3D Printing Disrupts Manufacturing

How Economies of One Create New Rules of Competition

3D printing may represent a disruption to the manufacturing industry as profound as the Industrial Revolution.

Irene J. Petrick and Timothy W. Simpson

Before the Industrial Revolution, goods were produced by local artisans and craftsmen relying primarily on locally available materials and selling primarily to local customers. These artisans conceived of and then made products, and they sold these products in their own small shops or out of their homes. In this environment, the customer was directly linked to the producer; there was no middleman and no supply chain.

The Industrial Revolution ushered in an era of innovation in production methods, mining methods, and machine tools that enabled mass production and allowed the replacement of labor with machines and of traditional energy sources such as wind, water, and wood with coal-powered (and later gas-powered) machines. In the past 200 years, the elements of production have been refined, but the underlying economics have remained: competitive advantage goes to the company or companies (organized into a supply chain) that can produce the highest quality part at the lowest cost. Fixed costs—infrastructure and machinery—became separate from variable costs—those expenditures that increased on a per-unit production basis, such as labor and materials. Economies-of-scale production models meant that high-volume production reduced the contribution of the fixed-cost portion of the cost equation, thus reducing the per-unit cost. Simply put, high throughput and efficiency yielded higher profits (Pine 1993).

Today we are entering an era many believe will be as disruptive to the manufacturing sector as the Industrial Revolution was—the age of 3D printing and the digital tools that support it (Koten 2013). At a EuroMold fair in November 2012, 3D Systems used one of its 3D printers to print a hammer. The *Economist* (2012) used this example to compare the traditional supply chain design-build-deliver model with the emerging 3D printing model:

> Ask a factory today to make you a single hammer to your own design and you will be presented with a bill for thousands of dollars. The makers would have to produce a mould, cast the head, machine it to a suitable finish, turn a wooden handle and then assemble the parts. To do that for one hammer would be prohibitively expensive. If you are producing thousands of hammers, each one of them would be much cheaper, thanks to economies of scale. For a 3D printer, though, economies of scale will matter much less. Its software can be endlessly tweaked and it can make just about anything.

According to Richard D'Aveni (2013), "businesses all along the supply, manufacturing, and retailing chains [will need] to rethink their strategies and operations" (34). Indeed, the rise of 3D printing and additive manufacturing will replace the competitive dynamics of traditional economies-of-scale production with an economies-of-one production model enabled by 3D printing and additive manufacturing, at least for some industries and products. In essence, future manufacturers will be governed by two sets of rules: economies of scale for interchangeable parts produced at high volumes, and economies of one for highly customizable products that can be built layer by layer. Each model brings its own sources of competitive advantage and economic factors (Table 1).

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TABLE 1. Economies of scale versus economies of one

	Economies of Scale	Economies of One
Source of competitive advantage	Low cost, high volume, high variety	End-user customization
Supply chain	Sequential linear handoffs between distributed manufacturers with well-defined roles and responsibilities	Non-linear, localized collaboration with ill-defined roles and responsibilities
Distribution	High volume covers transportation costs	Direct interaction between local consumer/client and producer
Economic model	Fixed costs + variable costs	Nearly all costs become variable
Design	Simplified designs dictated by manufacturing constraints	Complex and unique designs afford customization
Competition	Well-defined set of competitors	Continuously changing set of competitors

The Traditional Supply Chain and the Competitive Dynamics of Economies of Scale

Traditional manufacturing relies on a design-build-deliver model. In this competitive model, roles and responsibilities are well established between the various participants. Designers translate customer needs into viable products. Producers own facilities that emphasize efficiency and low-cost production. In the past four decades, these producers have increasingly relied on a distributed and extended supply chain, sourcing the lowest-cost providers to build components and subassemblies on a global scale. The production methods employed by these manufacturers have relied heavily on subtractive manufacturing methods, which begin with a solid physical form that is ground, cut, drilled, milled, lathed, and otherwise has material removed from it to make the shapes needed to build components, subassemblies, and ultimately complete products.

