad program for digitizing manufacturing with robots, artificial intelligence, the internet of things, and other technological advances. Encouraging companies to digitize and innovate by adding new technologies is a good thing. But some versions of Industry 4.0 still assume conventional, capital-intensive manufacturing techniques and supply chains. That could be a bad thing, because it consigns additive manufacturing to a largely supporting role of prototyping and providing a few specialized parts. Such an incremental approach to digitization will end up protecting the past and preventing the rethinking necessary to take full advantage of additive’s capabilities. Factories with heavy investments in conventional equipment will struggle to customize products, make complex parts, reduce assembly, and adjust production to changing market demand.

Consequently, companies that embrace Industry 4.0 are likely to lose out to nimbler rivals that take full advantage of additive’s capabilities. Many Industry 4.0 devotees could end up with fixed costs and operational inflexibilities that sink them in the long term.

THE COMING OF PAN-INDUSTRIAL MANUFACTURING

Coupled with a powerful software platform, additive manufacturing enables companies to diversify much more widely. For example, in 2015 GE built a remarkable factory in Pune, India. Previously every GE plant had been dedicated to serving a single division, such as aviation, health care, or power generation. But because Pune relies on 3-D printers, it can make parts for multiple divisions, which allows it to keep its capacity-utilization rate higher than if it were serving just one business. (It has some conventional manufacturing equipment as well, to make parts for which additive isn’t yet economical.) If jet sales are booming, Pune devotes much of its production to parts for jet engines. But if that business slows, and demand for renewable power takes off, those production lines start making wind turbines. A conventional plant would find it too expensive and time-consuming to make the switch.

The Pune plant relies mostly on a mass-segmentation business model for its diverse products, but as it moves along the learning curve, it may start to employ mass complexity as well.

Thanks to this plant and to other “brilliant factories” that GE has established or intends to build, the company’s diversified businesses will reap substantial benefits. To fully realize them, the divisions will need to collaborate. GE may not be a conventional conglomerate much longer. We need a new name to describe a diversified manufacturer that combines additive with software platforms to achieve operational synergies across the entire company. I suggest “pan-industrial.” (See my article “Choosing Scope over Focus” in the Sloan Management Review, Summer 2017.)

Pan-industrials won’t venture into just any industry: The technical expertise needed, the business model, or the materials available will limit their span. They might focus on consumer durables, metal parts, or plastic industrial goods. But that will still provide much wider scope than anything Wall Street currently tolerates. As companies learn to exploit the full potential of additive, diversification may even become a strategic imperative, ushering in a new era of competition among giant industrial companies.

MANY COMPANIES ARE intrigued by the potential of additive manufacturing but wary of the risks. At most they use it to make prototypes and a few low-volume niche products. Now is the time to take it seriously as an option for large-scale commercial production. Companies should move off the sidelines, get familiar with the new techniques, and explore how they might alter the competitive landscape.

Additive has the potential to shake up not just individual industries but the manufacturing sector as a whole. Eventually a technology that engineers once mocked for its slowness may become a dominant force in the economy.

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