3D Printing: A Game-changer in Manufacturing Cost Control

This paper reviews aspects and background of three dimensional (3D) printing and its impact on manufacturing, which is bringing big changes to engineering in the U.S. and internationally. The technology synchronizes with trends favoring,

- Variability or flexibility: 3D changes inventors' game, more speed and versatility
- Easier, faster customer satisfaction, making custom objects to produce and sell, using detailed responses, making enterprise more profitable *when*
- Location-neutral manufacturing is possible: Cost reductions in 3D approach easily combines effectively with 1) low labor-cost distributed production styles, for a potent industry expansion strategy; and 2) Internet sales and marketing strategy.

The new 3D printers, often using open-source standard operating systems with computer aided design (CAD) software, cost from $2100 to over $1 million, and have supported advances in additive, rather than traditional subtractive, manufacturing methods. 3D technology supports high-fidelity prototypes for less expensive pre-production stages, allowing test of tools and properties, through low-quantity lots, before scaling up to production operations.

> "Production is a sequence of functions that stretches from an innovation or idea for a product to manufacturing it and delivering it to a customer, sometimes also providing after-sales service…. Most valuable goods in the world today, whether cell phone service or $500 designer jeans – combine physical production and services… we can identify a common set of tasks that must take place between product definition and sale to a customer." (Berger, "Breaking up the Corporation", *How We Compete*, p. 63). [i]^

In addition to speed in the methods, the 3D printing contributes to savings in manufacturing by minimizing expense of traditional tool-and-die-mold creation, part of subtractive production methods. The technology relates historically to ways that cheap replicated toys were done with stereo lithography; but now 3D printing process turns out quality engineering objects or tools made of industrial strength material. In high-fidelity prototype testing, more customization can be brought into manufacturing sooner and on a repeated basis. Smaller scale design-to-sell processes become realistic and profitable. A "Consumer-to-Business," reverse-build, customer influence occurs, tailoring designs early, for individual specifications, also using distributed fabrication techniques. [ii]^

Cheaper lower-end versions of 3D printers have re-popularized "home engineering" and provide approaches for a wide range of niche products, easily marketable. From concept to Internet market becomes a short step. The CAD and data-driven additive manufacturing techniques produce 3D physical models and objects or parts in deposited layers. The U.S. tooling industry expects increased proliferation of 3D "finalized" production objects as the quality process improves. [iii]^ With a high fidelity prototype, whether hardware, software, testing and pre-production phase is easier:

What does a Prototype Do?

- Communicates critical engineering concepts
- Establishes the solution design, engineers' approach to building an object,
- Directly models a digital system design or end-object parts, and
- Reduces cost by finding design faults, and fast prototype improvements, prior to scale-up in manufacturing.

Lithography and Prototypes

The additive manufacturing process was first developed and known as stereo lithography (SLA), a technology still used by most Chinese and Japanese manufacturers today. In Asian industry, long roots already existed [iv]^ for duplicating decorative articles for example, inexpensively, to re-sell a popular image or decoration for quick profit. In SLA method, resin comes in contact with heat-application and forms layer on layer to build up the article. Then a finishing stage cleans the article for sale.

The focus changed when a 2008 Solid Freeform Fabrication Symposium, funded by National Science Foundation and sponsored by the Office of Naval Research (ONR), engaged Ming Leu of Missouri University of Science and Technology with David Rosen of the Georgia Institute of Technology to do a workshop to feature SLS additive manufacturing techniques with 3D printing for high potential R&D prototyping. [v]^ To understand the explosive impact that 3D printing has had on manufacturing, it helps to recall how wasteful the older manufacturing methods, with subtractive, could be. Molds, dies, and other machined parts that are produced have to be later filed-off or cleaned of burr's, resulting in loss of expensive material. In the case of rare metals, like titanium for aircraft parts, any waste is very undesirable.

CAD-based, 3D printing supports the lifecycle of engineering process to form metal, industrial thermo-plastics, advanced ceramics, and other complex tooling, such as jigs and fixtures for completing design-build of a larger scale product. Engineering Design Models (EDMs) can be made with exotic materials, and high tech materials such as advertised by "On Demand EDMs" of Minnesota,[vi] ^ preparing medical hardware parts in wide range of prototypes. Two doctoral students in Texas, following the Navy initiative, gained investment support afterward, to start a laser sintering company for additive manufacturing of "niche materials."

