BH 468

Business Horizons (2012) **55**, 155—162

Available online at www.sciencedirect.com

SciVerse ScienceDirect

KELLEY SCHOOL OF BUSINESS
INDIANA UNIVERSITY

www.elsevier.com/locate/bushor

3-D printing: The new industrial revolution

Barry Berman

Frank G. Zarb School of Business, Hofstra University, 222 Weller Hall, Hempstead, NY 11549, U.S.A.

KEYWORDS
3-D printing;
Rapid prototyping;
Additive manufacturing;
Rapid tooling;
Digital manufacturing;
Bridge manufacturing

Abstract This article examines the characteristics and applications of 3-D printing and compares it with mass customization and other manufacturing processes. 3-D printing enables small quantities of customized goods to be produced at relatively low costs. While currently used primarily to manufacture prototypes and mockups, a number of promising applications exist in the production of replacement parts, dental crowns, and artificial limbs, as well as in bridge manufacturing. 3-D printing has been compared to such disruptive technologies as digital books and music downloads that enable consumers to order their selections online, allow firms to profitably serve small market segments, and enable companies to operate with little or no unsold finished goods inventory. Some experts have also argued that 3-D printing will significantly reduce the advantages of producing small lot sizes in low-wage countries via reduced need for factory workers.

1. A multi-faceted technology: 3-D printing

The purpose of this article is to provide an overview of the 3-D printing process; its current and potential uses; its advantages as compared with other technologies such as mass customization, injection molding, and cutting-based machinery; and its limitations. Practical considerations concerning the adaptability of 3-D printing for a variety of applications are explored, as are prospective future developments concerning the technology.

E-mail addresses: mktbxb@hofstra.edu, bberman1@optonline.net

3-D printing employs an additive manufacturing process whereby products are built on a layer-by-layer basis, through a series of cross-sectional slices. While 3-D printers work in a manner similar to traditional laser or inkjet printers, rather than using multi-colored inks, the 3-D printer uses powder that is slowly built into an image on a layer-by-layer basis. All 3-D printers also use 3-D CAD software that measures thousands of cross-sections of each product to determine exactly how each layer is to be constructed. The 3-D machine dispenses a thin layer of liquid resin and uses a computer-controlled ultraviolet laser to harden each layer in the specified cross-section pattern. At the end of the process, excess soft resin is cleaned away through use of a chemical bath. 3-D printers can produce simple objects, such as a gear, in less than 1 hour. They

0007-6813/$ — see front matter © 2011 Kelley School of Business, Indiana University. All rights reserved.
doi:10.1016/j.bushor.2011.11.003

can also develop products with free-moving parts that do not have to be assembled. A 3-D printer making a set of fully-functioning ball bearings can be viewed online at http://www.youtube.com/watch?v=u7h09dTVkdw.

The definition of 3-D printing is somewhat inexact. While some experts in the field would restrict 3-D printing to units with inkjet-based print heads that create an object on a layer-by-layer basis, others would apply this term to office or consumer versions of rapid prototyping machines that are relatively low-cost and easy to use (Casey, 2009). The word 'rapid' relates to the ease of making a copy of an object due to the simplicity of writing a computer program that controls the object's shape. The term 'prototyping' refers to this process as being too slow for use in mass production (in contrast to injection molding technologies that yield large quantities at low per-unit costs).

Two important aspects distinguish 3-D printing from other rapid prototyping technologies. The first distinction is cost. While a 3-D printer can cost as little as $10,000, a rapid prototype machine can cost as much as $500,000. Desktop 3-D printers now run from $10,000 to more than $100,000. Current 3-D printer manufacturers include Zcorp (www.zcorp.com), Objet Geometries (www.objet.com), Dimension (www.dimensionprinting.com), Designcraft (www.designcraft.com), Stratasys (www.stratasys.com), and 3D Systems (www.3dsystems.com).

The second major difference between these technologies is that 3-D printers seamlessly integrate with computer-assisted design (CAD) software and other digital files like magnetic resonance imaging. At the end of the product design process, the designer's work can be saved as an STL (an industry-standard stereo-lithography format) or similar file. The designer simply clicks 'print' and then chooses the applicable 3-D printer. 3-D printers utilize native CAD data from commercial programs marketed by SolidWorks and Autodesk or free design packages such as Blender and Google SketchUp ("3-D Printing," 2011). These 3-D printers are driven by Magics RP, VisCAM, and Netfabb software.

