How is 3D printing revolutionizing business models, and how can leaders take advantage? What are the limits to these techniques?
Building Growth with Additive Manufacturing

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INTRODUCTION

Additive manufacturing — also known as 3-D printing — was developed in the 1980s and began moving beyond costly industrial manufacturing applications in the late 2000s when it was taken up by the open-source and do-it-yourself movements. This collection of articles from *MIT Sloan Management Review* takes a closer look at this disruptive technology, which is on the verge of going mainstream.

**From “Choosing Scope Over Focus”:**

- New digital technologies are changing the rules of competition by expanding the boundaries of what a company can handle and introducing new sources of advantage. Entering multiple industries will no longer be a drag on operations — it will bring competitive advantage.
- Big data analytics, cloud-based mobility, 3-D printing, and machine learning are combining to make complexity manageable and generate economies of scope.
- Digital technology has already upended the media and information sectors. It’s about to do the same to the manufacturing economy and pave the way for what can be called a “pan-industrial” strategy.
- Unlike the sprawling conglomerates of the 1960s, pan-industrials will need a certain level of focus, but they will be able to operate in much broader areas than today’s more targeted manufacturers. One could imagine, for example, “General Metals,” a company with underlying expertise in metal 3-D printing, which would be something like a combination of General Electric, General Motors, and General Dynamics, competing in a range of industries such as medical equipment, cars, and airplanes.

**From “Getting Past the Hype About 3-D Printing”:**

- The hope for additive manufacturing — also known as 3-D printing — is that it will revolutionize manufacturing. Many industry observers hope that 3-D-printed parts will cut lead times and make supply chains more efficient in a wide range of settings.
- Near-term expectations for additive manufacturing are modest, based on a study of the literature on the history of materials and process technologies, industry meetings, factory visits, and 80 interviews.
Additive manufacturing, for instance, makes it easier to design parts with complex geometries and internal cavities. But it is subject to some restrictions. Parts cannot be too thin or have overhanging sections unless these are properly supported. Knowing the parameters of what's possible requires skills that are currently scarce.

There are also limits on the extent to which additive manufacturing will be flexible manufacturing. In theory, a good 3-D printer ought to be capable of printing a wide range of designs. In practice — and especially in applications critical to safety — we may see regulations that control how 3-D printers and additive manufacturing equipment in general can be configured.

From “The Killer App for 3D Printing? The Circular Economy”:

- 3-D printing has the potential to alter how we use — and reuse — materials.
- In order to become a mainstream technology, 3-D printing needs an extremely valuable use, like spreadsheets were for PCs. That use could involve a role in the “circular economy.” 3-D printing could help eradicate waste from manufacturing processes and then throughout the full life cycles of products and their components.
- Because 3-D printing systems are capable of using a single plastic polymer to create a nearly infinite number of forms, 3-D printing fulfills one of the core principles that serve as the foundation of a viable circular economy: materials parsimony. And solar-powered 3-D printing systems would fulfill one of the other core principles, power autonomy, because they would run entirely on local renewable energy. Finally, 3-D printing systems can play an essential role in the third core principle, value cycling, because they can build new products from the raw material created after an old object has been ground down as part of an integrated recycling process.
- The elements for creating a “cradle-to-cradle” economy are present in manufacturing processes involving 3-D printing, meaning this technology could prove to be the death knell of our “take-make-waste” disposable society.

From “Supply Chains Built for Speed and Customization”:

- As 3-D printing begins to bring personalized manufacturing to scale, a new high-speed bespoke supply chain model is emerging.
- The goal of this approach is to fulfill orders for custom-made products quickly. When customers place orders, the goods they request are produced in nearby factories that use 3-D printing and robotics technologies, and the finished products are delivered via the fastest option available.
• Traditional supply chain operations are usually optimized for make-to-stock goods that are produced in advance based on forecasts of demand. In contrast, high-speed bespoke supply chains are designed for make-to-order goods that are produced in response to realized demand, not forecasts.

• Adidas, which offers customization of its shoes through its Mi Adidas (“My Adidas”) online platform, built its first “Speedfactory” in Germany to add high-speed manufacturing to its bespoke product offering—planning to dramatically slash the time between custom orders and delivery to four to five business days.

**From “Innovation Lessons From 3-D Printing”:**

• This article from 2012 provides an excellent base history of the evolution of the technology as well as how the market is changing and how companies can respond. It provides information on market leaders Stratasys (based in both Minnesota and Israel), Objet, 3D Systems, and Germany’s EOS.

• Early 3-D printing systems were expensive (typically priced at $250,000 and more), and they were designed for a limited market. By 2010, 3-D printing companies were having success with systems that cost $10,000 to $30,000, making 3-D printing viable for schools and midsize enterprises.

• The RepRap (a replicating rapid prototyper) was an open-source home-use 3-D printer. It was created in 2005, and it quickly grew in popularity from 2009 to 2012. Since many of the RepRap’s parts were made of plastic, the machine could largely replicate itself, with a kit that anyone could assemble if they had the time and materials and could afford a minor investment of about $400.

• 3-D printer companies have a range of options for responding to developments that take place within innovative user communities. Five strategic ways to respond, which may be applied in parallel, include (1) monitoring the activity in user communities; (2) attacking a user community, especially in cases where users infringe upon a company’s patents; (3) adopting the innovations that emerge from user communities; (4) acquiring startups founded within user communities, or at least recruiting talented users; and (5) facilitating the efforts of user communities.
Since the 1980s, Western business strategists have preached focus. To capture economies of scale, move quickly down the learning curve, and develop core competencies, it’s best to operate in only one industry, or perhaps a few adjacent industries. Diversifying into unrelated industries is dangerous, the thinking goes, because it leads to complexity and unmanageable size without yielding economies of scope and other operational synergies. Indeed, Wall Street has frequently penalized multi-industry companies with a “conglomerate discount.”

Since the 1980s, Western business strategists have preached focus. To capture economies of scale, move quickly down the learning curve, and develop core competencies, it’s best to operate in only one industry, or perhaps a few adjacent industries. Diversifying into unrelated industries is dangerous, the thinking goes, because it leads to complexity and unmanageable size without yielding economies of scope and other operational synergies. Indeed, Wall Street has frequently penalized multi-industry companies with a “conglomerate discount.”

Advances in manufacturing technology are about to change the rules of competition and unleash a sleek new version of the old-school conglomerate. Call it the “pan-industrial.”

BY RICHARD A. D’AVENI
Those dynamics, however, will soon go into reverse. New digital technologies are changing the rules of competition by expanding the boundaries of what a company can handle and introducing new sources of advantage. Big data analytics, cloud-based mobility, 3-D printing, and machine learning are combining to make complexity manageable and generate economies of scope. Entering multiple industries will no longer be a drag on operations — it will bring competitive advantage. Digital technology has already upended the media and information sectors. It’s about to do the same to the manufacturing economy and pave the way for what can be called the “pan-industrial” strategy.

The Pan-Industrial Advantage
A pan-industrial company may look like a conglomerate on the outside, but it will run quite differently. It will be driven by a software platform that monitors, facilitates, and optimizes operations, from product development to customer delivery, across a disparate product line. Although pan-industrials will need a certain level of focus — unlike the sprawling conglomerates of the 1960s — they will be able to operate in much broader areas than today’s more targeted manufacturers. One could imagine, for example, “General Metals,” a company with underlying expertise in metal 3-D printing, which would be something like a combination of General Electric Co., General Motors Co., and General Dynamics Corp., competing in a range of industries such as medical equipment, cars, and airplanes.

Armed with the software platform and these new manufacturing technologies, pan-industrial companies will gain several advantages not currently available to either conglomerates or focused companies.

Boosting Efficiency Most traditional conglomerates exert little control over their operations. Each division has its own research and development (R&D), factories, and distribution network, and tends to share few suppliers with the rest of the conglomerate. Headquarters gets involved primarily in finance, management development, and expansion decisions because it simply can’t know enough to make more specific decisions responsibly in such diverse industries. Pan-industrials will be very different because they’ll rely on sophisticated software platforms that coordinate most steps in the value chain. Conventional supply chain software can’t handle such diverse operations — it would be overwhelmed by the myriad potential options — but platforms with advanced cloud-based analytics can. They’ll integrate the value chains of the various business units and generate savings in purchasing, production, distribution, and overall risk management.

Any individual action will be more valuable because the platform will have more options in carrying it out efficiently. As for production, flexible 3-D printers will increasingly replace inflexible, scale-intensive injection molding, and the platform will direct factories when to switch from slow-moving products to the hot sellers. Factories will enjoy higher rates of utilization than are possible now, which is key to manufacturing efficiency.

Continuing with the “General Metals” example, headquarters would use the platform to centralize most of the supply chain decisions, and eventually the production decisions as well. Managers of the individual divisions would have less and less to do. Over time, the company would organize less around industries and more around geography, with smaller plants and supply chains located close to customers in order to boost responsiveness.

