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Making sense of 3-D printing: Creating a map of additive manufacturing products and services☆

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Abstract

Given the attention around additive manufacturing (AM), organizations want to know if their products should be fabricated using AM. To facilitate product development decisions, a reference system is shown describing the key attributes of a product from a manufacturability standpoint: complexity, customization, and production volume. Complexity and customization scales enable the grouping of products into regions of the map with common levels of the three attributes. A geometric complexity factor developed for cast parts is modified for a more general application. Parts with varying geometric complexity are then analyzed and mapped into regions of the complexity, customization, and production volume model. A discrete set of customization levels are also introduced. Implications for product development and manufacturing business approaches are discussed.

Keywords: Additive manufacturing; 3D printing; Product development; Complexity; Customization; Volume; Complexity factor; STL; Surface area; Features; Part geometry; Product mapping; Strategy

1. Introduction

Additive manufacturing (AM), also referred to as 3D printing, involves manufacturing a part by depositing material layer-by-layer. This differs from conventional processes such as subtractive processes (i.e., milling or drilling), formative processes (i.e., casting or forging), and joining processes (i.e., welding or fastening). Additive manufacturing has received tremendous attention recently. Arguably, the most prominent was President Obama's reference in the 2013 State of the Union address. However, the reaction among business leaders is varied. General Electric's CEO, Jeff Immelt, views additive manufacturing as a game changer. By 2020, General Electric (GE) Aviation plans to produce over 100,000 additive parts for its LEAP and GE9X engines. The company also plans a $3.5B investment in additive manufacturing [1]. On the other hand, Foxconn CEO Terry Gou stated "3D printing is a gimmick and has no commercial value" [2,3]. Why such divergent opinions on additive manufacturing?

Manufacturing business leaders must consider many factors when determining if additive manufacturing is an appropriate fit for their businesses. There is a wide array of different AM technologies that can make a part layer-by-layer including material extrusion, powder bed fusion, binder jetting, material jetting, vat photo-polymerization, directed energy deposition, and sheet lamination. Each AM technology has its own processing capabilities, advantages and limitations including materials, build volume, processing speed, part quality (mechanical performance, dimensional accuracy and surface finish), and the amount of post-processing required to improve the material properties, surface finish, and/or dimensional accuracy

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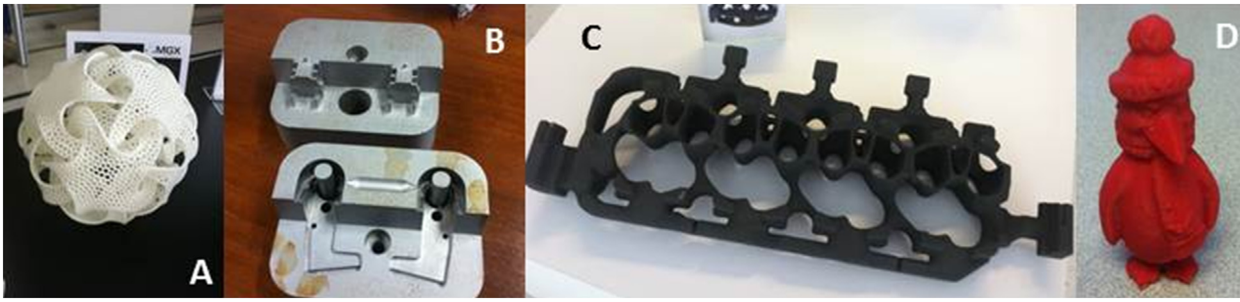

Fig. 1. Examples of 3D printed products. (A) A complex decorative piece printed from nylon-11 material using laser based powder bed fusion. (B) Injection molding dies printed out of stainless steel using laser based powder bed fusion. (C) 3D printed automotive cylinder head water jacket sand core printed used binder jetting. (D) A Youngstown State University penguin mascot printed using a desktop material extrusion printer.

(i.e., support removal or surface finishing). 3D printers themselves can range from desktop printers to printers capable of building parts measured in several meters.

As for products, there is a challenge in determining what defines value given the diversity of products being fabricated using additive manufacturing (see Fig. 1). Nowhere is this more evident than in a display found at the public-private manufacturing innovation partnership called America Makes located in Youngstown, Ohio. America Makes has transformed an abandoned furniture warehouse into high-tech facility housing additive manufacturing technologies. A display of 3D printed products includes artwork, automotive parts, ductwork for a mobile hospital, sand cores for automotive engine block castings, architectural models, dental bridges, jewelry, ball bearing assemblies, gear assemblies and the list goes on. The displayed items are just a sample of the myriad of items that are being printed today, and the tip-of-the-iceberg of what will be printed in the future.

Many products can be printed using additive manufacturing, but does it mean that additive manufacturing is the best manufacturing approach in all cases? In that regard, what are the desirable scenarios for a company to invest in additive manufacturing, in order to benefit from this opportunity? It has been recognized that the traditional economy-of-scale model is not relevant to 3D printing leading to what is called an "economy-of-one" [4]. Therefore, the typical conventions for product selection and design for manufacturing and assembly (DFMA) may not directly apply to additive manufacturing. Likewise, the low production rate of current 3D printing equipment tends to cause some to recommend it as primarily suitable for products that are of high value and low volume [5]. However, currently there are products that are being printed in high volume as will be discussed below.

Given all of this, there is a definitive need to identify criteria to navigate the sea of potential products that could be printed as well as guide the services that underpin the fabrication of these products by additive manufacturing. Such an over-arching platform would benefit executives, engineers, investors, government officials, students from K-12 to university-level, and those collectively referred to as "consumers."

2. Method – developing a reference system for manufactured products

Among all the aspects of manufacturing, we have identified three key attributes that can serve as a reference frame for comparing products to find underlining categories that call for similar strategies. By identifying key attributes of manufacturing it is possible to build a reference system and a map. The reference system is based on three attributes: production volume, customization, and complexity. Production volume simply refers to the number of parts made in a given timeframe such as a lot size or order quantity. When it comes to manufacturing, production volume can range from the billions of aluminum beverages cans produced in a year to a single set of dies used in injection molding or a single custom bio-implant. Complexity refers to the number of features a part contains, the geometry and location of the features. In general, the more complex a part is, if not impossible, it is more difficult to manufacture with the traditional subtractive or formative means. Customization involves uniqueness. Customization ranges from the mere monogram to an implant that is tailored to a specific person's anatomy. It should be noted that customization is not a volume of one. A carpenter may only be able to produce 20 custom china cabinets in a year. This is the carpenter's production volume. But each cabinet is unique and based on the customer's desires. This is an example of customization independent of production volume.

As shown in Fig. 2, these three attributes represent the sides of a cube comprised of eight regions describing any manufactured product regardless of how it is manufactured.

2.1. Region 1: mass manufacturing

Conventional manufacturing is primarily focused on mass manufacturing. Mass manufactured products are characterized as having one simple part or an assembly of several simple parts and practically no customization in order to reduce costs and sustain a higher production rate to support large volumes such as components for devices or vehicles. While the parts may go into a complex assembled system such as a cellphone or automobile, our focus in this model is on the parts themselves.

Significant capital investment is necessary to create assembly lines and production centers for mass manufacturing. Before a

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