ADDITIVE MANUFACTURING AS A DISRUPTIVE TECHNOLOGY: HOW TO AVOID THE PITFALL

Winston Sealy
C112 Trafton Science Center
Minnesota State University
Mankato, MN 56001
United States of America
Winston.sealy@mnsu.edu

Abstract. This paper proposes a framework for management as a viable approach in preparation for Additive Manufacturing (AM) as a disruptive technology. This framework by no means guarantees total preparedness, as many other factors influence a company's dynamics. However, what it does is, create awareness of a possible threat and provide a framework that managers can utilize to help minimize the impact and better position their organizations for future success. The nature of AM is discussed and compared to conventional manufacturing processes. Constraint Management (CM), a derivative of the Theory of Constraints (TOC), is also discussed and proposed as a guide for management in the event AM becomes a disruptive technology to conventional manufacturing processes.

Keywords: Additive Manufacturing, Rapid Prototyping, 3D Printer, Computer Aided Design, Constraint Management, Theory of Constraints, Disruptive Technology, Strategic Management

Introduction

Some of the best organizations that have been successful for many years in their markets, and have been known as market leaders can and will fall if oblivious to disruptive technologies. In his book, *The Innovator's Dilemma*, professor Christensen states, "…they often fail because the very management practices that have allowed them to become industry leaders also make it extremely difficult for them to develop the disruptive technologies that ultimately steal away their markets." He further adds, "…the attributes that make disruptive technologies unattractive to mainstream markets are the attributes on which the new markets will be built" [1]. Additive Manufacturing is a rapidly growing technology that threatens conventional manufacturing processes. Additive Manufacturing utilizes processes, methods, techniques, tools and equipment to build parts directly from a Computer Aided Design (CAD) image. Technology denotes the set of physical processes, methods, techniques, tools, and equipment by which products are made or services rendered [2].

According to Todd Grimm, in his book, *User's Guide to Rapid Prototyping* [3]:

As with many new technologies, research and development is at a significant level. New methods, new applications, and new materials are in labs around the world. Many more will follow. What this means to the users of rapid prototyping is that the future is likely to reveal not only many small, incremental changes, but also a handful of disruptive technologies that change the game entirely. Be it five, ten, or twenty years into the future, rapid prototyping will have broader application, wider acceptance, and greater impact on industry.

Background of Additive Manufacturing

Thanks to Professor Herbert Voelcker, who, back in the late 1960s was searching for novel ways of doing the same old things and developed solid modeling. Voelcker wanted to find a way to take the output from a computer design program and use it to program the automatic machine tools [4]. This in turn, led to the development of the mathematical algorithms for solid modeling. This was the basis that current parametric modeling software like Pro Engineer, Inventor and Solid Works, are built on. However, as Murray concluded in his book, *Borrowing Brilliance*, “originality is an illusion…your ideas are the children of other ideas…there are no truly original thoughts. Originality lies in the construction of other concepts, for brilliance is borrowed” [5]. It wasn’t until 1987, when University of Texas researcher Carl Deckard used Voelcker’s solid modeling techniques to create a new process of manufacturing. Instead of using the old way of removing material from a larger piece to create a part, he developed a method of building the part layer by layer. Consequently, Charles Hull, another major contributor in the development of AM filed the first patent. While earlier work in Japan is quite well-documented, proving that this concept could be realized, it was the patent by Charles Hull that is generally recognized as the most influential since it gave rise to 3D Systems [6]. The following table illustrates historical developments of AM.

Table 1. Historical Development of Additive Manufacturing (adopted from Chua et al)

Year of Inception	Technology
1770	Mechanization
1946	First Computer
1952	First Numerical Control (NC) Machine Tool
1960	First commercial Laser
1961	First commercial Robot
1963	First Interactive Graphics System (early version of CAD)
1988	First commercial Rapid Prototyping System

As with most technologies, the supportive infrastructure must be in place to fully explore and apply the technology. Table 1 documents the many support technologies that had to be fully developed and available in order to achieve the first commercial rapid prototyping system. First and foremost, computers had to be affordable and capable of supporting resource-intensive graphical applications. Additionally, computers had to be capable of driving various manufacturing tools.

The process of creating parts by adding material versus removing material has evolved and transformed as new players enhanced and developed new processes. Originally called *Free Form Fabrication*, the process transformed *to Rapid Prototyping* and now *Additive Manufacturing*. Although the tittles have changed, the overall process of building parts one layer at a time still remains the same.

