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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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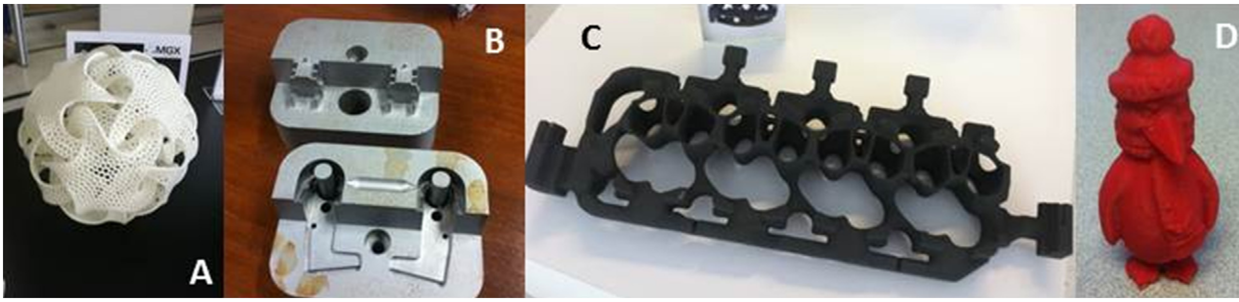


Fig. 1. Examples of 3D printed products. (A) A complex decorative piece printed from nylon-11 material using laser based powder bed fusion. (B) Injection molding dies printed out of stainless steel using laser based powder bed fusion. (C) 3D printed automotive cylinder head water jacket sand core printed 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

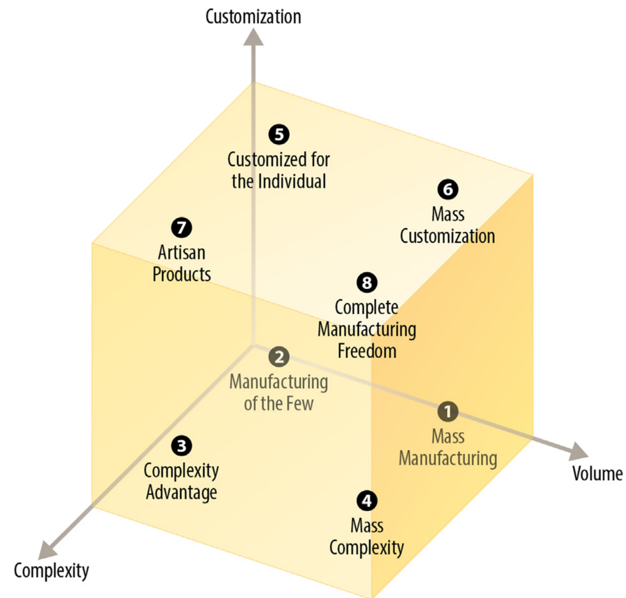


Fig. 2. Three axis model of manufactured products.

single part is produced, tooling and fixturing must be fabricated resulting in both lead times of weeks or even months and significant investment in tooling costs [8]. Examples of tooling and fixturing include dies for injection molding of plastics or stamping dies for automotive sheet panels. Tooling and fixturing can be expensive but the costs are amortized over total units of parts produced (often in millions). The business model for mass manufacturing is well established and is primarily cost driven to lower the unit cost of each part and is not value driven (i.e., lighter weight, greater thermal conduction, anatomical fit, etc.) with higher customization and complexity of each part.

It is very clear that with the existing global pervasiveness of capital equipment for mass manufacturing as well as established business models and cost structure, products within this region should not be fabricated using additive manufacturing due to their limited complexity and customization. However, as shown in Region 2 there is an opportunity to use AM to fabricate the tooling for conventional mass manufacturing which reduces the lead-time associated with tooling for mass manufacturing.