Spreading Out Platform Costs The software platforms we are discussing in this article — those capable of managing the complexity of real-time optimization — are expensive. Besides the up-front software and hardware costs, there’s also the implementation and training time required, as well as the work of converting supply chain and production data into a consistent format readable by the platform. Pan-industrials will be able to spread those costs across multiple industries. They’ll be able to move faster down the platform learning curve in each industry because of what they’ve learned and developed elsewhere. They will automate the routine transactions and build out a richer
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menu of options to handle new kinds of activities. They’ll have the heft to invest in machine learning to speed things up as well. So they’ll realize the efficiencies, quality improvements, and innovation from digitization a good deal faster than smaller, less diverse companies.

After all, digital integration is not a onetime decision. It’s a gradual process of installing the software platform ever deeper into operations. Pan-industrials will gradually remove legacy structures that get in the way of realizing the new capabilities. They’ll develop entirely new ways of organizing production, much as manufacturers did when they electrified their plants in the early 20th century. At first, the factories simply replaced their central steam engines with electrical equivalents, but eventually they gave each machine its own electric motor and created a much more efficient layout.

An even better analogy is from the 1950s and 1960s, when new accounting and management methods gradually spread through the U.S. economy. Conglomerates that had already perfected these methods bought up smaller operations and whipped them into shape. The marketplace eventually caught up, and now consultants and private equity companies provide this service better. But for decades, conglomerates had a decided competitive advantage. A similar process will play out with the digitization of manufacturing.

Fostering Innovation We tend to think that big companies inevitably suffer from the “innovator’s dilemma” — the tendency of successful companies to focus on their high-margin customers and dismiss innovations that (initially) fall short on quality standards. Pan-industrials won’t be so susceptible for two reasons: (1) Digital manufacturing is lowering the cost and complexity of experimentation, and (2) 3-D printers can generate new products at low cost, and the software platforms provide rapid feedback from distributors and customers. Chasing after new ideas won’t be such a risk.

That’s going to help all big companies in the future, but pan-industrials have a special advantage with innovation. Because they will operate in multiple industries, they won’t be caught up financially and culturally in serving a specific customer base. Having invested so much in a platform, they’ll be more flexible on what goes into that platform than a focused rival. They’ll be committed to economies of scope, so they’ll have a bias toward adding new nodes on the platform’s network, not expanding their existing operations.

A company like Ford Motor Co., after all, is not likely to build minifactories in dozens of cities or stray into a variety of nonautomotive products. It’s too deeply invested in a vertically integrated, assembly line-based manufacturing system with a long supply chain feeding its main customers: the dealerships.

It’s true that pan-industrials may suffer from not having any single customer base. They won’t have the customer intimacy that a focused company can achieve. Ford is investing in 3-D printing, but even with this technology, it’s likely to face the innovator’s dilemma. By contrast, a pan-industrial emerging from, perhaps, a newer motor vehicle manufacturing company, such as Tesla Inc., based in Palo Alto, California, or Local Motors Inc., based in Chandler, Arizona, will be much more open to new kinds of products and factories.

It’s true that pan-industrials may suffer from not having any single customer base. They won’t have the customer intimacy that a focused company can achieve. Their platforms will connect them tightly to the marketplace, so they’ll see substantial changes in customer preferences, but they may miss out on the more subtle developments that digitized information can’t convey. That’s why it will be essential for pan-industrials to eventually organize geographically so that they can be physically close to their customers.

That said, a pan-industrial approach may actually foster some kinds of innovation: those that happen at the boundaries of industries. With so many industries starting to converge, pan-industrials will avoid traditional industry-centered thinking and be open to new possibilities.

Generating Information With Network Effects Over time, this may be the biggest pan-industrial advantage of all. Once they develop a reliable, feature-rich platform to handle their own activities, pan-industrials will gradually bring outside suppliers, distributors, and customers directly onto their platform. Those outsiders will be motivated to join: to have better access to the pan-industrial company’s products and technology or to partner with the pan-industrial company as a preferred supplier or pooled purchaser. They’ll also appreciate how the platform will help improve their own activities. The more transactions on the platform, the better the software can optimize production flows for everyone. Some pan-industrials might eventually decide to spin off manufacturing and focus on their platform, making it the centerpiece of a broad ecosystem.

Because it will “see” all this activity across several industries, the pan-industrial company will know more about overall business activity than a focused company, which sees within only a single industry. It will become aware of emerging trends in product
development, supply and demand, and inventories. A big focused company could still use a platform to optimize its supply chains, but it won’t have the breadth of information of a pan-industrial.

Over time, the insights provided by the platform will help the pan-industrial predict and optimize its activities even more, further boosting its attractiveness to partners. The more companies join, the greater the knowledge, and this network effect will give pan-industrials a powerful advantage over smaller rival platforms.

Managing Complexity

Let’s see how these advantages are already starting to develop at real companies. Jabil Inc. (formerly Jabil Circuit Inc.) is based in St. Petersburg, Florida, and is one of the largest contract manufacturers in the world, with more than $18 billion in revenue. It has 102 factories in 28 countries, and its 138,000 employees make products in dozens of industries. The company originally treated its thousands of job orders as separate projects. But in recent years, it has developed an “intelligent digital supply chain” platform that integrates the activities across its system, from product concept to distribution.

The cloud-based system tracks the flow of materials and products and sends orders on what to do at each step. Jabil developed the platform to give it better visibility into its diverse activities. But as the platform improved its data collection, Jabil added analytics around optimizing those operations. No longer a mere dashboard, the platform has become the centerpiece of an integrated industrial enterprise.

An old-style conglomerate would be overwhelmed by the challenges of managing the broad diversity of its combined multi-industry operations. Conventional supply chain software would break down if confronted by the thousands of possible choices of materials, suppliers, volume levels, and timing. That’s why conglomerates separate their myriad activities into largely isolated divisions. But Jabil’s platform puts everything in the same mix. It can pool procurement across multiple supply chains to get better prices, as well as schedule production to keep factories running at a high level without missing delivery deadlines.

Thanks to Jabil’s broad reach, it has relationships with thousands of suppliers of hundreds of thousands of parts and materials — far more than a company focused on one or two industries. When a customer comes with a job, Jabil’s platform selects the combination of suppliers, logistics, factories, and timing that best meets the customer’s priorities on cost, speed, quality, and risk. Using predictive analytics, it optimizes not just production but even product development — designers can know instantly if a certain choice of material will add expense or risk to the production process. And Jabil is now starting to introduce 3-D printers to many of its factories, which will eventually complete the circle of digitization and further improve optimization. As it increasingly integrates its operations and expands its capabilities, it will gain more of the pan-industrial advantages, even without actually owning the products it generates. Jabil has now taken steps to license its supply chain platform technology to other companies.

Achieving Production Synergies Across Industries

General Electric, having invested heavily in a digital platform and 3-D printing, is also moving along the pan-industrial path. Whereas Jabil’s platform started with a supply chain and logistics, GE’s began in the factory. Predix, GE’s manufacturing software platform, continually monitors plant equipment and production flows, crunches the data with artificial intelligence, and recommends improvements. The manufacturing process is expressed digitally, monitored via the internet of things, and optimized with analytics.

Although GE sells a wide variety of products across its various divisions, it is not yet a true pan-industrial — Predix still operates mainly within each division, so it doesn’t achieve the economies of scope Jabil is achieving by integrating supply chains and production across multiple industries. But GE is much further along than Jabil in another key element of pan-industrialism: 3-D printing. The company has already invested $1.5 billion in advanced manufacturing and additive manufacturing for its aviation and medical device businesses. In addition, in 2016, GE put up more than $1 billion to buy majority stakes in two European metal 3-D printing companies: Arcam AB, based in Mölndal, Sweden, and Concept Laser GmbH, based in Lichtenfels, Germany, whose technologies will boost the quality and speed of GE’s existing processes. It also built a $40 million 3-D printing research and training center in Pittsburgh. Because 3-D printers work purely from digital files, they mesh well with digital platforms to turn information into physical goods in a pan-industrial structure.

Most important for the pan-industrial story is GE’s $200 million factory in India’s Pune district. Unlike other GE factories,
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which focus on just one of the company’s divisions, the Pune plant, which opened in 2015, serves multiple divisions. It takes advantage of 3-D printing’s flexibility to make parts for airplanes, locomotives, and gas turbines. If jet orders are falling but railroads are booming, it can switch over the production lines and keep the factory running at a high level. Pune has conventional injection-molding equipment as well as 3-D printers, but it has enough of the latter to gain significant flexibility. So far those switchovers are still slow and difficult, but as GE moves down the learning curve with 3-D printing and expands Predix to handle the complexity of possible options, the switchovers should get easier and cheaper.

A higher utilization rate isn’t the only advantage of plants like Pune. GE’s divisions generally rely on a few big specialist factories, with their economies of scale, to supply the entire world. Because it produces for several industries, Pune can achieve volume from only a regional customer base. Besides putting the plant closer to its customers, a regional approach also offers a timely political boost. As GE CEO Jeffrey Immelt recently pointed out, rising protectionism around the world is pushing manufacturers to localize.