Additive Manufacturing Process

Despite the fact that AM is synonymous to the type of equipment used, the process is much more involved than just the equipment. The AM process involves a Computer Aided Design (CAD) system, a printer and some form of finisher. Three Dimensional (3D) drawings are created using parametric modeling to create feature based geometries. Common 3D CAD applications such as Pro-Engineer, Solid Work and Inventor are used to create the conceptual 3D design. In preparation for the printer, CAD drawings are translated into Stereolithography (STL) files. STL files are a mesh of polygons representing the 3D CAD image. Commonly referred to as tessellation, these files are often verified for accuracy before being converted into slice build data. Slicing of the STL file generates each individual layer that consists of a cross section of the part. 3D Printers interprets the STL files into parts. Parts are cleaned by removing excess material and support structures. Again, since the technology varies depending on the equipment, each part requires different methods of cleaning. Some are chiseled, while others are washed. Some parts may also require a final finishing step. Finishing may involve sanding, filing, baking or painting. 3D printers are categorized into one of three technological functions.

- Liquid-based
- Solid-based
- Powder-based

Most liquid-based rapid prototyping systems build parts in a vat of photo-curable liquid resin - an organic resin that cures or solidifies under the effect of exposure to laser radiation, usually in the UV range [7]. Exposure to the laser hardens the photo-curable liquid. The formed layer is lowered and the next cross section gets exposed. This process continues until the part is completed. The vat is drained and the part is prepared for further processing. Charles Hull’s Stereolithography Apparatus (SLA), for example, is a liquid-based system. The main advantages of SLA include, continuous operation with little or no monitoring, good accuracy and material flexibility. The SLA can use a variety of material for various applications. Contrary, some disadvantages include, requiring support structures for design overhangs, requiring post processing for cleaning and post curing to fully secure the finished part.

Solid-based rapid prototyping machines all use solids as the primary medium to create the part. Fused Deposition Modeling (FDM), for example, utilizes a filament that is heated and extruded to create the part. After the layer hardens, a new layer is deposited. This process is repeated until the part is done. Some of the advantages of FDM include minimal wastage, ease of support removal and ease of material change. FDM filament style spool allows for easy and quick exchange of material. The main disadvantages of FDM include limited accuracy due to filament size, slow processes and unpredictable shrinkage. The heating and rapid cooling of the extrude head induces stresses, which in turn creates unpredictable shrinkages.

Powder-based rapid prototyping are 3D printers built on inject printing technology. Z Corp. a spin-off from Massachusetts Institute of Technology (MIT) developed and marketed 3D printing. 3D printing starts with a layer of powder spread over a piston driven table. The printer applies binder solution to bond and create the layer. The table is lowered and the process repeated until the part is completed. Excess powder is vacuumed away from the part. Major advantages of 3D printing include high speed, simple to operate and no waste of material. However, 3D printers are known for their limitations to fully functional parts, limited material selection and poor surface finishes as compared to solid and liquid based technologies.

Strengths and Weaknesses of Additive Manufacturing

Most manufacturers are cautious to using AM as a viable manufacturing process due to the repeatability and consistency of the manufactured parts. Manufacturers are skeptical of the structural integrity of the finished products as compared to conventional manufacturing processes. For example, repeatability for conventional manufacturing processes requires and utilized closed loop systems for dynamic feedback during part creation. Contrary to conventional processes, AM does not utilize a closed loop system for immediate feedback. Therefore AM is viewed as a process that is difficult to control. Even with serious considerations to manufacturers' concerns to AM, the benefits certainly outweigh the concerns.

Although barriers to production exist for AM, certain unique capabilities make AM processes superior to conventional manufacturing processes [8]:

- Shape complexity
    - Can build virtually any shape
        - Complex cellular structures
        - Optimized material distribution
        - Integration and consolidation of parts
- Material and property tailoring
    - Material can be processed by points or layers
- Functional complexity
    - Component integration
        - Embed hardware, sensors, actuators, conductive materials
        - Manufacture functional devices

Another critical advantage that AM has over conventional manufacturing processes is from a design perspective. The designer must be aware of the capabilities of the manufacturing process to make the more complicated part [9]. Most designers today designing for conventional manufacturing processes must not only be aware of the manufacturing processes, but must also take into account the skillset of the production workers. Designs that cannot be manufactured are merely conceptual and will never be realized as a working tangible product. Designers must be aware of the capabilities of manufacturing. They must take into account machine limitations and worker skillset in designing products. On the one hand, knowledge of the process is beneficial to the organization if manufacturing is done in house. However, if any component of manufacturing is outsourced, the required knowledge for manufacturing becomes difficult to acquire by the designer. Most organizations are protective of their processes mainly due to the competitive nature of the business. This in turn creates a disconnect with the designer which discourages the more intricate, complex designs. Also, AM processes are immune to conventional manufacturing limitations. Since AM builds parts layer by layer, more intricate, complex parts can be realized.