### 2.2. *Region 2: manufacturing of the few*

This region describes products with limited complexity and customization but also in low production volumes. There is not a specific number to distinguish between low and high volume. The Center for Automotive Research defined 30,000 vehicles per year as the upper bound for low volume production of automobiles [6]. However, in the aerospace sector it is different. In June 2008, the production of F/A-18 Super Hornets stood at 42 aircraft per year. At that time, its replacement, the F-35 Lightning II, was projected to reach 230 aircraft per year by 2016 [7]. While such a production volume would not be considered mass manufacturing from an automotive industry or from a consumer products' standpoint, for a manned aerospace fighter this is a large enough volume that it would impact the selection of manufacturing processes and tooling. When using the model, it is best advised to use the low or high volume definition that best suits the industry. For the purpose of this discussion, 10,000 parts per year or less is arbitrarily used for regions of the map defined as low volume. Tooling and fixturing costs are substantial for low volume production [8]. The lead times for tooling and fixturing are often longer than the time to fabricate the product itself. Examples of products in this region would include product prototypes subsequently mass manufactured, high value parts for low volume applications like ships or satellites, and tooling and fixturing. When fabricated through conventional processes, complexity is minimized due to the limitations of conventional manufacturing processes and/or the need to reduce the number of fabrication steps in order to minimize cost.

The genesis of additive manufacturing occurred in this region with the concept of rapid prototyping. The first 3D printing technology, stereolithography (a type of vat photopolymerization), was invented, in part, to support the creation of visual prototypes to support design and marketing. As 3D printing processes became more precise (enabling tighter tolerances for nesting of parts) and printing materials became stronger and more durable, rapid prototyping evolved beyond visual prototyping to include functional prototypes that can be used in fully functioning mechanical systems [9]. By eliminating the need for tooling and fixturing, these printed prototypes are more cost effective and take far less time (hence "rapid") than conventionally manufactured prototypes. This reduces time-to-market while ensuring the desired final product functionality.

Certainly if one can make functional prototypes using AM, one can also have direct part production. For low volume production of products with minimal part complexity and customization, the use of AM results in lower cost and reduced lead times when compared to conventional methods. For example, Hopkinson and Dickens [10] analyzed the costs of fabrication of a small plastic lever by additive laser sintering, a powder bed fusion technology and conventional injection molding. The cost model was further refined by Ruffo et al. [11]. Both studies showed that for a production volume less than about 10,000 parts, a lower unit cost is realized using laser sintering when compared to injection molding.

As noted earlier, AM can be used to fabricate tooling and fixturing for conventional manufacturing processes. By using AM, tooling and fixturing can be more affordable and faster than conventional means. For example, a method of metal casting involves the use of sand for mold walls and cores. Conventionally, this process is labor intensive and time consuming. A pattern (representative of the part) is fabricated and used to shape the sand mold. The patterns are permanent and must be stored for future use. Various pathways and reservoirs for the flow of metal are formed in the sand by hand. Besides being costly, this method of fabrication limits the design of certain final part geometries. 3D binder jetting of sand is being used to fabricate molds and cores eliminating the need for patterns and reducing labor costs [12].

### 2.3. Region 3: complexity advantage

This region describes products with increased complexity in order to enhance the functionality of a product or provide aesthetic appeal. With conventional manufacturing processes, complexity leads to increased costs due to multiple operations, longer production times and therefore lower production rates. For subtractive manufacturing, increasing geometric complexity of the part which are feasible for machining can result in increased number of machining steps, more (and probably longer) tool paths, and possibly a need to acquire additional tooling or even create expensive custom tooling.

Another method to fabricate complex parts using conventional means is to fabricate simpler components to join them together using through welding or fastening. This results in increased costs due to tracking and inventory of multiple parts before assembly, labor costs (i.e., qualified welders) and/or capital costs (i.e., specialized fastening equipment) to perform the joining, inspection of the joints, consumables costs in joining materials (i.e., fasteners or weld wire), scrap, additional process planning required, and more intensive certification. Further, joined structures can be less durable than unitary structures. Because of the limitations and costs involved in making complex parts, they are primarily found in aerospace and medical applications where the performance improvements can justify the costs. In general, engineers and designers are trained in design for manufacturing and assembly (DFMA). In traditional DFMA, complexity is driven out of design, limitations of conventional manufacturing methods are taught, and the consciousness of cost is raised.

However, in additive manufacturing, complexity is essentially free [13]. As the product is made layer-by-layer, the cost and time it takes to produce a complex part is essentially the same as that for a simple part. As compared to conventional manufacturing, the following complexities are possible [14]:

- Features: "undercuts, variable wall thicknesses, and deep channels"
- Geometries: "twisted and contorted shapes", "blind holes", "high strength-to-weight ratio" geometries, high surface area-to-volume ratio designs, lattices, topologically optimized organic shapes
- Parts consolidation: integrate parts that would otherwise be welded or joined together into a single printed part.
- Fabrication step consolidation: nesting parts that would be assembled in multiple steps if fabricated conventionally can be printed simultaneously as demonstrated with the ball bearings shown in Fig. 3.