In this production model, reducing variation to enable repetitive production of interchangeable parts provides a competitive advantage. In the 1990s, companies built on this advantage by pursuing design for manufacturing (DFM) strategies (see for example, Ulrich and Eppinger 1995; Boothroyd, Dewhurst, and Knight 2002), which emphasized designing parts that could be built cost-effectively using traditional manufacturing processes. This model, which changed the object of design from creative expression to cost-effective production and assembly, required simplified designs developed according to a series of design rules that favored reproducible parts optimized for high-volume manufacturing and material-handling methods. Several generations of designers and engineers have been schooled in this approach; many now view design as a creative process of circumnavigating the constraints imposed by traditional manufacturing processes.

Under the design-build-deliver model, the companies that could achieve high-quality products at the lowest cost were more successful, and as transportation improved and coordination between companies was facilitated by digital technologies, the low-wage countries began to dominate in the production phase. The China price was born, and distributed supply chains became the norm as the labor savings significantly offset the added costs of shipping and transportation.

This extended supply chain functioned with a linear handoff between suppliers, with complex assembly and delivery often controlled by the original equipment manufacturers (OEMs). OEMs drove the conceptualization of product needs, often acting as product designers. The path to the customer for companies within these supply chains was through the OEM, which controlled much of the supply chain participants' activities, and which often reaped the lion's share of the profits.

The 3D Production Model

The terms *3D printing* and *additive manufacturing* are often used interchangeably, as both refer to the layer-by-layer creation of physical objects based on digital files that represent their design. 3D printing has been used for more than two decades, primarily for rapid part prototyping and small-run production in a variety of industries (Gibson, Rosen, and Stucker 2010). Meanwhile, the term *additive manufacturing* has come to represent the use of 3D printing to create final parts and metallic components, differentiating from the more traditional subtractive manufacturing processes.

3D printing uses computer-generated designs to create "build paths" that reproduce a digital model through consolidation of materials with an energy source. The process typically uses a binder, a laser or an electron beam that solidifies material as it is directed along the build path or scanned over a pre-placed layer of material. To date, this method has been used successfully with polymers, metals, and ceramics.[1] Polymers have the highest proportion of functional prototypes and finished parts produced with this method, often requiring only limited additional finishing. Metals, on the other hand, are still in their infancy in terms of finished part production. Metallic parts produced with 3D printing methods frequently require additional heat treatment or other finishing and post-processing steps to achieve specified tolerances. Capabilities continue to improve for all three types of material systems. Similarly, there is a tradeoff between how fast a part can be produced and its final quality—the slower the build rate, the better the surface finish, for example. Parts producers still need to experiment with 3D printing speeds and feeds depending on the material system, and there are not well-understood

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[1] For a detailed description of 3D printing, see Lipson and Kurman (2013) or Barnatt (2013).

standards or design rules to adequately address this challenge at the present time. This is, however, an area of much active research.

Any 3D printing process begins with a digital solid model, often created through computer-aided design (CAD) and analyzed with computer-aided engineering (CAE) software. For complex product geometries and material combinations, CAE is often further facilitated by high-performance computing resources. The combination of hardware and software returns to manufacturing the ability to produce anything that can be imagined, rather than limiting designs to production constraints. For instance, a polymer mesh can be made on a 3D printer without any assembly; this mesh, which is flexible and interlocking, is produced by the melting and deposition of the polymer filament. Digital technologies also exist to scan physical objects and reverse engineer the computer models and designs needed to reproduce them on a 3D printer.

3D printing has been used successfully for single-unit and very low-volume production in a variety of sectors ranging from aerospace (*Economist* 2012) to prosthetics (Shinal 2013), dental implants (Murray 2012), hearing aids (Sharma 2013), sports equipment (Luna 2013), and even art (Rawsthorn 2013) and fashion (Brooke 2013). When it comes to metal 3D printing, aerospace appears to be leading the way, seeing opportunities to produce lightweight components, reduce manufacturing lead-times, and improve the "buy-to-fly" ratio of components—the amount of material purchased to produce a part versus the amount of material actually in the part. Meanwhile, the ability to produce sophisticated internal geometries using additive manufacturing has sparked considerable interest in the turbine and energy industries, and the medical industry sees opportunities to produce customized devices and implants for individual patients. Even tool-makers in the oil and gas industry see opportunities to create functionally graded parts that provide different material properties to prolong tool life and reduce down-time of well operation. While some of these opportunities may take several years to realize, test flights with 3D-printed airframe components are under way, and several FDA-approved titanium hip and knee replacements are now being fabricated using additive manufacturing processes. It may be a while before the automotive industry invests heavily in additive manufacturing, as the build rates and speed of the current technology are too low to support their high-volume production needs.