3-D printing has been compared to such disruptive technologies as digital books and music downloads that enable consumers to order their selections online, allow firms to profitably serve small market segments, and enable companies to operate with little or no unsold finished goods inventory. Current applications of 3-D printing typically involve small-quantity production runs of small, complex items. These include mass-customized products, prototypes and mockups, replacement parts, medical and dental applications, and bridge manufacturing. Some experts have also argued that 3-D printing will significantly reduce the advantages of producing small lot sizes in low-wage countries via reduced need for factory workers ("Print Me," 2011).

1.1. 3-D printing and mass customization

3-D printing has been both compared to and contrasted with mass customization. Advocates of 3-D printing argue that this technology, like mass customization, enables firms to economically build custom products in small quantities. While both processes can profitably make limited-quantity lot sizes and share other benefits, they are very different in terms of their manufacturing technology and logistics requirements.

Unlike 3-D printing, mass customization relies on either using different combinations of pre-assembled modular parts or delayed differentiation strategies. Dell, for example, mass customizes computers by assembling different combinations of display cards, hard drives, microprocessors, and computer memory based on a customer's individual preference. Other firms that use mass customization rely on delayed differentiation production systems that complete the building of partially-constructed products based on a customer's order requirements (Berman, 2002).

In contrast, 3-D printing uses CAD software and additive manufacturing-based technologies to print objects through fusing a variety of materials with a laser. While the raw materials in mass customization are typically component parts, 3-D printing uses such raw materials as plastics; resins; super alloys, such as nickel-based chromium and cobalt chrominium; stainless steel; titanium; polymers; and ceramics.

Since the component parts that are used in mass customization typically come from multiple suppliers, mass customization requires a high degree of supply chain integration to ensure that the right parts are available in the right quantities at the right times. 3-D printing, on the other hand, uses readily-available supplies that can be purchased from a small number of vendors.

And while mass customization production is often team-based, in 3-D printing, the manufacturing process is automated and based on CAD software. According to the chief executive officer of 3D Systems Inc., a maker of 3-D printers, the technology does not require constant attention by an operator, or jogs or fixtures to create a part: "All you have to do is load a file and you can replicate shapes that are not manufacturable through traditional methods. . . .I call it a flexible factory in a box" (Alpern, 2010, p. 47).

3-D printing and mass customization share certain economic characteristics. For example, both manufacturing processes minimize inventory risk,

Table 1. A comparison of mass customization and 3-D printing

Characteristic	Mass Customization	3-D Printing
Manufacturing Technology	Based on pre-assembled modular parts in different combinations or delayed differentiation.	Automated manufacturing based on CAD software and additive manufacturing.
Supply Chain Integration Requirements	Need for highly-integrated supply-chain management to ensure right goods at right times from multiple supplies.	Uses readily available supplies available from multiple vendors.
Economic Benefits	Ability to produce custom products at relatively low prices. Low inventory risk. Improved working capital management.	Ability to produce custom products at relatively low prices. Low inventory risk. Improved working capital management.
Range of Products	Computers; watches; windows; shoes; jeans.	Prototypes; mockups; replacement parts; dental crowns; artificial limbs.

since products are made only after orders are received and paid for. And as with mass customization, there is no unsold finished goods inventory. Finally, both 3-D printing and mass customization improve working capital management, as goods are paid for before being produced.

Due to the nature of the processes and materials, mass customization and 3-D printing have generally each been applied to a different range of products. Mass customization has been applied to products such as computers, watches, windows, shoes, and jeans. These utilize component parts with a wide range of materials. In contrast, 3-D printing has been applied to making prototypes, mockups, replacement parts, dental crowns, and artificial limbs using single materials (see Table 1).

1.2. 3-D printing and injection molding and cutting-based machinery

This sub-section examines the major advantages of 3-D printing as compared to injection molding or machining/subtractive technologies. These advantages relate to cost effectiveness and speed.