Once it integrates the divisions with the software platform and 3-D printers, GE will stop being a conglomerate and become something much more integrated and cohesive: a pan-industrial company. The old GE captured synergies in financing and in management development. The emerging GE, with an integrated manufacturing platform and 3-D printing, will have synergies in supply chains, production, and distribution. And as its Predix software gets ever more capable, GE may extend it well beyond its supply chains, production, and distribution. As and its Predix software gets ever more capable, GE may extend it well beyond its existing operations. Already, the company is licensing Predix externally, and Immelt announced in 2015 that GE hopes to become one of the 10 largest software houses in the world by 2020.

Manufacturing Back in the Center
In recent decades, finance has been the driving force in most Western economies. But with the world awash in capital, we can expect power to shift toward those most able to harness the power of data. Wall Street may benefit in the short run from the wave of acquisitions and alliances driven by the pan-industrial strategy. But the result will be platform players with both operational efficiencies and access to aggregate information that further cement their strategic advantages and ability to create value.

Not every company should become a pan-industrial, and some industries may never switch over to 3-D printing, which is a central component of the pan-industrial strategy. But as costs continue to fall and capabilities rise, it’s likely that many industries will see at least some product areas move heavily to digitally coordinated manufacturing systems. Companies that stay devoted to focus will eventually lose out to large, broadly diversified, efficient pan-industrials that thrive on economies of scope and network effects. Pan-industrials will be large, agile, and aggressive competitors playing by different rules. They’ll overwhelm rivals that continue to follow today’s conventional wisdom.

We won’t see full-fledged pan-industrials for at least a few more years, as Jabil, GE, and other companies continue to work on filling out their digital manufacturing infrastructure. But it’s not too soon to start preparing for pan-industrials as dominant competitors — and to consider how you’ll seek advantage in such a competitive landscape. These newly agile giants are going to lead the digital manufacturing revolution — and absorb those that fail to adjust to the new industrial order.

When digital manufacturing first emerged, proponents predicted a democratized economy of small “makers” with customized products and markets. The opposite is now more likely. Because of economies of scope, the world will be ruled by behemoths managing proprietary networks to achieve impressive gains. Current constraints on company size and scope are disappearing. After all the attention splashed on media giants such as Google Inc. and Facebook Inc., the industrial digital economy is finally poised to take off.

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Getting Past the Hype About 3-D Printing

Although additive manufacturing techniques hold great promise, near-term expectations for them are overoptimistic.

BY JAIME BONNÍN ROCA, PARTH VAISHNAV, JOANA MENDONÇA, AND M. GRANGER MORGAN

THE HOPE FOR additive manufacturing is that it will revolutionize manufacturing. Although additive manufacturing — also known as 3-D printing — was developed back in the 1980s, it has garnered increased attention in recent years as managers look for ways to improve efficiency and reduce production costs. Managers hope that, much the way GE’s new printed nozzle for jet engines has reduced the need for expensive materials and energy, other 3-D-printed parts will cut lead times and make supply chains more efficient in a wide range of settings.

Despite the potential of additive manufacturing, we believe that near-term expectations for it are overblown. We base this conclusion on our research, which included 80 interviews as well as extensive study of the literature on the history of materials and process technologies, industry meetings, and factory visits. (See “About the Research,” p. 58.)

Examining Three Myths

In our view, three important myths about additive manufacturing need to be dispelled. The first myth is that additive manufacturing will allow producers to make parts of any complexity as easily and economically as parts that are manufactured in traditional ways (in other words, that it will make complexity essentially “free”). The second myth is that additive manufacturing will prod manufacturing to become local. And the third myth is that additive manufacturing will allow producers to replace mass manufacturing with mass customization. None of these expectations is likely to be realized in the next several decades, especially in the case of 3-D printing in metal.

**MYTH 1:** Additive manufacturing allows producers to make complex
parts as easily and economically as parts that are manufactured in traditional ways. Additive manufacturing makes it easier to design parts with complex geometries and internal cavities. For instance, a manufacturer using additive manufacturing would be able to make jet engine turbine blades with cooling channels. Cooling channels allow jet engines to operate at very high temperatures — so high that blades without such channels would ordinarily melt. Additive manufacturing would enable manufacturers to produce parts with more complex geometries than is currently feasible, opening the way for engines that are both cleaner and cheaper to run. It could make high-quality parts quickly.

Additive manufacturing can also allow companies to produce parts such as engine brackets that are lighter, resulting in increased fuel efficiency. In a competition organized by General Electric Co., the winning design using additive manufacturing was 80% lighter than the one it replaced. Additive manufacturing also enables simpler designs. In developing a new nozzle to inject fuel into the combustion chambers of its jet engines, GE, for example, merged 20 parts into one. Colin Chapman, the late founder of Lotus Cars, which manufactures sports and racing cars, once famously encouraged designers to “simplify, then add lightness.” Additive manufacturing makes it possible to do both.

Nevertheless, additive manufacturing has drawbacks and is subject to some restrictions. For one, parts cannot be too thin. They can’t have overhanging sections unless these are properly supported. Knowing the parameters of what’s possible requires skills that are currently scarce. Engineers (including us) have been trained on tools and approaches to design that are tailored toward conventional manufacturing. Training engineers to take advantage of the freedom that additive manufacturing will provide while understanding its limitations will require time. Indeed, limitations are still being discovered. In addition, the software tools that engineers are currently trained on may not be suited for additive manufacturing, and it is difficult to find faculty capable of teaching the new tools.

All this is beginning to change. America Makes, the National Additive Manufacturing Innovation Institute, a public-private consortium set up to advance additive manufacturing in the United States, currently has more than 30 academic institutions as members, many of which are introducing additive manufacturing into their core curricula. The new skills are being built at all levels; for example, two of the America Makes members are community colleges. Relatively inexpensive plastic 3-D printers are also appearing in high schools, thereby introducing students to their possibilities at an impressionable time. Some of the machines are specifically designed for educational environments.

Contrary to what many people may think, not all additive manufacturing systems and processes are the same. There are fundamental differences in terms of feedstocks, heat sources, and machine configurations. The material science behind plastic additive manufacturing is totally different from the material science of metal additive manufacturing — and expertise in one doesn’t easily transfer to another. Each requires a long learning process adapted to the particular application.

In the labor market, there is growing demand for people who have been educated in additive manufacturing.
manufacturing processes. In addition to those with bachelor’s degrees, there are opportunities for master’s degree holders who have the skills to set up, operate, and troubleshoot 3-D printing machines.

In addition to training issues, there are safety issues and technical issues. Some of the safety concerns stem from the fact that the technology is new. In an effort to reduce the possibility that parts will fail, some manufacturers are using parts that are heavier than optimal. Clever new structures such as very light meshes have different vulnerabilities from solid, chunky components; this is especially true in applications where parts need to rotate or are repeatedly loaded and unloaded. Understanding these potential weaknesses, and learning to design parts to avoid them, will take time.

On top of that, more work needs to be done to reduce variability, so that additive manufacturing machines and processes can produce components that are identical given the same set of inputs. To understand why this is important, it’s helpful to recognize a fundamental difference between 3-D printing and other manufacturing technologies. Take machining, for example. Machining involves starting with a block of metal and cutting away the parts you don’t need. It’s reasonable to expect that after the machining process the material that’s left has essentially the same properties as the block you started with. But that is not necessarily the case when a part is made with 3-D printing.

That’s because some metallic additive manufacturing involves zapping adjacent microscopic particles of a powder with a powerful laser so that the particles melt and fuse. The process of zapping particles occurs over and over — millions, perhaps billions, of times — until the part is completed. Each particle in the resulting component is rapidly heated and cooled many hundreds of times. What finally emerges depends on a number of factors, including how much each particle was heated, how many particles were heated at one time, how many times the particles were heated, and how quickly they cooled. If the process is not consistent from beginning to end, you can’t have consistent results.

To ensure that the process has been properly controlled requires finished-part testing. However, some of the necessary testing methods — for example, how to inspect the insides of hollow parts without having to slice them open and destroy them — are still being invented. Ultrasound does not always work well for metals, and another technology, industrial CT scanning, is slow and expensive, and cannot be used for all geometries. Yet unless we can resolve these issues, the savings that might be generated by one-step manufacturing processes, especially for parts critical to product safety, could be swallowed up by the need for additional testing.

Quality control is challenging enough when components are made within the same four walls; working with third-party suppliers makes for even greater difficulty. A part made using additive manufacturing that performs well on tests designed for conventionally produced components may for a variety of reasons perform poorly in service. For example, although the properties at the surface of a part may be the same, they could be different from those a few millimeters deep.