Additive Manufacturing

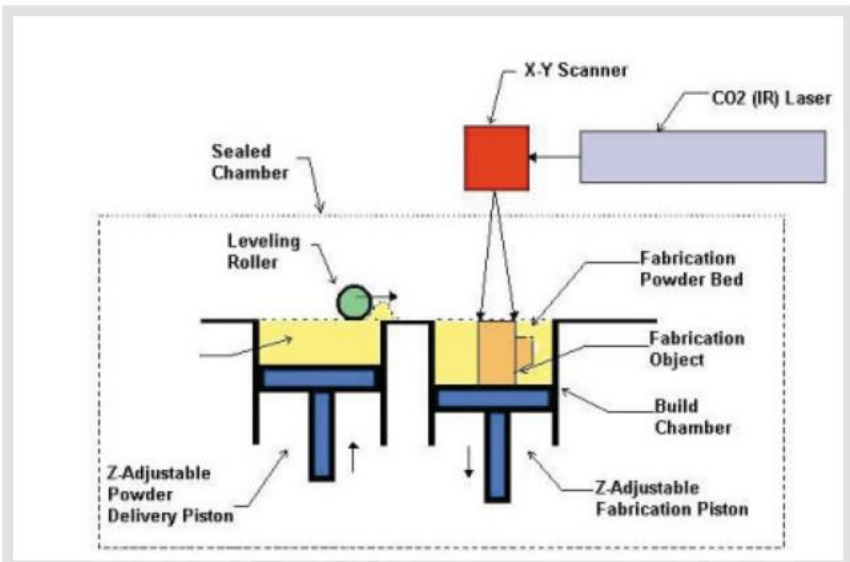
Commercial 3D printing works with many kinds of materials: industrial resins or plastics, metals, and ceramics. Some kinds of 3D manufacture have been around for a relatively long time, such as for custom dental fittings or resin-based images of popular culture objects (like holiday ornaments) or decorations. 3D printers can support the following kinds of additive manufacturing:

- Selective Laser Sintering (SLS) uses a directed energy beam to sinter (or melt) powdered material in layers, see Stratasys, leading commercial firm in the U.S., references (*endnotes* 3, 4, 5).
- Selective Laser Melting (SLM) works with a metal powder, and completes dense parts done in one single step. The leading commercial firms are found in Germany
- Electron Beam Melting (EBM) makes homogenous metal parts, by the melting of oxygen reactive metal powders in a vacuum, performed for aerospace metal parts using material like titanium. The leading commercial firm is found in Sweden.

Design companies today face huge pressure to quickly optimize test and development costs, and get the objects or parts out to sales. Traditional and mechanical engineering disciplines use production methods like metallurgy in automotive manufacture, or custom circuit chip design (with silicon) builds for embedded computer systems. Inventors benefit from *faster manufacturing* to try out customized versions and create high-fidelity prototypes to test for errors, satisfy customer responses, and produce better margins with outsourced distributed process. Improvements might reduce major tooling expenses and human resources commitment (engineers and craftsmen are very expensive!) supporting a large scale production build, and accurate contracts or budget.

Polymer based stereo lithography (SLA) uses material like resin, is used: In this case, raw material that will be liquid during intermediate phase and requires a support structure during the process. (See Charles Hull of 3D Systems. [vii]^)

With improvement of thermoplastics, metal alloys, and ceramics in the last 5-10 years, selective laser sintering process, 3D printing, and additive manufacturing techniques can be used more widely. The following "Figure 1" from the University of California at San Diego illustrates and example of tracing cross-sections of an object with the 3D machine and fusing or "sintering" them into one layer by laser pulses. The platform then drops, a small fraction of a millimeter, and a new layer of the powdered material would be traced and fused. The resulting object produced by SLS generally requires little finishing, unlike stereo lithography or DPM. It wastes very little of the foundation material.