In contrast to injection molding processes that require costly molds, 3-D printing entails relatively low fixed costs. Since 3-D printing does not require expensive tooling, forms, or punches, it is particularly cost effective for very small production runs. This enables firms to profitably use 3-D printing to economically fill custom orders and serve niche markets.

In comparison to subtractive technologies, which use multi-axis cutting machines to carve plastics and metals to the desired shape, there is less waste material with 3-D printing: no scrap, milling, or sanding. According to one source, the waste material in metal applications associated with 3-D printing is reduced by 40% in comparison to machining/subtractive technologies. In addition, 95% - 98% of waste material can be recycled in 3-D printing (Petrovic et al., 2011). Other sources state that subtractive technologies can remove as much as 96% of the raw material when creating a product (Wagner, 2010). In contrast to injection molding and cutting-based machinery, in 3-D printing, the variable costs per part do not decrease with large production runs.

3-D technologies are also able to produce initial products much more quickly than injection molding and cutting-based operations since no set-up time is required. Further, considerable time savings are incurred when producing revised designs.

Table 2 outlines the characteristics of 3-D printing in comparison to other technologies. The advantages of 3-D printing include the ability to economically build custom products in limited production runs, the ability to share designs and outsource manufacturing, and the speed and ease of designing and modifying products. These characteristics lend themselves to small and medium production run applications such as mass-customized products, prototypes, replacement parts, medical/dental applications, and bridge manufacturing. These applications will be discussed more fully in a subsequent section. Table 2 also lists the major limitations of 3-D printing that must be overcome for this technology to be more widely used.

1.3. Additional characteristics of 3-D printing

3-D printing facilitates outsourcing, as well as the sharing of designs among designers and users. Software programs such as Alibre and Autodesk enable a person to design a product at home or in the office, and then send the design via email to a customer. Designs can also be very easily shared in 3-D printing. Consider Nick Starno, a mechanical design engineer

Table 2. Characteristics of 3-D manufacturing

Advantages of 3-D Printing in Comparison to Other Technologies

- Can economically build custom products in small quantities as if mass production were used. Sources of cost effectiveness include:
  - No need for costly tools, molds, or punches
  - No scrap, milling, or sanding requirements
  - Automated manufacturing
  - Use of readily available supplies
  - Ability to recycle waste material
  - Minimal inventory risk as there is no unsold finished goods inventory
  - Improved working capital management as goods are paid for before being manufactured
- Ability to easily share designs and outsource manufacturing
- Speed and ease of designing and modifying products

Important 3-D Printing Applications

Small Production Run Applications of 3-D Printing
- Mass-customized products
- Prototypes
- Replacement parts
- Medical/Dental applications

Medium Production Run Applications of 3-D Printing
- Bridge manufacturing

Current Limitations of 3-D Printing

- Higher costs for large production runs relative to injection molding and other technologies
- Reduced choice for materials, colors, and surface finishes
- Lower precision relative to other technologies
- Limited strength, resistance to heat and moisture, and color stability

who developed a device that was successful in extracting the last few drops from a cosmetics tube. After designing the tube squeezer, he posted a prototype on a community website for 3-D printer designs. Within hours, several 3-D print enthusiasts in Europe had downloaded the design and made the tool. As of October 2010, over 500 downloads were performed (Stemp-Morlock, 2010).

Shapeways (www.shapeways.com) and Ponoko (www.ponoko.com) are two firms that undertake production, logistics, and billing functions for designers. After accepting a product design, Shapeways—a division of Royal Philips Electronics—computes the cost of making the design on its industrial 3-D printers. The designer sets the retail price and receives the gross profit, less a 3.5% fee. Shapeways' website currently features items designed by 30,000 people (Olivarez, 2010).

On the negative side, the availability of CAD design software descriptions on the Web has significant implications for intellectual property security. Since objects are described digitally, they can very easily be copied and resold. A major fear is that shortly after a product's blueprints are posted on a website, product clones or pirated products will appear on the market. This is a particular concern for firms with large sales of replacement parts such as appliance lids, control knobs, and plastic product housings. Some writers have noted the need for governments to tighten existing intellectual property rules due to the ease of copying designs through 3-D printing technologies ("Print Me," 2011).