Initiatives are underway to solve these problems. ASTM International and the International Organization for Standardization are collaborating to develop standards for additive manufacturing. In the United States, the Materials Genome Initiative, an inter-agency program designed to create public policy and infrastructure for the development of advanced materials, aims to create powerful software simulation tools and create shared material databases. Some companies are pushing the boundaries of additive manufacturing with new materials and techniques. For example, Impossible Objects LLC of Northbrook, Illinois, is applying additive manufacturing techniques to composite materials to produce components that are much stronger than...
ordinary plastics; these materials can use high-throughput manufacturing techniques that have traditionally been applicable only to plastics. Another startup, XJet Ltd., of Rehovot, Israel, is suspending metallic particles in ink so that metallic parts can be printed using fast printing technologies.

While there are a number of innovative startups like Impossible Objects and XJet, the road to the mass market for products and technologies that cater to safety-critical applications can be long. GE recently announced that it would acquire a majority ownership stake in Concept Laser GmbH, a supplier of additive manufacturing equipment that is based in Lichtenfels, Germany, and that was founded in 2000. In 2012, GE Aviation purchased Morris Technologies Inc., an additive manufacturing company that was founded in 1994. Indeed, it has taken an amalgamation of GE’s own investments and decades of investments by others to bring additive manufacturing to market in the aerospace industry. Smaller companies that seek to master more basic additive manufacturing materials and processes may want to begin by building products where requirements for safety and reliability are less stringent than they are in aerospace.

**MYTH 2: Additive manufacturing will encourage manufacturing to become local.** Many people are anticipating that additive manufacturing will bring manufacturing closer to markets and consumers. But in our opinion, this scenario has been greatly exaggerated. In concept, the idea of sending raw materials, instead of finished products, to a manufacturing location close to the users so the company can produce on demand what’s needed makes sense. A company could have machines and raw materials in cities and neighborhoods where its customers are, produce in the right quantities, and thereby reduce lead times while cutting transportation and inventory costs.

However, additive manufacturing, like other methods of production, is subject to economies of scale. Since it takes skilled operators and sophisticated machines to produce reliable and durable products using 3-D printing, having one person in charge of 10 machines would be cheaper than producing at 10 different locations with one person each. Furthermore, additive manufacturing parts often require a number of complex postproduction steps and tests, many of which require specialized machinery of their own. For a simple titanium-alloy aerospace component, such costs would make up 10% to 15% of the total cost of the component. Clearly, it’s better to do the postproduction work at one site to support many different machines than to distribute the capability across multiple locations.

Companies should, however, use additive manufacturing to accelerate and streamline product development. For example, additive manufacturing allows designers to produce and test prototypes for a wide range of concepts, which may not require extensive post-processing or rigid quality control. Early feedback on prototypes avoids expensive surprises later in the product development process. Additive manufacturing also makes it possible to build tools for short production runs. This enables companies to beta test physical products. For example, the automotive molds industry in Portugal uses simple prototype molds to produce sample components. Because successful product development requires early and frequent engagement with customers, there are clear advantages to being able to do this locally.

Nevertheless, we think many governments would be making a mistake to invest large sums of public money in developing a broad additive manufacturing capability in the hope of “bringing back manufacturing.” The United States, China, Singapore, and the European Union are investing hundreds of millions of dollars in national programs to create new or retain existing competitive advantages in manufacturing. The United States, for its part, has identified additive manufacturing as critical to maintaining its technological superiority in the military and in aerospace. However, the case for public investment in building additive manufacturing capability is less compelling for other countries, particularly when the local market isn’t large enough for the economies of scale that a capital-intensive technology needs. For example, our conversations with Portuguese manufacturers revealed that additive manufacturing parts made in Germany had better mechanical properties due to manufacturers’ greater know-how and were also cheaper than similar parts manufactured in Portugal by suppliers who catered only to the Portuguese market.

In our view, governments should concentrate on identifying sectors in which their industries are already competitive and support the development of
focused additive manufacturing capabilities in those sectors. Portugal’s highly successful automotive mold makers, for example, may need to incorporate additive manufacturing into their suite of capabilities in order to meet customer expectations of fast lead times and performance. But the possibilities for another country may be different.

**MYTH 3: Additive manufacturing will allow producers to replace mass manufacturing with mass customization.** Many people have predicted that additive manufacturing will result in a decisive shift from mass manufacturing to mass customization. But the likelihood that this will occur quickly is slim. Wohlers Associates Inc., a leading additive manufacturing consulting firm, estimates that in the long term additive manufacturing might represent 5% of total manufacturing worldwide. Moreover, there are forces other than additive manufacturing that will hasten mass customization.

The Spain-based fashion retailer Zara, for example, is able to launch a new collection within weeks. Rather than using additive manufacturing within local markets, it achieves this by managing its supply chain masterfully. Manufacturers of IT hardware, for their part, have relied on modularization to assemble bespoke products on demand, and to do so close to their customers.

We see limits on the extent to which additive manufacturing will be flexible manufacturing. In theory, a good 3-D printer ought to be capable of printing a wide range of designs. In practice — and especially in applications critical to safety — we may see regulations that control how 3-D printers and additive manufacturing equipment in general can be configured. This could mean that every time a machine is reset to produce a part that’s different from the one it made before, the system will have to be rechecked. Depending on what this entails and how involved the inspection is, it might turn out to be less costly and safer to have different machines dedicated to the production of different parts.

To be sure, additive manufacturing’s flexibility can be, and is being, harnessed to produce products where safety standards are less of an issue — for example, wearable technologies and jewelry. Companies will find the use of additive manufacturing for such products increasingly appealing as production speeds improve and costs decline. (See “Should You Move Into Additive Manufacturing?”)

For example, last May, HP Inc. delivered its first polymer additive manufacturing machine, which it claimed was up to 10 times faster than previous models and cost half as much.

In general, additive manufacturing holds great promise, but in many areas the cart has gotten ahead of the horse. Much of the technology is still under development. The history of comparable technologies such as composite materials and high-performance...
castings shows that the problems may take decades to resolve. For now, additive manufacturing is cost-competitive only in niche applications — for instance, those involving plastics. Businesses that want to plunge into additive manufacturing should be cognizant of the challenges. Determining whether it makes sense to invest in additive manufacturing will require experimentation and learning.

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The Killer App for 3D Printing? The Circular Economy

GREGORY UNRUH

3D printing has the potential to alter how we use — and reuse — materials.

3D Printing, the additive manufacturing process that “prints” objects, is a classic disruptive technology looking to go mainstream. It has been around for some time — it was originally developed in the 1980s — but until recently it has been limited to costly industrial manufacturing applications. That changed in the late 2000s when 3D printing was taken up by the open-source and do-it-yourself movements. Then cheap desktop 3D printers produced by companies like Makerbot started appearing in workshops and college laboratories around the country. But even with the explosion in interest and investment, 3D printing remains a niche and hobby product.

What 3D printing needs is a “killer app” — a use so valuable that it mainstreams a technology, like spreadsheets were for PCs and email was for the Internet. My favorite candidate is the circular economy.

When I was researching cradle-to-cradle business models for my 2010 book Earth, Inc., I envisioned a manufacturing system that worked like our only sustainable production model: the earth’s biosphere. The biosphere is sustainable thanks to a few core principles. The first of these is materials parsimony, meaning that a minimum number of material types are employed in production. The biosphere, for example, uses only four kinds of matter — carbon, hydrogen, oxygen, and carbon — to produce over 90% of every organism on the planet. Next is power autonomy, the idea that energy needs for production are generated locally and renewably, just as a tree taps into renewable solar power to manufacture blossoms in spring. Finally, there is value cycling, the principle that old products are up-cycled into equal- or higher-value applications. These three principles are why sustainability expert Gregory Unruh sees 3D printing as an opportunity to fundamentally alter how we use and recycle raw materials.
a creature like a rabbit can be biologically broken down and sustainably reassembled into a cactus, fish, or even another rabbit.

The amazing thing is that 3D printing can employ all three of these principles, setting the foundation for a viable circular economy. 3D printing’s additive manufacturing approach means that a single plastic polymer can be used to create a nearly infinite number of forms, fulfilling the principle of materials parsimony. Next, the recent development of a solar-powered 3D printing fulfills the power autonomy principle, allowing printers to work entirely on local renewable energy. And the final piece has also been demonstrated: An integrated recycling process that can take an old object, grind it down, and reuse it as raw material for the next printing run.

Imagine that you have your own 3D printer in your garage, or perhaps you use a printing merchant at your local shopping center. Most of the products in your home — tableware, furniture, finishings, doors, and so on — are printed products. When you tire of your side table, you pop it in your car and go to your printing merchant, who promptly throws it into a hopper to grind it down into new raw material. Then you select the new table design you want from the merchant’s terminal and press “print.” When you come back from your grocery shopping, your brand new table is ready and waiting for you.

While not all products can currently be produced by the technology, it is easy to imagine a large percentage of our goods being 3D printed, absorbing a big chunk of production into the circular economy. As novelist William Gibson said, “The future is already here — it’s just not evenly distributed yet.” The elements for creating a “cradle-to-cradle” economy are here. It is the killer app for 3D printing. With luck it will also be the death knell of our “take-make-waste” disposable society.