Selective Laser Sintering Process
(Picture Credit: University of California at San Diego)

Figure 1, UC San Diego Image, SLS Manufacturing [viii]^

Fab Labs and Maker-Space

Cost reduction from 3D encourages a "do-it-yourself" mindset, blossoming cottage industries, offering a high-speed path from concept to product to sales via the Internet that combines well with using distributed production strategies taking advantage of international labor cost differentials. In the 19th century, revolutionary manufacturing integrated functions vertically and horizontally, to gain economies of scale and create bigger profit margins using assembly line process. In *Makers*, (References, #1), Chris Anderson quotes William Rosen concerning the Industrial Revolution in the U.K. and claims it was mainly a "radical transformation in the process of invention itself." [ix]^ Assembly line production economics in Great Britain enabled the resulting industrial scale and profits:

> "The arrival of machines to turn agricultural commodities into goods that could be sold around the world promised the opportunity to shift from a nation that commanded power by force to one that used trade instead." (Chris Anderson, on the Industrial Revolution in the 19th century, *Makers*, p. 35) [x]^

In today's 3D printing revolution, the boost to *customization,* rather than uniform functional process, encourages a "do it yourself" mindset in addition to reduced cost impact due to wide methods' applicability: the "Fab" model of outsourced production. This 3D-supported manufacturing "edge" relates to fast, flexible design, together with cheaper, distributed and custom production, using savings from low labor costs contracted "as needed."

Neil Gershenfeld at MIT started the idea of Fab Labs at a popular class about 10 years ago called "How to Make (Almost) Anything." Anderson notes (*Makers*, p. 46) that there are now at least 53 of these kinds of fabrication labs in 17 countries around the world currently, using traditional manufacturing tooling like lathes and drills as well as (now) 3D printers (2013).

Equipment for Changing the Competitive Edge

In the U.S., Scott Crump invented the method known as "fused deposition modeling" (FDM) a follow-on innovation to stereo lithography – a manufacturing process directly supported by the contributions of 3D printing. [xi] Crump started this high-speed modeling process for rapid manufacturing with desktop 3D printers to use in "idea development" and founded the StrataSys Company. He has established more than 10 proprietary FDM-based methods for making 3D prototypes out of thermoplastic materials. 3D printing systems work well for modeling, prototyping and short-run production of parts and can fit easily on a desktop. One example in the StrataSys tutorial described custom-design-build motorcycle, using the 3D printing process, for prototyping and claimed reduction of time-to-market of 71%, with find-fix of 83 design errors, using 2 prototypes within an 8-month period. [xii]^

Prototyping process with 3D printing, additive manufacturing, and low-run productions can complete the idea-design-test process far faster and cheaper than traditionally. ^ [xiii] In commercial work, by a proportion of about 80% to 20%, the result will be a prototype rather than production-releasable parts; the objects then serve performance testing as prototypes in the design.^[xiv] Proprietary software often forms a major part of the company's engineering design palette, providing smoother finish on the parts or prototypes, or to improving results and reliability in other ways, such as reduction in bubbles in the deposited layers for better adhesive properties.

Meanwhile, reorganization and distributed location of manufacturing assets transformed many operations in U.S. industry between the late 1990s and 2008, when economic challenges in the U.S. added desirability to a more flexible manufacturing strategy. Corporate structures of the 1980s had to be tightened, integrated, and managed in an updated "network effective" way, both internally and for customers with more slender budgets.

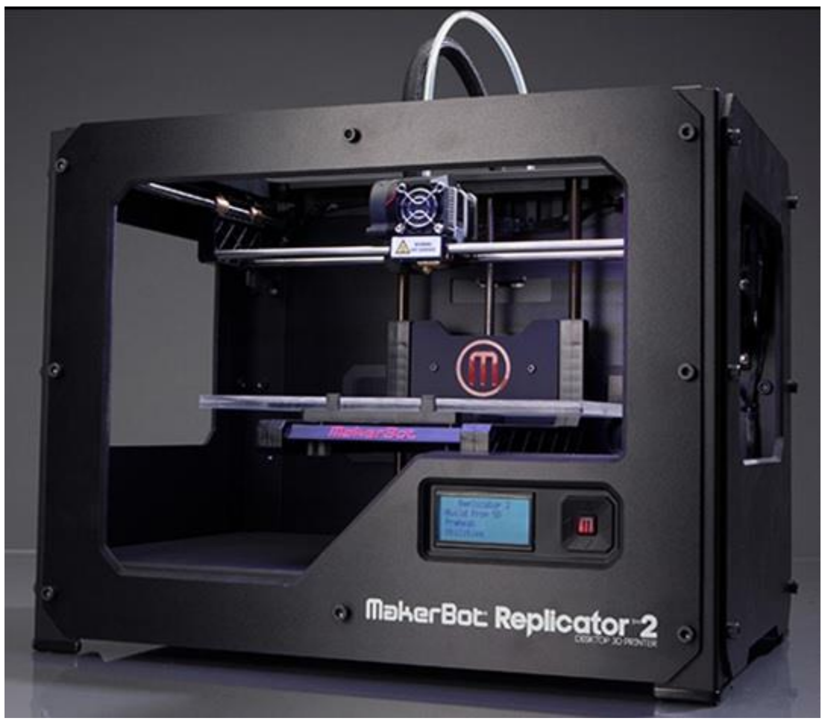
The class of 3D-printing machines depends on the degree-of-finish expected with the product, the volume of work, and goal for which the equipment is used. For example, a 3D printer might work in a:

1. Service Bureau (for R&D Engineering): This kind of company uses a 3D printer about the size of a department laser printer, which has high performance and availability, costs about $50k to over $1 million, and can be optimized for varied performance details. It uses a wide choice of resulting materials in the product. These produce "test objects" go to the design customer to check the concept's form, fit, and function.
2. Many kinds of engineering firms use a relatively lower-end printer that has a process based on supplying an STL file (to the print department). The engineer gets a "part" from this technology, in a 3-10 day turnaround. This category of 3D printer would cost about $10k to $50k.
3. A smaller "any man" kind of 3D printer now on the market gives individuals their own production edge, characterized best by the successful MakerBot (see marketing photo next page), available for hobbies, small business, and consumer uses.

Outsourced and distributed manufacturing brings just-in-time supply chain management to traditional activities needing timely supply, like plumbing and building construction, or sellers of home theatre equipment today, like "…big boxers … Wal-Mart, France's Carrefour, Britain's Tesco." These mega-firms look for labor and manufacturing savings in the new industrial corridors like "Chinese Printing City" – Wenzhou. [xv]^ Similar development patterns can be found around competitive factory zones in Mexico, Vietnam, or Brazil.

Chinese industry even recruits European- and American-trained Chinese to return to south China, where they can take advantage of inexpensive labor to build a small empire, use techniques like 3D printing for fast fabrication, and shared profits from blossoming tech or automotive enhancement markets. [xvi]^ Manufacturing Economist Joseph Schumpeter noted the quickness of Chinese industry, based on 20th century hardships, to scrap the old and use the new technology, in a famous comment: “Chinese have learned that capitalism is an exercise in creative destruction.” And, “Chinese leadership itself (has been) unprepared for the dynamism of its own people” [xvii]^

ANY-MAN’S 3D PRINTER



[MakerBot Replicator 2, for desktop, starting at $2,199, http://store.makerbot.com/replicator2.html?gclid=CKaK_8y1xroCFQyZ4Aod_gEAOQ]

World R&D: Technology not Proximity

Under several patents emerging from Scott Crump’s work, [xviii]^ selective laser sintering (SLS), has been deployed in manufacturing approaches, supported by 3D printing technologies and related CAD software. Crump’s FDM process, rapidly moved prototyping into a new era.^[xix] StrataSys recently merged with the Israeli manufacturing company, Objet, December 2012, to form a multi-billion-dollar international company for prototyping and parts with inkjet and wax casting.^[xx] The company’s international marketing claims to be ready to deliver world-class R&D support alike for consumables and advanced systems like aircraft parts (endnote 3). For aerospace (planes, satellites), "Late to market by 6 months” can translate to lost profit as high as 66% (end note 1).

Added costs can come from poor material quality, errors not discovered due to inaccurate (low fidelity) prototyping, or other ineffective process like repeated corrections.

An engineering firm with a new design concept, needs to consider bridging methods to later manufacturing to avoid expensive or too-slow tooling, as for drills, gauge, alignment fixtures, masters and patterns, even software engineering. 3D printing process particularly helps this step: to test a concept with sufficiently high fidelity prototype earlier, reduces long lead times in the budget and checks if process and physical function are working as expected. Engineering Design Models (EDM) are significant parts of the life-cycle for larger scale programs. Many firms contract their support needs for early phase out to a design or model organization, possibly abroad to reduce labor cost. These are the companies beginning to use 3D printing in greater numbers for prototypes or designed parts. In other words, “*We minimize transaction costs* (in development) *with technology, not proximity.”* [xxi]^