2. The evolution of 3-D printing

3-D printing has undergone a three-phase evolution process. In phase one, architects, artists, and product designers used 3-D printing technology to make prototypes or mockups of new designs. Most 3-D printing still revolves around the manufacturing of prototypes and mockups.

3-D printers have several key advantages in developing prototypes and mockups, including (1) ease of duplicating products, (2) low cost, and (3) product security and privacy considerations. For example, prototypes and mockups can be produced with the same color, texture, and finish as a mass-produced product. Moreover, due to the low costs of modifying prototypes, marketers can more easily test different product versions based on customer and design feedback. According to the chief designer of FutureFactories: "It's cheap to do this stuff. . . .It costs the same to produce two different variants as two identical ones. The economies-of-scale rationale of serial production does not apply" (Thilmany, 2009, p. 39). A senior CAD designer for running shoe manufacturer New Balance adds that the company's 3-D printing machines "run pretty much nonstop." Each machine produces up to 100 models a month (Pullin, 2009).

Less-expensive materials can also be used in prototype and mockup development. For example, when appearance is the major consideration, prototype parts can be produced from plastic materials and resins while the actual objects are made from metals. Prototype development costs and time requirements are also significantly reduced since no tools and dyes are required in 3-D printing. Savings in tools and dyes can result in hundreds of thousands of dollars. The manager of technology at Black & Decker reported that prior to using 3-D printers, it would typically take 3 - 5 days to get a prototype back from the service bureau. With 3-D printers onsite, however, prototypes can be produced in just a few hours ("Simplifying," 2010). Finally, security and privacy issues are not a concern because 3-D printing enables in-house production.

The second evolutionary phase of 3-D printers involves their use in creating finished goods. This stage is sometimes referred to as 'direct digital manufacturing' or 'rapid tooling.' A popular second phase application is larger production runs that encompass bridge manufacturing and the manufacturing of goods to be used in test marketing. In test marketing, multiple prototypes—different sizes, styles, and colors—can be more easily produced and market tested. According to Terry Wohlers, manager of a market research firm specializing in 3-D printing, over 20% of the output of 3-D printers is now in final products as opposed to prototypes ("3-D Printing: The Printed World," 2010). Wohlers predicts that this will rise to 50% by 2020.

In the third phase, 3-D printers will be owned and used by final consumers, just like traditional desktop laser printers. A co-founder of the firm that makes the $750 CupCake CNC 3-D printer said: "My hope is that people, instead of going to the store, will go online and download what they need and print it out" (Olivarez, 2010, p. C4). Arts-and-crafts applications and replacement parts are important aspects of this stage. 3-D manufacturing technology, for example, can be used to produce colorful action figures, chess pieces, and even replacement knobs for gas ranges.

According to a former technology and engineering teacher: "In the near future, we will have a desktop 3-D printer in our homes that can produce parts for our cars, computer widgets, and toaster knobs. We'll all have factories in our homes" (Klaft, 2010, p. B5). We won't be able to make ocean liners, but we'll be able to make the fittings. For this stage to be reached, though, the purchase price of 3-D printers will have to lower significantly. That might be just around the bend: in addition to the CupCake unit mentioned earlier, MakerBot Industries sells a hobbyist 3-D printing kit called the Thing-O-Matic for $1,299.

3. 3-D applications

Whether or not a specific 3-D application is technically possible or economically feasible largely depends on its production volume, part size, complexity, and material cost. 3-D printing is most widely used in applications with low production volumes, small part sizes, and having complex designs. According to one source, 3-D printing is cost effective with plastic injection molding on production runs of 50 to 5,000 units (Sedacca, 2011). Another source states that 3-D printing is competitive with plastic injection molding of runs around 1,000 items ("Print Me," 2011). In the future, some experts feel that the range of efficient production may be further increased as raw material costs drop in price; this would occur as more firms use 3-D printing to produce finished goods and as final consumers begin to purchase 3-D printers. 3-D printing is also especially suitable for manufacturing parts that are small in size, such as ball bearings.