About the Author

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The newest wave of digital customer engagement is developing in one of the oldest of industries: manufacturing. Thanks to emerging technologies like 3-D printing, manufacturers can offer consumers customized products and do so with unprecedented speed. Intrigued by a new product you saw in a YouTube video? Well, soon you may be able to personalize it, order it via the company’s website, and have it in your hands in a matter of days.

We are seeing this phenomenon emerge in a variety of consumer product sectors, including personalized running shoes pioneered by the likes of Adidas AG and Nike Inc. The age of mass customization is finally here, backed by a new kind of supply chain.

Across product categories, we find companies engaging with customers online and inviting them to customize and order products from a company website. Orders are produced quickly —
Supply Chains Built for Speed and Customization (Continued from page 7)

in factories that are located close to the customer and that use 3-D printing and robotics — and delivered via the highest-speed options available.

We call these new supply chains high-speed bespoke supply chains, because they provide both quickness and product customization. And while the emergence of this new model is a function of the manufacturing of personalized products, its value extends to other uses, such as the manufacturing and fulfillment of rarely ordered products. High-speed bespoke supply chains also offer the promise of unprecedented market intelligence for manufacturers by capturing demand signals directly from online customers about specific features they are seeking in existing products and prototypes.

These manifold opportunities also bring new challenges for manufacturers, who will need to strategically integrate a wholly new supply chain model into their operations.

A New Supply Chain Option

Having the right type of base supply chain — one that is lean for cost efficiency or agile for time efficiency — is well-understood by manufacturers. It is a choice that depends on whether the products are commodities — functional goods for which cost matters most — or fashion goods — innovative products for which time to market is critical. Many leading companies split their supply chains between the two types of products. Spanish clothing retailer Zara, for instance, makes its fashion goods in Europe, to be shipped quickly via truck to European customers, while sourcing its commodity goods from China or India and shipping them by sea.

High-speed bespoke supply chains add a third option to this framework. Whether a company employs a lean supply chain or an agile supply chain or a combination of both, its operations are usually meant to be optimized for make-to-stock products based on forecasts. By contrast, high-speed bespoke supply chains fit the needs of make-to-order products based on realized demand, not forecasts.

There’s another advantage to extending the lean-agile framework with a high-speed bespoke supply chain: Supply chain managers gain a potentially more cost-effective option for fulfilling ultra-low-volume items, such as replacement parts for outdated product models. Instead of relying on lean or agile supply chains to fulfill orders for products with low, sporadic demand from a slow-turning inventory of finished or semifinished goods, companies could fulfill such orders by high-speed bespoke supply chains.

German automaker Daimler AG, for instance, is experimenting with 3-D printed plastic spare parts for Mercedes-Benz trucks, no matter how old the model. By moving these replacement parts to on-demand production, the company not only decreases inventory but also is able to retire a large number of molds and related equipment. Without this overhead, an order can be fulfilled from the nearest of the company’s manufacturing or development locations worldwide using 3-D printing.

Developing a high-speed bespoke supply chain also allows marketers to add more product variety with niche demand, fattening the so-called “long tail” of product demand to reap additional profits from niche products.

Although unit manufacturing costs in a high-speed bespoke supply chain are higher than in the base (lean or agile) supply chain, the total supply chain’s cost per unit can be lower for products with low levels of sporadic demand, because inventory- and transportation-related costs are greatly reduced. And for customized products, customers have shown their willingness to pay more — sometimes much more — for products they’ve shaped themselves.

Finally, the high-speed bespoke supply chain is premised on manufacturing facilities close to customers for quick delivery. Thus, high-speed bespoke supply chains translate into in-country manufacturing jobs, which are being sought by governments in many countries, including the United States. The bulk of manufacturing, however, would remain in low-cost offshore locations, because customized products will remain a small but valuable portion of overall unit sales.

The Model in Action

Some leading global manufacturers have already begun experimenting with high-speed bespoke supply chains. Sports apparel company Adidas, which offers customization of its shoes through its Mi Adidas (“my Adidas”) online platform, has built its first “Speedfactory” in Germany to add high-speed manufacturing to its bespoke product offering. The company plans to open additional Speedfactories in Western countries, including one in Atlanta, Georgia, in 2017. While Adidas will continue to make the vast majority of its shoes via the Asian contractors in its base supply chain, it wants the Speedfactories to be able to produce an estimated 1 million custom-designed pairs of shoes annually to meet high-priced demand for customized products in Western countries.

With these Speedfactories, Adidas plans to dramatically slash the time between custom orders and delivery to four to five business days. A customer could design and order his or her dream
shoes on Monday and receive the pair on Friday. The company can monitor its customers’ creations on the web. If particular designs or features recur at high enough rates, Adidas can incorporate them into standard shoes in the base supply chain. Personalized orders thus offer insight into customers’ desires.

Nike also offers customization with its NikeiD program; customized shoes can be ordered via its website. According to Nike chief operating officer Eric Sprunk, the eventual plan is for customers to be able to walk into a Nike store and have a 3-D-printed shoe made within a matter of hours.

In the toy industry, Mattel Inc. is tapping into the maker movement and bringing on-demand manufacturing directly into customers’ homes (essentially giving people their own at-home, high-speed bespoke supply chain) via a microwave-size 3-D printer and computer app for children called ThingMaker. Set for release in fall 2017, the package’s app will let a child customize toys such as dinosaurs, robots, and dolls and then send the resulting stereolithography file to the 3-D printer. The parts will be printed with ball-and-socket joints to be assembled by the child.

Although Mattel’s idea is for customers to create their own stereolithography files, nothing stops Mattel from offering retired models and “trial balloons” as stereolithography files for 3-D printing at home. Analyzing orders for these files would help the company spot new market trends and bet on potential winners more confidently when deciding what to manufacture for store sales, say, in the Christmas period. Likewise, Mattel could retire some existing cash-cow products earlier based on trends it observes on falling orders for stereolithography files. Of course, retirement of a product now would mean only that the product is moved to the bespoke supply chain, potentially available forever for 3-D printing at home.

**Barriers to Adoption**

Certainly there are barriers to a company setting up a high-speed bespoke supply chain to complement its existing base supply chain. First, companies should be sure they understand whether and how they stand to benefit from a high-speed bespoke strategy — to enable customized manufacturing to produce ultra-low-demand parts or to simply sense changes in customer demand patterns much earlier than is possible now.

Next is the issue of additional investment. The direct cost of outfitting asset-light 3-D printing facilities is low compared with the capital costs for traditional factories. But significant learning costs can arise related to adopting new technologies and a new supply chain model.

Another barrier is operational: 3-D printers — supplemented with other highly flexible and automated manufacturing equipment such as robots — must be able to actually make the company’s products, or at least some components that lend themselves to quick and easy assembly. At present, Daimler is offering 3-D printed plastic spare parts but not, say, replacement gearboxes or engines. This obstacle will lessen over time as 3-D printing capabilities improve.

And then there is distribution. Most manufacturers are accustomed to delivering in bulk at low cost across long distances, with speed often a secondary concern. High-speed bespoke supply chains flip this model on its head. They are short in distance, light in volume, and offer quick delivery. The last mile of a high-speed bespoke supply chain resembles Amazon Prime more than any traditional manufacturing or wholesale delivery system.

The solution for most companies building high-speed bespoke supply chains is not to develop distribution on their own. Instead they could either piggyback onto the efficient in-country infrastructure already built by e-commerce leaders like Amazon, Alibaba, and, increasingly, Google, or outsource to in-country local delivery services. Other options may emerge: For example, Amazon plans to launch an Uber-like app that would, among other things, connect individual truck drivers to shippers that need goods moved.

While the financial and operational barriers to launching a high-speed bespoke supply chain are not trivial, they are modest in comparison to what it took companies to build their legacy manufacturing and distribution networks. Companies would be wise to ride this newest wave of digital customer engagement. They should consider not only how adding a high-speed bespoke supply chain could improve their existing business but also what new businesses and business models such a supply chain would enable.

**Retirement of a product now would mean only that the product is moved to the bespoke supply chain.**

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Innovation Lessons From 3-D Printing

When people in online user communities start collaboratively developing open-source innovations that have the potential to change an industry, how should the existing companies in the industry respond?

BY JEROEN P.J. DE JONG AND ERIK DE BRUIJN

THE LEADING QUESTION
Is open source innovation a threat or an opportunity?

FINDINGS
* Collaborative user innovation is most likely to happen in three kinds of environments.
* Existing companies have five possible responses.
* Proactive companies can take advantage of user-improved designs.

THESE DAYS, 3-D PRINTING is big news.¹ The use of 3-D printing and other related technologies is seen as having potentially transformative implications. "Just as the Web democratized innovation in bits, a new class of 'rapid prototyping' technologies, from 3-D printers to laser cutters, is democratizing innovation in atoms," Wired magazine’s longtime editor-in-chief, Chris Anderson, stated in his new book Makers: The New Industrial Revolution.² "A new digital revolution is coming, this time in fabrication," MIT professor Neil Gershenfeld wrote in a recent issue of Foreign Affairs.³

But in addition to 3-D printing’s technological implications, recent evolutions in 3-D printing offer important management lessons for executives about the changing face of technological innovation — and what that means for businesses. In this article, we examine the rapid emergence of a movement called open-source 3-D printing and how it fits into a general trend toward open-source innovation by collaborative online communities. We then discuss how existing companies...
can respond to open-source innovation if it occurs in their industry — and whether such collaborative innovation projects represent a threat or an opportunity for existing businesses.