Disruptive Technology

In the event Additive Manufacturing becomes a disruptive technology to conventional manufacturing processes, most organizations will find it difficult to compete and adapt to AM. Therefore, organizations must address a fundamental concern of management constraints by answering the following question*; What in my business has to change in order for it to be successful?* According to Woeppel, in his book, *Manufacturer's Guide to Implementing the Theory of Constraints*, "Constraint Management begins with one underlying assumption: the performance of the system's constraint will determine the performance of the entire system [10]. Analogous to a chain being as strong as its weakest link, constraints in the organization must be identified and eliminated.

Dr. Eli Goldratt, an educator, who grandfathered the concept of Theory of Constraints, defines constraints as, "Anything that limits or prevents higher system performance relative to the goal." Currently, AM can be considered a constraint to conventional manufacturing due to its cost and low volume production. Therefore, before the technology is further developed and become disruptive to conventional manufacturing, applying Constraint Management as a framework to analyzing and documenting AM will better position organizations for future success. Woeppel states, "The big idea behind constraint management is not that there is a silver bullet to fix all your problems, but there is a framework, which allows you to effectively analyze and make decisions, that is fundamentally different and better than the prevalent cost-based paradigm." He further adds," A successful implementation is one where the management team is, on a regular basis, considering constraint implications in the daily decisions of allocating resources and making customer commitments [10].

Developing a design plan provides the necessary guidance to analyzing AM. It is a critical document in getting organizational buy-in. The design plan consists of identifying the new processes required to exploit the constraint, developing a process map and creating strategies to fully adopt the new process. The following must be considered in developing the design plan [10]:

- Choosing the constraint

- Financial performance
- Market responsiveness
- Growth strategies
- Workforce strategies
- Pricing
- Sales strategies
- Promotions
- Distribution

Create an AM process that is aligned to the organization's strategy. This process will be separate from and not interfere with the conventional manufacturing processes. To be successful, the new process must receive approvals from top management. Management must also allocate separate funds and resources for the new process.

The effects on return on investments are also considered. Management must be aware of where capital investments are pooled, where the largest single investment of capital occurs and the ability to outsource. Identify low volume specialty market to supply products to and request feedback from customers. Develop a growth strategy for the new process. Carefully consider the internal resources, process flexibility and customer service levels. Assign the highest skill workers to the new processes. Develop a training program to determine ground rules and communicate tasks and responsibilities. Employee buy-in is critical to successfully achieving results. When employees believe their work has a deeper purpose, their results will vastly exceed those who use only their minds and their bodies. This will become the company's competitive advantage [11]. Finally, evaluate the price of product, raw material, time at constraint and throughput.

Conclusion

The AM industry is on the cusp of a new set of opportunities, as many of the original process patents are expiring [8]. In the early nineties, many manufacturing experts were skeptic towards the chance of those slow and inaccurate rapid prototyping processes to be good for any other purpose than producing look-at prototypes. Today, a great deal of the challenge has been won to turn AM into a production technique with a wide scope of application that may further revolutionize the manufacturing world beyond the year 2000 [12]. As with any new and emerging technology, the need isn't always apparent. Currently, mainstream markets have little or no need for it. The compelling evidence from industry experts dictate AM is improving and may become a disruptive technology to conventional manufacturing processes. What this means to the users of rapid prototyping is that the future is likely to reveal not only many small, incremental changes, but also a handful of disruptive technologies that change the game entirely [3]. Capacities and the potential of rapid prototyping technologies have attracted a wide range of industries to invest in these technologies [13]. Although further developments need to be achieved in AM processes, the real breakthrough of AM will mainly depend on cost and productivity improvements, which have to be accompanied with further technical progress in material properties and most of all in accuracy and reliability [14].

The question is not if but when will Additive Manufacturing or any associate technology become disruptive to conventional manufacturing processes. In preparation, organizations must currently treat Additive Manufacturing as a major constraint to their operations and apply the Constraint Management technique to eliminate and/or improve the constraint. In closing, I remind you of the following example according to NSF, "The advances that built on Ivan Sutherland's ground-breaking Sketchpad work at MIT would bring computer graphics out of the laboratory, off the military base, and into the commercial marketplace, creating a steadily growing demand for computer-generated images in a variety of fields. [4].

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