Advances in 3-D printing have enabled this technology to be employed across a broader range of applications. Earlier versions of 3-D printers could only utilize laser-hardened acrylics. Unfortunately, these parts produced were often fragile and required post-manufacturing treatment. Currently, a wider range of materials can be used including aluminum; super alloys, such as nickel-based chromium and cobalt chrominium; stainless steel; titanium; polymers; and ceramics.

3.1. Small production run applications of 3-D printing

This sub-section explores current 3-D applications based on the size of the production run. Small production run applications of 3-D printing include mass-customized products, prototypes, replacement parts, and medical/dental components. These applications are typically high-value objects that are either customized or produced in very small quantities.

With mass-customized products, retailers can position 3-D printers in a store and create customized products for patrons. Via one application, custom-made shoes can be designed specifically for an individual based on his/her foot size and walking gait. While these are currently more expensive than mass-produced shoes, experts feel the price differential will shrink over time.

3-D printing has been extensively used in the development of prototypes. While objects can be seen in three dimensions on a computer screen, many designers and new-product planners would rather examine, touch, and hold an item before committing to a large investment. Unlike clay, wood, or metal mockups that have in the past been created by hand, 3-D machines can produce objects with moving parts (such as a working model of a bicycle chain or even a small gearbox) and can utilize multiple materials (such as a plastic remote control with rubber-like buttons). A second major advantage in prototype development is the ability of 3-D printing to produce prototypes quickly and to make different versions, for consumer versus lab testing and for different market segments, without the need for costly retooling.

Shoe manufacturer Timberland used to spend roughly $1,200 and 1 week of time in designing a new sole for one of its shoe models. Using a 3-D printer, however, a model can be produced in 90 minutes for a cost of $35 (''Case History,'' 2009). Alessi, an Italian manufacturer of high-quality housewares, has also used 3-D printers to develop plastic prototypes of new products. According to Alessi's prototype manager, 3-D printing cut 5 - 6 weeks from its new-product development process. It also costs Alessi about 70% less than the traditional method of making prototypes (''3D Systems,'' 2011).

Architectural firms are using 3-D printing to create models of buildings and resort complexes. According to the founder of a firm that specializes in architectural applications of 3-D printing, it used to take 2 months and $100,000 to build models; now, the firm is building $2,000 models in one evening with 3-D printing (Vance, 2010a).

3-D printing is an ideal technology for making replacement parts for washing machines and food processors, as well as camera lens accessories and small gears (Bradshaw, Bowyer, & Haufe, 2010). Using injection molding technologies, replacement parts manufacturers had to turn out large quantities at a time. This has resulted in uncertain demand, low inventory turnover, and high storage costs. With 3-D printing, though, these parts can be made on an as-needed basis. In some cases, replacement parts have even been produced by third-party providers utilizing designs provided by the products' manufacturer.

Due to improvements in precision, detail, and surface finish, 3-D printing has been increasingly used for such medical applications as hearing aid molds, dental crowns, and prosthetic limbs. Since an individual's ear canal is unique in size and shape, a hearing aid needs to fit perfectly for optimal performance. Using CAD software, the contours of a patient's ear can be digitized within minutes. And within hours, a custom-made hearing aid shell can be produced from liquid photopolymer via 3-D printing (Alpern, 2010).

For their part, dental labs can use 3-D technology to handle digital files in-house without the need for physical impressions. As a result of this technology, labs are able to complete a dental restoration within 3 days of the intraoral scan (''Dentistry,'' 2011).

Medical companies have also used 3-D printing to make patient-specific knee replacements that mimic the patient's own anatomy; CT scan data permits a custom fit, unlike those provided by standard models. Bespoke Innovations sells dishwasher-safe customized limbs that cost a tenth of comparable artificial limbs made using traditional methods (Vance, 2010b). Porous scaffolds that resemble natural bone structure have recently been developed for use in 3-D printing. These materials make the implant function almost as an integral part of the body (Sedacca, 2011).

3-D printing has applications in the testing of medical procedures, physician training, and evaluation of medical devices. Orthopedic surgeons at Walter Reed Medical Center have developed models of the human knee using 3-D printing technologies. These models have been used for surgical procedures when a wound is near a nerve/arterial junction, with little tolerance for error (King, 2008).