Therefore, when making products using additive manufacturing, it is an advantage to make complex parts to enhance performance or create visual appeal. This study [14] quantified the effects of re-designing an aluminum aircraft main landing gear taking advantage of laser sintering, a powder bed fusion technology to consolidate into a single part while reducing weight and increasing strength. Laser sintering of the redesigned part cost less than the conventional die-cast assembly for volumes of 42 parts/assemblies or less which was adequate to meet market demand for that aircraft. The landing gear could be produced 2.5 days after receipt of the drawings whereas just starting the die-cast production would take weeks.

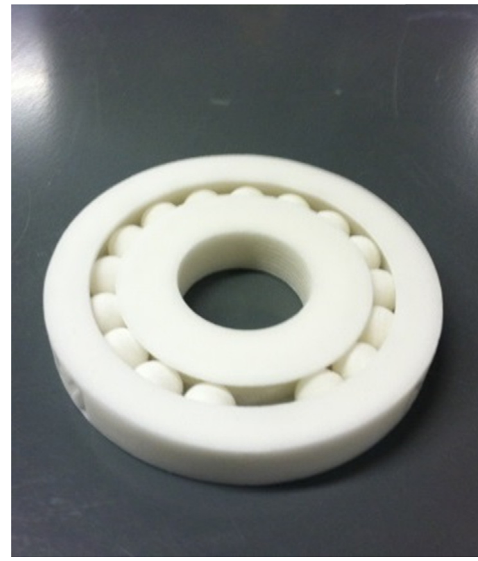

Fig. 3. A printed nylon-11 ball bearing assembly. This was fabricated as-assembled at America Makes using selective laser sintering, a powder bed fusion process. Fabricating this using conventional manufacturing would involve making 18 different parts then assembling the parts together.

GE's LEAP engine fuel nozzles were originally designed with twenty conventionally fabricated titanium parts welded together into the final complex nozzle assembly. Using 3D laser melting, a powder bed fusion process the nozzle was redesigned into a single cobalt-chromium part with increased durability and reduced the weight by 25% [1]. Cobalt-chromium was chosen because of its relatively lower density, corrosion resistance, toughness, ability to maintain strength at high temperatures up to 982 °C (1800 °F), relatively lower cost compared to titanium, and existing performance data from medical applications [15]. There are cascading benefits such as reducing the number of parts to track, increased part quality through weld elimination, and reduced certification process and paperwork. Instead of buying super-alloys to machine into the final shape, fabricating the fuel nozzle by printing into net shape or near net shape reduces the ratio of material purchased versus the material on the flying part, called the "Buy-to-Fly" ratio. During machining parts from stock volume, much of the material is lost in machining scraps and chips. This is critical as raw titanium material is expensive and additionally, it is relatively very difficult to machine when compared to traditional metals [8]. There are 19 nozzles per LEAP engine and over 4500 LEAP orders [1].

### 2.4. Region 4: mass complexity

In this region, products are not customized, but are complex and the volumes are greater than those in Region 3. In the United States, there are nearly 440,000 total hip replacement surgeries a year [16]. The metal acetabular cup is the portion of the implant that holds the ball socket into the hip bone. Using

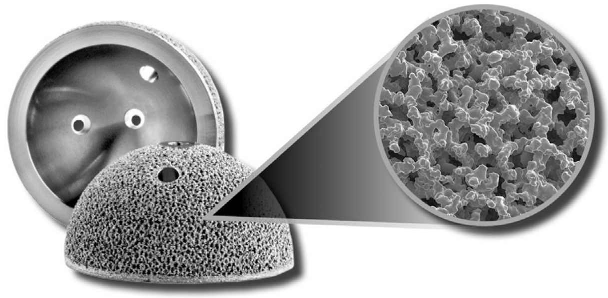

Fig. 4. A titanium acetabular cup produced using electron beam melting. Inset shows close up of highly complex surface.
Courtesy of Arcam AB.

conventional manufacturing methods, the first step in fabricating the acetabular cup is forging a titanium hemisphere which is near-net shaped. The hemisphere is machined into the final cup geometry and coated with a porous surface enabling bone adherence to the implant coating [17,18]. Alternatively, a powder bed fusion process developed by Arcam AB is being used to print parts using an electron beam to melt metal powder to produce highly complex titanium acetabular cups for implants [18]. The process not only fabricates the cup layer-by-layer but it can also build porosity into the surface layers of the implant as shown in Fig. 4. This eliminates not only the expensive forging step but also the coating step. Currently, 98% of these printed cups are not customized but rather produced in off-the-shelf sizes akin to small, medium, and large [19]. This off-the-shelf product is an example of mass complexity. Contrary to the mass manufactured part described in Section 2.1, recent developments on producing mass custom cell phones illustrate growing popularity of mass customization.