The Competitive Dynamics of 3D Printing

The 3D production ecosystem will have major effects in each of the three major stages of the design-build-deliver model. It will change the nature of design, it will increase the interactivity between design and production, and it will radically localize manufacturing as consumers interact more directly with each other and with manufacturers, some of which act as printer hubs, offering services to anyone with a design to print.

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The Changing Nature of Design

In the simplified version of the traditional supply chain, designers are the precursor to production. The roles and responsibilities between design and production are well established and clearly delineated. In the 3D printing world, these roles become blurred, and the notion of who is a designer is called into question, as anyone can design products to be printed. Likewise, the traditional coupling between computer-aided design and computer-aided manufacturing (CAD/CAM) is fractured, as numerous players may be needed to translate from 2D to 3D, as the unique operating codes for the various printers may require additional expertise in file preparation. These shifts have implications across the manufacturing process, from the initial imagination of a product to its translation into a physical thing.

Design has already expanded beyond the expert realm to include hobbyists and prosumers (people who both produce and consume a product) who work with digital design kits (like those available at GrabCAD.com) and other resources to develop their own customized products. Chris Anderson has explored the rise of hobbyist manufacturers in *Makers* (Anderson 2012), and we hear of "Maker Guilds" starting to emerge in large multinational companies like GE to support designers and engineers who have long been divorced from the physical production due to global supply chains (Dods 2013). Innovations in solid-modeling software that allow sophisticated models to be accessed and manipulated through user-friendly interfaces will bring the power once available only to experts to a much wider audience. AutoDesk, which now offers a free app to turn images into 3D objects (see www.123dapp.com), and other software vendors are building these sophisticated systems and beginning to integrate hardware, software, and even cloud services into a unified 3D printing–based production chain.

Finally, digital models will not come only from a diverse array of designers; they will also be created through reverse engineering using digital scanning devices that model both external and internal features, creating new intellectual property challenges that are just starting to be explored (Weinberg 2010). 3D printing frees designers from the constraints of traditional manufacturing processes; some even argue that it flips DFM—design for manufacturing becomes manufacturing for design (Beaman 2013).

There are some bumps in the road toward this vision for design, including software and hardware compatibility issues. Realizing a design requires production models that

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specify build paths. While the STL (STereoLithography) file format has become standard input, many 3D printers use unique software to generate instruction sets and machine code to operate the specific machine. A 3D print file developed for one printer is not necessarily viable for use on a different printer, although companies like Microsoft are hoping to change that (Boettcher 2013). The 3D printing software, and CAD packages in particular, are becoming the limiting factor in the design-build-deliver process.

Experimental Design

Not only will the nature of design change, but there will be a very tight coupling between how a product is conceived, how it is manufactured, and how it is tested and qualified. The traditional handoff between companies along the supply chain and between stages of production within a company will no longer be advantageous. A process parameter framework unique to the 3D printer will emerge. Process plans, tool paths, speeds, feeds, and build orientation will be directed by the designer-specified product features and will ultimately determine the actual features of the 3D-printed part.

In addition, material characteristics will become a critical aspect of design and production. In many cases, materials are supplied as powders, and the powder characteristics (particle size, shape, and distribution) influence the resulting microstructure based on the selected processing parameters, which in turn impacts material properties. This requires collaborative innovation between materials suppliers, product designers, and product producers at a level never before seen, and the interaction will result in a highly iterative design process where the goal will be to fail fast and often to achieve a workable product.

Here, too, some challenges remain. The net or near-net shapes resulting from additive manufacturing will still require finishing and post-processing (for instance, heat treatment) to achieve functional tolerances and performance targets. Many industries are wrestling with how parts built using additive manufacturing will be qualified. Many 3D printing systems do not have the process monitoring and feedback tools needed to control the process in real time, and the machine-to-machine and part-to-part variation that currently exists worries end users. To date, we have sophisticated destructive and nondestructive tests to assess strength, flexibility, density, and other critical product characteristics, but the variation between parts built on the same machine is forcing many to rethink methods for inspection and testing, particularly when only a single custom part is needed. Likewise, validating complex internal geometries remains an issue. While full density may be a very important characteristic to mimic a cast part, for example, in many applications, planned porosity or complex geometric shapes inside a part are going to be more difficult to test and qualify. This remains a barrier to achieving finished quality products, particularly in metallic components, but ongoing research with sophisticated computed tomography equipment should soon change that.