3.2. Medium production run applications of 3-D printing

3-D printing is also used in bridge manufacturing, 'bridging' the time span from when a part design is complete and when the part is ready for mass production. Bridge manufacturing using 3-D printing is commonly employed when tooling operations are complex, costly, and time consuming. It is also necessary if a firm needs to secure several thousand parts prior to molds being generated. Caterpillar has used bridge manufacturing to make a new oil-filter assembly (Sherman, 2009). The firm has also used

3-D printing to produce hundreds of wiring harness assemblies in between design completion and mass production readiness.

4. The future of 3-D printing

The promise of 3-D printing is based on custom products that are made to order, such as dental and medical devices, and low-turnover replacements parts. These goods are typically ordered in unique configurations and in very small quantities. A significant advantage of 3-D printing is a firm's ability to quickly and cost-effectively supply low-demand parts without the risk of carrying an unsold finished goods inventory. Since items are made only when ordered and paid for, designers are able to undertake risks they would not otherwise pursue. With 3-D printing, the risk of a poor design is based on wasted design time rather than inventory investment.

A major advantage of 3-D printing is the separation of product design from manufacturing capabilities. Since design and manufacturing can be easily outsourced in 3-D printing, designers can contract with firms such as Shapeways to produce, ship, and collect proceeds for goods based on their designs. Alternatively, a consumer can download a CAD software design for a replacement part online—as easily as he/she would download digital music—and then download and print the part on his/her 3-D printer.

A number of issues relating to cost, accuracy, and strength of 3-D products need to be overcome before this technology can achieve widespread adoption. For instance, in terms of cost, materials suitable for 3-D printing can run 10 to 100 times more than typical injection molding thermoplastics (Sherman, 2009). Material choices, colors, and surface finishes suitable for 3-D printing are also more limited than with typical mass-production processes. According to a vice-president at Stratasys, a manufacturer of 3-D printers: "The industry doesn't have a catalogue of 20,000 materials available today. Right now, I'd say it sits around 50" (Alpern, 2010, p. 47). High material costs currently limit the use of 3-D printing to applications that are high value, and/or when speed or privacy is critical.

Today, 3-D printing works with plastics, resins, and metals, with a precision of around one-tenth of a millimeter ("Print Me," 2011). According to one source, the robot arm of a 3-D printer needs to be 10 times more precise before it can compete with industrial engineering processes (Rudd, 2011). There are also some strength issues relating to weak bonding between layers that can lead to delamination and breakage under stress; additionally, the materials' strength, viscosity, dimensional stability, resistance to heat and moisture, and color stability need careful evaluation (Sherman, 2009; Stemp-Morlock, 2010). Strength-related issues are especially critical when parts made with 3-D printing are load bearing.

As the prices of raw materials drop and material quality gets better, the use of 3-D technology will expand beyond its present scope. Applications that can increase include bridge manufacturing, to fill orders prior to product commercialization and to fill emergency orders; custom manufacturing for jewelry and hobby applications; parts for machinery and aircraft, where strength is a major issue; emergency shipments of parts; and situations where inventory carrying costs are high relative to production costs.

A secondary promise of 3-D printing lies in separation of product design from product manufacturing. As 3-D printing evolves, consumers will be able to purchase designs online and then build products at home. Appliance companies can also contract out the manufacturing of spare parts to third parties, which will then build parts based on CAD software provided by the appliance manufacturer. Since no inventories will have to be kept, parts costs could decrease. Spare parts availability can also expand, as it is less costly to retain old designs than excess inventories of spare parts.

Within the next 5 years or so, one can reasonably forecast a number of significant 3-D printing supply chain developments on not only the design side, but also the production side. A large number of firms will soon offer CAD-CAM designs for downloading by final consumers, as well as retailers. These designs will enable final consumers to produce customized products at home and allow firms to produce replacement parts on an as-ordered basis. The widespread adoption and use of the Internet will increase individuals' ability to examine the CAD-CAM library of available designs, and allow for these to be easily downloaded.