**Trends in 3-D Printing**

Also known as “additive manufacturing” or “rapid prototyping,” 3-D printing is the printing of solid, physical 3-D objects. Unlike machining processes, which are subtractive in nature, 3-D printing systems join together raw materials to form an object. Drawing on a computer-aided design (CAD) file, the design for an object is first divided into paper-thin, cross-sectional slices, which are then each ‘printed’ out of liquid, powder, plastic or metal materials in sequence until the entire object is created. The use of 3-D printing makes it possible to build physical models, prototypes, patterns, tooling components or production parts. Design and manufacturing organizations use it for product parts in the consumer, industrial, medical and military markets.

The longer-term implications of 3-D printing technologies are believed to be large. Direct advantages include enabling designers to operate more efficiently and conveniently. They can quickly prototype their designs in order to test their viability or demonstrate them. In addition, 3-D printing is increasingly used to manufacture products or parts in small batches that would be too costly for a traditional production line. Moreover, 3-D printing enables entirely new products to be developed. With layer-wise 3-D printing processes, many limitations of existing production processes are removed, allowing a wider range of design options. Widespread use of 3-D printing will also likely have implications for production, logistics and retail, since there will be less need to centrally fabricate products and distribute them if individuals can download and locally print a product’s design.

However, 3-D printing is not new. Industrial 3-D printing manufacturers have been offering their products for more than 20 years now. Their machines were initially sold to larger R&D-based organizations that require high-quality objects and are able to afford a premium price. Currently, more than thirty 3-D printing companies around the globe offer a range of industrial 3-D printing systems drawing on various technologies. More expensive systems produce fine-grained metal and polymer parts, while simpler systems use plastics to create 3-D objects. In 2011, total industry revenues for industrial and professional purposes had grown to more than $1.7 billion, including both products and services. The industry’s compound annual growth rate has been 26.4% over its 24-year history, and double-digit growth rates are expected to continue until at least 2019.

In terms of unit sales, Stratasys Ltd., which now has headquarters in both Eden Prairie, Minnesota and Rehovat, Israel, is the world market leader in 3-D printing; Stratasys recently finalized a merger with Objet Ltd., an important producer at the higher end of the 3-D printing market. Another significant 3-D printing supplier is 3D Systems Corp., based in Rock Hill, South Carolina, which recently acquired a company known as Z Corp. Another major supplier is also EOS, based in Munich, Germany, a producer of higher-end 3-D printing systems.

While early systems were mainly sold to large, multinational customers, 3-D printing manufacturers more recently started to focus on the lower end of the market, offering increasingly cheaper machines to make 3-D printing a viable option for small businesses, self-employed engineers and designers, schools and individual consumers. Indeed, 3-D printing is expected to eventually become a mass market.

In the past two years, 3-D printers for home use have emerged on the scene. Not very long ago, no such product existed, but thousands of 3-D printers for home use are now being made annually by new startup companies. Five years ago, users started to collaboratively develop home printer designs and to share their open-source designs on the Web. This attracted new users, some of whom also made innovative contributions, and an open-source 3-D printing community soon developed. More recently, users started to found their own businesses, which are now commercializing open-source-based 3-D printers.

**How the 3-D Printing Market is Changing**

Early 3-D printing systems were expensive — typically priced at $250,000 and more — and were designed for a limited market. Stratasys, for example, initially sold its products to major corporate customers such as General Motors and Pratt & Whitney for use in those companies’ internal R&D processes. As their technologies evolved, 3-D printing compa-
panies started to focus on the lower end of the market, and applications of 3-D printing for medical uses such as hearing aids and dental implants became more common. More recently, 3-D printing companies started to have success with systems priced at $10,000 to $30,000, making 3-D printing viable for schools and medium-sized enterprises. Stratasys also collaborates with traditional printing giant Hewlett-Packard Co., which is now selling Stratasys’s lower-end products as HP-branded machines. New companies are also forming to offer 3-D printing as a service. Shapeways Inc., for example, a spinoff of Dutch multinational Royal Philips Electronics, prints consumer designs using excess industrial 3-D printing capacity. Meanwhile, 3D Systems recently introduced its Cube, advertised as a home-use 3D printer, starting at $1,299.

The RepRap (replicating rapid prototyper) is an open-source home-use 3D printer whose popularity has grown quickly in the past three years. Like Stratasys’s machines, the RepRap’s design revolves around a heated nozzle from which a fine filament of molten plastic is extruded. The nozzle is then moved in X, Y, and Z dimensions by computer-driven motors to successively create each layer of the object to be made. Since many of the RepRap’s parts are made from plastic, the machine can largely replicate itself, with a kit that anyone can assemble given time, materials and a minor investment, typically of about $400.

The RepRap was created in 2005 by Adrian Bowyer, a lecturer in mechanical engineering at University of Bath in the United Kingdom. Bowyer envisioned a machine that would be owned and used by people to make things at home. Bowyer shared his design for free under the GNU general public license. In its first two years, the project did not receive much attention, but after early members of the RepRap community managed to self-replicate the machine, adoption began to take off in the summer of 2007. By mid-2010, the size of the RepRap community was estimated to be more than 3,800 individuals and was estimated to be doubling every six months.8 More recently, in early 2012, an estimate of the total number of RepRap machines, including derivative commercial kits, was 29,745.9

Thousands of enthusiasts built copies of the RepRap for themselves and collaboratively improved Bowyer’s original designs. It did not take long for some members of the RepRap community to start selling commercial versions of the RepRap. By 2012, user-founded companies were shipping thousands of machines annually, at prices of $2,500 or less. These are mostly offered as kits that buyers need to put together themselves. Such printers are more standardized, thus offering more reliability but at the expense of some flexibility, and it still takes an effort to get a RepRap operational. In the past year, however, user-founded companies started to offer fully assembled home-use 3-D printing systems. Examples of user-founded companies include Bits From Bytes, based in Clevendon, United Kingdom; Makerbot Industries, based in Brooklyn, New York; and Ultimaking Ltd., based in Geldermalsen, the Netherlands. (Ultimaking plans to change its name to Ultimaker soon.)

All three companies were founded by active RepRap community members who stepped into the lower-end market segment of 3-D printing, serving individual designers, artists, inventors and students. These open-source printers represent an incipient challenge to existing 3-D printer companies at the low end of the market. In response, 3D Systems, for example, acquired Bits From Bytes and Botmill, another user-founded business. 3D Systems also recently introducing a fully assembled Cube 3-D printer to serve individual end users.

Innovation by User Communities

The rapid growth of open-source 3-D printing is a typical example of the broader and emerging phenomenon of open collaborative innovation. An open collaborative innovation project involves contributors who share the work of generating a design and also reveal the outputs from their individual and collective design efforts openly for anyone to use. Contributors to such open-source projects typically contribute for personal need, enjoyment and/or reputational gains, to help others or to develop their skills.

While open-source communities are probably best known for software development, they are by no means restricted to software or even information products; as the RepRap community demonstrates, such communities are also viable for developing physical products. Moreover, innovation by user...
communities may be expected to increasingly compete with and, in some cases, displace corporate innovation in many parts of the economy. This shift is driven by new technologies — the transition to increasingly digitized and modularized design and production practices, coupled with the availability of very-low-cost, Internet-based communication — and a general trend toward better-educated citizens capable of engaging in innovation activities.10

Key questions for innovation-oriented companies then become:
1. Under what circumstances are companies most likely to see innovation by user communities?
2. Does user innovation pose a threat or opportunity for our company?
3. How can we respond — and how can generally useful innovations be identified from user communities?

Anything that can be cost-justified for development by a user collaborative and that does not involve significant economies of scale in replication and diffusion is theoretically a candidate for open collaborative innovation and diffusion. Such collaborative innovation is more likely to happen in three types of environments: nascent industries, industries where some potential users are not yet served and industries where some users are not served adequately.