Economies of scale and economies of one will continue to coexist, but they will not be used for the same things.

Localized Distribution and Printer Hubs

A 3D printing environment where consumers interact directly with producers will bring two critical changes to the traditional distributed supply chain. First, because manufacturing no longer needs to be centralized for high-volume production, low-cost sourcing of suppliers no longer makes economic sense. This will result in the localization of both production and sourcing and further reduce economies of scale. Inventory and shipping that now happens in warehouses and large-scale containers will be replaced by smaller-scale shipping methods such as the US Postal Service, FedEx, and UPS. It is even feasible that inventory management will be entirely transformed; we are already seeing signs of this transformation. UPS and Stratasys recently announced a partnership to offer 3D printing in UPS stores across the United States (Nanowerk News 2013), and Staples, the first major retailer in the United States to sell 3D printers directly to customers (Cautela 2013), has begun offering 3D printer services in some of its stores (Senese 2012). Even Microsoft is getting into the hardware game and will start selling MakerBot 3D printers in several of its US stores (*De Zeen Magazine* 2013).

The largest shift in distribution, however, may be the rise of printer hubs that directly support hobbyist and prosumer needs. These are already emerging. For example, Shapeways, a 3D printing services company that spun out of Royal Phillips Electronics, allows clients to post or access designs, modify them, and upload them to the site via the Internet. Shapeways then feeds these digital files into their 3D printers to produce the desired object. In 2011, Shapeways shipped nearly 750,000 parts in materials ranging from plastic and stainless steel to silver and ceramics. In this business model, the customer pays per part built; equipment goes from a fixed cost to a variable cost, completely disrupting the economies-of-scale model.

Conclusion

Lipson and Kurman (2013) note, "Bursts of innovation happen when an emerging technology removes a once prohibitive barrier of cost, distance, or time" (59). Certainly 3D printing removes the cost barrier of traditional fixed-equipment manufacturing and the distance barrier raised by widely distributed suppliers sourced based on cost. From a time perspective, 3D printing has the potential to reduce the time barrier through a tighter coupling of design and production in an experimental fashion. Meanwhile, the capability to print 3D metal parts opens the door to innovations in numerous industries, such as aerospace, medical, and oil and gas.

Economies of scale and economies of one will continue to coexist, but they will not be used for the same things. Companies based on economies of scale will still support commodity and high-volume production, but in instances where end-user customization is highly desirable, where production is single unit or very small volume, or where the end product requires features that cannot be manufactured by traditional means, 3D printing and additive manufacturing will become a viable and competitive option.

The emerging dynamics of economies of one have five likely outcomes:

1. There will be few clear boundaries in the design-build-deliver paradigm.
2. Design and production will be tightly coupled through experimentation.
3. Competitive advantage will reside in *both* designs that are simple to manufacture and assemble and designs that are highly customized and complex; the challenge will be in arenas where manufacturers are seeking simple designs, and customers are seeking customized, complex products.
4. Proximity between supplier, manufacturer, and customer will matter, and localized production will be not only more feasible but more desirable.
5. Planning will go from long term to real time.

In the coming decade, economies of one will make competition increasingly uncertain. Gibson, Rosen, and Stucker (2010) coined the term *digiproneurship* to describe the transformation of the digital to the physical product through entrepreneurship. In many sectors, manufacturing digiproneurship will allow anyone to return to the garage and make things that satisfy the needs of one or a very few customers. Entry-level 3D printers are now at the same price point as laser printers were when they became desktop fixtures, and prices on high-end machines are dropping. Existing companies need to understand the challenges of this future and begin to think about changes needed in several key areas. The very resources and practices that have acted as barriers to entry for their competitors will become barriers to change for themselves. This will be particularly true for companies that have a large installed base and a hierarchical organization staffed with highly seasoned employees in clearly defined and differentiated roles.

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