The heightened number of CAD-CAM applications, the availability of higher-quality materials, and lower material costs will also result in a larger number of home and professional-quality 3-D printers. One can anticipate that many noncompeting professionals and firms may also choose to jointly purchase 3-D printers to reduce their investment costs, as well as the risk of technological obsolescence.

In the long term, the range of industrial 3-D printing applications will skyrocket as new 3-D printers are able to accommodate larger products and achieve greater levels of precision. There should also be significant declines in material and machinery costs as more individuals and firms adopt this technology. Additionally, the usage of 3-D printing will expand due to the availability of materials with greater strength and resistance to heat and moisture.

When the price of 3-D printers is reduced, perhaps to $300 or so, the number of machines used for home applications will drastically expand from current levels. At this price level, the market penetration of home-based 3-D printers will begin to resemble that of small laser printers. As with the industrial market, increased market penetration will result in additional 3-D home applications. Material costs will also decrease as a result of higher market penetration. The future holds great promise for 3-D printing as a technology and for end users as a result.

References

3-D 'printing' goes mass market. (2011, January 18). *MyPaper*, p. A13.

3D systems success story. (2011). Retrieved June 9, 2011, from www.3dsystems.com/french/datafiles/3dm/AlessiCoffee_3DM_CaseStudy.pdf

Alpern, P. (2010). Beam me up, Scotty. *Industry Week, 259*(2), 46—47.

Berman, B. (2002). Should your firm adopt a mass customization strategy? *Business Horizons, 45*(4), 51—60.

Bradshaw, S., Bowyer, A., & Haufe, P. (2010). The intellectual property implications of low-cost 3-D printing. *Scripted, 7*(1), 5—31.

Case history: A factory on your desk. (2009, September 5). *The Economist*. Retrieved from http://www.economist.com/node/14299512

Casey, L. (2009). Prototype pronto. *Packaging Digest, 46*(8), 54—56.

Dentistry: Objet to showcase 3-D printing solutions for digital dentistry at LMT lab day, Chicago. (2011, March 7). *Health and Medicine Week*, 1054.

King, R. (2008, October 6). Printing in 3-D gets practical. *BusinessWeek Online*. Retrieved from http://www.businessweek.com/technology/content/oct2008/tc2008103_077223.htm

Klaft, L. (2010, October 17). Open-source 3-D printers head to a desktop near you; instantly make a part to replace what's broken. *Worcester Telegram and Gazette*, B5.

Olivarez, N. (2010, June 14). 3-D printers go beyond paper and ink: Mostly celebrated by hobbyists and geeks, 3-D printers may be commonplace one day. *Buffalo News*, p. C4.

Petrovic, V., Gonzalez, J. V. H., Ferrando, O. J., Gordillo, J. D., Puchades, J. R. B., & Griñan, L. P. (2011). Additive layered manufacturing: Sectors of industrial application shown through case studies. *International Journal of Production Research, 49*(4), 1071—1079.

Print me a Stradivarius: How a new manufacturing technology will change the world. (2011, February 17). *The Economist*, p. 7.

Pullin, J. (2009, April 29). Getting physical. *Professional Engineering*, 41—42.

Rudd, M. (2011, January 16). Next, we'll print out a curly iPhone. *The Sunday Times Review*, p. 7.

Sedacca, B. (2011). Hand built by lasers. *Engineering and Technology, 6*(1), 58—60.

Sherman, L. M. (2009). Additive manufacturing: New capabilities for rapid prototypes and production parts. *Plastics Technology, 55*(3), 35—45.

Simplifying power tool prototyping. (2010, March 7). *Rapid Prototyping and Manufacturing*. Retrieved March 21, 2011, from www.dimensionprinting.com

Stemp-Morlock, G. (2010). Personal fabrication. *Communications of the ACM, 53*(10), 14—15.

Thilmany, J. (2009). A new kind of design. *Mechanical Engineering, 131*(1), 36—40.

Vance, A. (2010a, September 15). With 3-D printing, manufacturing is a click away. *International Herald Tribune*, p. 19.

Vance, A. (2010b, September 14). 3-D printing spurs a manufacturing revolution. *The New York Times*, p. A1.

Wagner, S. (2010, June 14). UK engineers speed 3D printing technology. *The Engineer,* 10.