The 3D printing technique can work on many kinds of materials, but they must be available in powder form. While Deckard of University of Texas patented the process of selective laser sintering, his team was far from the 1st to use it (endnote 5, “Roadmap to Additive Manufacturing”). The MakerBot – a startup operation purchased in recent months by StrataSys (see picture of marketing image, page 6) is a 4th generation version and has achieved fine layer resolution of 0.1 millimeters. Products from SLS typically do not need sanding and save time, labor, wasted foundation material, and other finishing costs. The MakerBot’s company, prior to take-over, won significant awards - for example, "Top 20 startups" in New York, and IEEE citation per *The Wall Street Journal*, CNN, and more. [xxii]^

Quality of Materials and UC San Diego’s Rocket

As better materials have been able to be processed by 3D-supported method, aerospace and high science took greater notice. At University of California, San Diego, students have used 3D printing to create rocket motors. [xxiii] The University group tested the rocket in the Mohave Desert in October of 2013, a first-of-a-kind flight for “3D-printed liquid fueled metal rocket engine” sponsored by NASA’s Marshal Center and the Illinois printer-manufacturer, (*see* Atyam, endnote [xiii]).

Materials available to this process have evolved quickly. For example, quartz chip carriers in computers, in 3D-printing based experiments, began using silicon carbide, an advanced ceramic, to substitute for more expensive materials in the computer clocking mechanisms (essential to many high-tech applications equipment). The ceramic endures high temperatures and is found in applications such as car brakes or nuclear fuel coatings. [xxiv]^

"YouTube" Examples: BB-Gun Loader and Prosthetics

To see the diversity of 3D-enabled printing patterns and results, the World Wide Web offers many resources. A recently posted "YouTube" gave a tutorial on how to load a high-capacity magazine for a BB gun using a MakerBot 3D printer devised "thimble." Airsoft's patented "thimble prototype" offers a safe way to load higher quantities of BBs into a pistol. It claims to reduce jamming within magazines, finger injuries, and to provide a safer way to load the weapon. [xxv]^

Chris Anderson's article in *Wired.Co.UK* [xxvi]^ responds to gun regulators' concerns on 3D printing technology, saying that it's less dangerous than Wal-Mart, since gun sales at sources like Wal-Mart provide plenty of cheap weapons already (in the U.S.) For guns, 3D printing may be unsafe, since common materials lack tensile strength. Anderson thinks the technology is more likely to encourage creativity and individuality in custom manufacturing rather than large jumps in arms manufacture. However, advanced materials research has moved forward, illustrated by U.C. students' experiment on rocket flight (discussed above, quality of materials).

Among the most encouraging stories, showing the impact from both 3D printing design process *and* the increased stimulus to individual creativity have been highlighted by the story of a South African carpenter, Richard Van As, who lost 2 fingers and damaged both hands in a table saw accident. He formed a determination to find a way to get back to work using 3D printing technology.^[xxvii] Good prosthetics cost many thousands of dollars, which Van As could not afford, so he sought industry help, using information from a "YouTube" video (Ivan Owen, from Bellingham, WA, in the U.S.) ^[xxviii] He learned about using steel cabling to "act like tendons." Owen had worked on special effects and built a "hand" for a science fiction project. After much Skyping® and collaboration, the carpenter and cabling designer built a mechanical finger for Van As, to help him get back to work.

In the course of these Internet consultations, the 2 inventors came to the attention of a family that wanted help for a child born without fingers due to a rare birth condition. The men agreed to look into helping the child, and they contracted with MakerBot in NY, a producer of low-end 3D printers, to develop and prototype the "Robohand." [xxix]^ Further, they posted and shared the entire design-build process on "Thingiverse," an open source website for sharing digital designs. [xxx]^

According to Dr. Matthew Garibaldi of the Department of Orthopaedic Surgery, University of California, manufacturing options for pediatric prosthetics had been pretty limited and expensive, due to variability of child body-fit ^ [xxxi] and growth rates, making suitable options limited and expensive. The pattern, with 3D printing based technology, donated by Van As and Owen, [xxxii]^ made an immediate impact to increasing possibilities for a large group of patients previously under-served, decreasing manufacturing and production costs, and adding rapid-turn customization. It’s an outstanding example of the potential in 3D-printing technologies.

In conclusion, the technical and manufacturing applications enabled by 3D printing offer considerably more positive impacts than negative. However, challenges for public policy are seen in safety of materials, and in moderating the chaotic influence on competitive international manufacturing strategies, with attendant human resources and pollution considerations.

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