**Type 1: Nascent Industries** A lot of innovation activity by users takes place in emerging new industries, when commercial markets do not yet exist or are still too small and uncertain to attract established companies. User communities may innovate and use new products prior to commercial production. The Wright brothers, for example, developed aircraft for personal need rather than anticipated commercial benefits. They were representatives of a worldwide community of aviation pioneers seeking after the “holy grail” of controlled flight, while commercial aviation companies emerged only later.11 Similar patterns have been witnessed in new sports such as kitesurfing, snowboarding and whitewater kayaking. Initially, users may justify their investments based on expected personal benefits, while commercial manufacturers must be concerned about a larger market potential upon which their profits depend. This uncertainty is reduced after a period of use and experimentation by early users. Accordingly, a common pattern of industry emergence is that users first innovate on their own, somewhat later in communities, while commercial production is seen only later, when demand is more certain.12

In the earliest days of 3-D printing, users were influential sources of innovation, too. While some incumbent 3-D manufacturers are academic spinoffs, Stratasys was founded by Scott Crump after he tried to make a toy frog for his young daughter using a glue gun loaded with a mixture of polyethylene and candle wax. His idea was to create the shape layer by layer. This triggered him to automate the process and invent the technology that became the heart of Stratasys’s products.13

**Type 2: Existing Industries, Where Some Potential Users Are Not Yet Served** After a new industry emerges, user communities can still be influential. The second type of industry in which this is the case is those in which some potential users are not yet served. This situation applies to products that are targeted initially toward high-end users able to afford the high prices necessary to overcome initial investment costs. For example, early cell phones were too expensive for a mass market and were mainly used by mobile professionals such as doctors; mass-market products were introduced and sold only later. Many high-technology industries, after their inception, can be characterized by a sequence in which only big customers are initially served — think of governments and multinational corporations. Medium-sized and small organizations follow later, and individual end consumers are served last, after the technology has sufficiently matured.14

In such instances, user communities may emerge building their own versions of high-end products before a consumer version of the technology is widely available commercially. In particular, individual end users may collaborate to develop do-it-yourself personal products that are still insufficiently affordable for an individual. Such communities are most likely to form in the case of hobbyist products — when use provides enjoyment as opposed to providing pure economic benefit, and with significant lifestyle benefits. Beyond engaging in communities, hobbyist users are also more likely to found businesses to commercialize their

User-founded 3-D printing businesses regularly incorporate community innovations in their newest releases.
inventions. Typically, they launch undertakings that might be viewed as costs, but which they consider fun and in line with their personal needs.

The case of 3-D printing is an example of this type of industry. Commercial 3-D printers have been available for commercial purposes for 20 years, but the systems available for many years were expensive and mainly focused on high-end corporate customers. More recently, cheaper systems have made 3-D printing viable for basically all industrial users, but individual consumers had to create their own machines because low-end machines were still comparatively unaffordable. In effect, the RepRap community and its commercial spinoffs have jumped into the gap at the bottom of the market.

**Type 3: Existing Industries, Where Some Users Are Not Adequately Served** Another environment in which open-source innovation is likely is when commercial products have limited variety and are, in effect, one-size-fits-all. Manufacturers tend to follow product development strategies to meet the needs of homogenous market segments. They are motivated by perceived opportunities to serve sufficiently large numbers of users to justify their innovation investments, but this potentially leaves some users dissatisfied with the commercial products on the market. Especially when demand is heterogeneous, many users may not get precisely what they want, and some of them will be motivated to modify the product or spend time and money to develop a home-built version that exactly satisfies their needs. A well-known historical example of this phenomenon was the Model T Ford, which was produced and sold in only one type. Users engaged in massive modification activities to make this car a better match with their personal needs. In fact, Model Ts were modified to form both snowmobiles and tractors, and these modifications were sold as do-it-yourself kits at the time.

Note that manufacturers may have good reasons not to invest in tailor-made products. User segments may be too small for commercial viability, or companies may just overlook an opportunity if it’s not easy to spot. Nevertheless, industries characterized by heterogeneous customer preferences and many peripheral segments are more likely to contain innovative user communities and businesses founded by former consumers.

**Opportunity or Threat?** Innovative user communities do not necessarily pose a threat to existing companies already doing business in an industry. In nascent industries, user communities, in effect, reveal features commercial products are still lacking, and proactive companies with relevant capabilities and/or similar products may take advantage of this and step in. In existing industries, users may also develop complementary innovations that increase the value of an existing manufacturer’s current products. Both potential roles of innovating user communities are discussed next.

**Competing Innovations** User communities may develop direct alternatives to the products of existing companies that are cheaper or more suitable to their personal needs. Such innovation alternatives are more likely (but not necessarily or exclusively) found in industries in which some potential users are not yet served. As real-life examples such as Linux demonstrate, the existence of user-developed competitive innovations does not imply that existing companies in the industry will be wiped out. Potential users of the product developed by the user community may face high adoption costs, so that a product ends up being available either via a peer-to-peer channel (in other words, through a user community freely revealing a design) or the traditional marketplace (in other words, through companies with commercial offerings).

The current situation in 3-D printing is an example of this dynamic. It takes time, skills and effort to build a RepRap, and the self-assembled printer typically breaks down from time to time. Printer kits sold by user-founded businesses are better in this respect but still require skills to build and maintain, so some users prefer a traditional commercial product made by an established business.

The presence of competitive user-developed innovations has two types of implications for existing companies in that industry. On the one hand, such innovations decrease users’ willingness to pay for a commercial product, so price discipline is imposed on existing companies. Not surprisingly, we
Currently see that existing 3-D printing manufacturers are offering their products at increasingly lower prices. On the other hand, existing companies may benefit from user-developed competing innovations that are potentially commercially attractive. These innovations identify what is currently missing in commercial products, and companies may just adopt these designs and further improve them to offer better products, realize cost savings and so on. Thus, innovating users are a source of free ideas and prototypes that can enhance a company’s offerings.

**Complementary Innovations** User communities can also create products that are essential or useful complements to existing companies’ offerings. In such cases, user communities may well increase existing companies’ profit potential. Complementary innovations are more often found in industries where some users are not adequately served. For example, toolkits were sold to modify a Model T Ford into a tractor, and this enhanced Ford’s revenues.

Complementary innovations by user communities are found in 3-D printing, too. The 3-D printing user community, for example, delivers content for Thingiverse, a community website that allows anyone to post his or her CAD designs, which other users can then download, modify and print. Likewise, users have developed easy-to-use CAD modeling software, which has been further refined by user-founded businesses. While early RepRap enthusiasts needed to master professional CAD software, today they can generate input data by medical scanners, entertainment software and simple drawing and sketching programs. These complementary tools have increased the general value of lower-end 3-D printers to consumers — regardless of whether those 3-D printers are open-source or based on a manufacturer’s proprietary design.

**Five Ways Existing Companies Can Respond**

To respond to innovative user communities, existing companies have a range of options, and they may be applied in parallel. Five strategic responses include: (1) monitor, (2) attack, (3) adopt, (4) acquire, and (5) facilitate.

1. **Monitor** Whatever the industry, it never hurts an existing company to keep track of what user communities are doing — so that one can react or appropriate what is observed. Close monitoring enables existing companies to make more accurate sales forecasts and optimize their supply strategies. In 3-D printing, for example, lower-end manufacturers keep track of how the RepRap and derivative commercial machines are evolving, and most of them have employees who build these machines, either as part of their jobs or in their leisure time.

   If user communities develop potentially competitive products, existing manufacturers should be concerned with understanding users’ adoption costs and the size and growth of the do-it-yourself community, which need to be accounted for in their own pricing strategies. Moreover, user communities’ innovation activities may inform existing manufacturers about their own products’ weaknesses, which they can then address in subsequent product development and product improvement.

   To monitor user innovation effectively, companies need to be able to identify users who are innovating. What’s more, because prior research has found that the majority of consumer innovations are not ad-
opted by others, companies need rules of thumb to identify which user innovations have the most potential to be seen as useful by others and spread.

In the RepRap community, many innovations are developed, but only a few prove generally useful and are therefore picked up by many other community members. To explore the determinants of innovation and its diffusion in this community, we organized a Web survey. (See “About the Research,” p. 48.) We identified rules of thumb regarding what kinds of community members are likely to innovate and which of their innovations are most likely to be adopted by others.

We found that RepRap community members are more likely to innovate the more they are experienced with building 3-D printers, maintain personal contact with other community members and focus their 3-D printing time on developing improvements. In other words, experienced “village elders” who are well-connected to other members are more likely to innovate than the average RepRap community member.

### WHO INNOVATES IN OPEN-SOURCE 3-D PRINTING?

Our research found that members of the RepRap open-source 3-D printing community are more likely to innovate the more they are experienced with building 3-D printers, maintain personal contact with other community members and focus their 3-D printing time on developing improvements. In other words, experienced “village elders” who are well-connected to other members are more likely to innovate than the average RepRap community member.

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF COMMUNITY MEMBERS</th>
<th>INNOVATES?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO (sample of 182)</td>
</tr>
<tr>
<td>Experience in open-source 3-D printing, in years</td>
<td>0.5</td>
</tr>
<tr>
<td>Advanced degree (master’s or Ph.D. degree)</td>
<td>29%</td>
</tr>
<tr>
<td>Technical skills (in mechanical systems, CAD, rapid prototyping systems and tooling; 1 = rookie; 4 = expert)</td>
<td>2.2</td>
</tr>
<tr>
<td>Personal contact with ... other members (number of members met face-to-face in past 3 months)</td>
<td>1.8</td>
</tr>
<tr>
<td>Time spent on 3-D printing, in hours per week</td>
<td>8.4</td>
</tr>
<tr>
<td>Division of time:</td>
<td></td>
</tr>
<tr>
<td>• Build/fix 3-D printers</td>
<td>54%</td>
</tr>
<tr>
<td>• Use 3-D printers/print objects</td>
<td>16%</td>
</tr>
<tr>
<td>• Develop improvements/innovating</td>
<td>9%</td>
</tr>
<tr>
<td>• Help other community members</td>
<td>7%</td>
</tr>
<tr>
<td>• Learn/improve personal skills</td>
<td>14%</td>
</tr>
</tbody>
</table>

* o indicates no significant relationship with innovation
+ indicates significant relationship with innovation at 5% level
++ indicates significant relationship at 5% level when other variables are controlled for
Those users who spend much time trying to innovate are, not surprisingly, more likely to innovate, but interestingly, their innovations do not have a better chance of being adopted by others. Simultaneously, those spending their time using the machine are not more likely to innovate, but if they do, their innovations are more likely to be picked up by other users.

2 Attack Another strategy existing companies may consider is attacking innovating user communities, which might seem viable in cases where users infringe upon a company’s patents. In some instances, such a response makes sense — for example, if users modify a company’s product in an undesired way, such as to create a weapon. In general, however, bringing individual users to court is not likely to be effective. While direct competitors can be sued, fighting thousands of individuals around the globe is usually impractical, not beneficial in terms of revenues and potentially harmful to the company’s reputation among customers. Attacking users may well escalate into a conflict in which users appeal to higher principles and inflict substantial damage.23 In 3-D printing, system manufacturers have so far refrained from bringing individual user community members to court. This might change if user-founded companies become increasingly competitive, or set a new industry standard, but existing manufacturers should still be aware of potential negative reactions.24

3 Adopt In some instances, companies will want to adopt or copy the technologies, methods or improvements developed by user communities. These can generally be obtained for free, as many innovators in user communities do not protect their contributions with patents. In 3-D printing, incorporating community innovations is an almost routine practice. For example, Delta Micro Factory Corp., based in Beijing, China, introduced an extrusion-based portable printer called UP! at the lower end of the market which incorporates some of the innovations developed by the RepRap community. Likewise, user-founded businesses like Makerbot and Ultimaking still intensively collaborate with the communities from which they emerged, regularly incorporating community innovations in their newest releases.

4 Acquire Companies may absorb relevant knowledge and skills from user communities via individuals in the community. Key community members may be recruited to join a company and/or accept to collaborate with a company. Existing companies may also acquire startups founded by community members in order to get a foothold in an emerging market. Such initiatives make particular sense when user communities develop innovations that could compete with a company’s products. In 3-D printing, some existing system manufacturers have engaged in quite proactive acquisition behaviors. For example, 3D Systems bought the user-founded venture Bits From Bytes in October 2010. As Bits From Bytes offers low-cost, extrusion-based systems based on the RepRap design, this gave 3D Systems a foothold in the hobbyist and educational marketplace. In addition, 3D Systems has been active in acquiring service providers.25

5 Facilitate Existing companies may also seek to influence the direction and nature of the efforts of user communities. This option may make particular sense when communities develop innovations that are complementary to, rather than competitive with, a company’s existing products. The more individuals are able to contribute and use these complements, the more customers there will be for the company’s own commercial products. Accordingly, companies may want to stimulate the emergence of such user communities and facilitate their innovation and sharing activities. This can be done by methods such as online toolkits that facilitate user innovation and product modification, contests and awards, or sponsoring websites or key community members’ contributions.

When companies try to influence user communities, they first need to understand why community members participate in the community. LEGO’s experience with its user communities, for example, suggests that companies should not just focus on getting a job done, but rather recognize that users’ needs are different from those of employees, and intrinsic rewards (recognition, social bonding, fun) generally may be more helpful than money in motivating users. Moreover, community members often do not like intellectual property protection. The potential tension is that a company often would prefer that users freely provide...
their ideas, prototypes and/or solutions for feedback and further improvement by the company, but on the other hand, the company would like to keep knowledge within its own doors in order to protect it.26

What’s Next?
The emergence of open-source 3D printers illustrates how quickly high-tech markets can be changed by innovative, collaborative users and the companies they form. And, as the case of 3-D printing shows, emerging user communities offer lots of opportunities to existing producers — as well as competition.

What’s more, we believe that innovation by user communities will be increasingly seen in more industries in the future. This is due to several exogenous trends, including increased understanding of modular design practices, decreasing design and collaboration costs thanks to cheaper and more capable computerized design tools, decreasing communication costs thanks to the Internet, and increasingly better educated populations of citizens across the globe. These same advances also diminish the costs of innovation diffused via peer-to-peer networks. Indeed, these factors are all drivers behind the emergence of open-source 3D printing, but they will also affect other industries in the future. Smart companies should start rethinking their innovation management practices accordingly.

WHEN DO INNOVATIONS IN OPEN-SOURCE 3-D PRINTING SPREAD?
Our survey found that, in the RepRap 3-D printing community, innovations were more likely to be adopted by other community members if they were freely revealed by the innovators, were easy to adopt and were software innovations rather than hardware innovations. Innovations were also more likely to spread if they were developed by members who are well-connected within the community and who allocated more of their 3-D printing time to printing objects and/or using their printers.

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF THE INNOVATOR</th>
<th>DIFFUSION OF INNOVATION?</th>
<th>SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO (sample of 177)</td>
<td>YES (sample of 69)</td>
</tr>
<tr>
<td>Experience in open-source 3-D printing, in years</td>
<td>1.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Advanced degree (master’s or Ph.D. degree)</td>
<td>23%</td>
<td>26%</td>
</tr>
<tr>
<td>Technical skills (in mechanical systems, CAD, rapid prototyping systems and tooling; 1 = rookie; 4 = expert)</td>
<td>2.4</td>
<td>2.5</td>
</tr>
<tr>
<td>Personal contact with ... other members (number of members met face-to-face in past 3 months)</td>
<td>2.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Time spent on 3-D printing, in hours per week</td>
<td>11.5</td>
<td>15.7</td>
</tr>
<tr>
<td>Division of time:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Build/fix 3-D printers</td>
<td>44%</td>
<td>28%</td>
</tr>
<tr>
<td>• Use 3-D printers/print objects</td>
<td>14%</td>
<td>24%</td>
</tr>
<tr>
<td>• Develop improvements/innovating</td>
<td>20%</td>
<td>24%</td>
</tr>
<tr>
<td>• Help other community members</td>
<td>8%</td>
<td>14%</td>
</tr>
<tr>
<td>• Learn/improve personal skills</td>
<td>14%</td>
<td>10%</td>
</tr>
<tr>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CHARACTERISTICS OF THE INNOVATION</th>
<th>SIGNIFICANCE*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concerned with hardware (versus software)</td>
<td>69%</td>
</tr>
<tr>
<td>Developed in collaboration with other members</td>
<td>27%</td>
</tr>
<tr>
<td>Time investment, in days</td>
<td>28.3</td>
</tr>
<tr>
<td>Money investment, in dollars</td>
<td>112.0</td>
</tr>
<tr>
<td>Was freely revealed (for example, via blog or wiki)</td>
<td>44%</td>
</tr>
<tr>
<td>Is easy to adopt (according to innovator)</td>
<td>20%</td>
</tr>
</tbody>
</table>

* o indicates no significant relationship with innovation diffusion
+ indicates significant relationship with innovation diffusion at 5% level
++ indicates significant relationship with innovation diffusion at 5% level when other variables are controlled for
Jeroen P.J. de Jong is an associate professor of strategic management and entrepreneurship at Rotterdam School of Management, Erasmus University in Rotterdam, the Netherlands. Erik de Bruijn is a cofounder of Ultimaking Ltd., a startup in Geldermalsen, the Netherlands that manufactures Ultimaker 3-D printers. He is a member of the RepRap core development team. Comment on this article at http://sloanreview.mit.edu/x/54212, or contact the authors at smrfeedback@mit.edu.

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REFERENCES

1. In newspapers and magazines, 3-D printing has been described enthusiastically as everything from “the technology that could re-shape the world” to “one that is about to transform every single aspect of our lives.” See, for example, S. Richmond, “3D Printing: The Technology That Could Re-Shape the World,” The Telegraph, July 28, 2011; and H. Lipson, “3D Printing: The Technology That Changes Everything,” New Scientist, July 30, 2011, p. 20.


5. Ibid., p. 125 and 131.


7. Ibid., p. 65 and 256.


17. For an extensive discussion, see Shah and Tripsas, “The Accidental Entrepreneur.”


19. For a detailed discussion, see Raasch and von Hippel, “Modeling Interactions.”


24. 3D Systems recently sued Formlabs, a new venture offering a home use system printing high-resolution metal parts. See www.3ders.org/articles/20121121-3d-systems-files-patent-infringement-lawsuit-against-formlabs-and-kickstarter.html. Although Formlabs did not originate from the RepRap community, the case is also marked by negative responses from home users: see http://lucent.com/2012/11/24/3d-systems-suing-kickstarter/, accessed on November 28, 2012.


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