### 2.5. Region 5: customized for the individual

This region describes low volume products with low complexity but high customization. Most of the items produced on desktop 3D printers would fall into this category such as luggage tags, personalized key chains, and items created or modified using software packages such as Tinkercad or Autodesk 123D™. Other products would include customized prosthetics and implants with low complexity but produced at low volumes. AM technologies are being employed to repair parts such as engine shafts, injection mold tooling, and deep drawing tooling [20]. Given that are no two exact repairs, these are essentially customized products.

As for conventionally produced examples of products in this region, the cost and time needed to fabricate tooling and fixturing leads to limited opportunity in this region. For example, a bowling tournament trophy has a small customized etched or engraved name plate but the trophy itself was mass manufactured.

### 2.6. Region 6: mass customization

The concept of mass customization is a daunting task with conventional manufacturing processes. However, the reality of mass customization enabled by AM is happening today. Align Technologies is using 3D stereolithography printers as part of its process to make clear plastic Invisalign® braces [21,22]. Using the patient's X-ray images, photographs, and dental impressions, a series of braces are fabricated and are worn by the patient for two week periods during the course of treatment [21]. The braces themselves are not printed but are thermoformed plastic. However, the molds for thermoforming the plastic braces are 3D printed [8,19]. The 17.2 million customized orthodontic Invisalign® braces fabricated in 2012 are a clear example of mass customization [23].

Custom braces are one of the growing examples for mass customization. Considering that New Balance® has printed customized track and field spikes [24], it is clearly possible that in the future we could see foot scanners in sporting goods stores enabling customizing running shoes to be mailed to one's home. As machine costs go down and increased processing speeds are realized perhaps the shoes will be printed at the store while the customer waits.

### 2.7. Region 7: artisan products

In conventional manufacturing, simplicity and symmetry in part design is extremely encouraged as such part complexity favors the processing capabilities. Using conventional manufacturing means to produce unique artwork with 'non-traditional' design attributes is costly, labor-intensive, and time consuming. However, the value of artistic freedom to produce complex, customized artwork is beneficial to society. Part design and its manufacturability can be constrained by the manufacturing method and material. AM opens the doors to products that are both highly complex and highly customized and in less time and cost than ever before. Beyond artwork, products within this region would include complex articulating prosthetics and even F1 race car components. The racing industry has espoused additive manufacturing enabling complex structural and aerodynamics parts that are customized for the race car, the driver's and team's tactics, and even the race track [19,25].

### 2.8. Region 8: complete manufacturing freedom

The ultimate objective of any manufacturing technology with respect to these three attributes is the ability to produce highly complex and highly customized products without limitations to production volume. As of yet, such products have not reached the market but additional efforts are required to incorporate the part complexity, degree of customization, and build volume envelope with regard to production volume and relevant business model. At the moment, 3D printing processes are relatively limited in terms of geometric build volume and production rate. As with any new manufacturing processes, additional research and development is required to improve additive manufacturing process technology accuracy, repeatability and overall processing capabilities to include most materials. While small Invisalign® brace molds can be printed in the millions using numerous stereolithography (SLA) machines [22], additive process technology is not currently commercially available to produce millions of larger parts for high-volume markets such as automotive. One reason is due to market demand. Currently, there is no near-term large-size product identified that would drive a scale-up of existing technology or new technology development of a large build envelope machine with high production rates. However, the customer infrastructure, design technology, and education needed to develop highly customized and complex products at lower production volumes would be transferrable to higher volume products. For example, the mass production of customized, highly complex printed titanium acetabular cups would be enabled by the design of the implant from the patient's CT and MRI data [27].

## 3. Calculation: developing customization and complexity scales

The mapping outlined above provides general guidance for selecting additive manufacturing versus conventional manufacturing based on the three criteria: production volume, customization, and complexity. The development of scales for both complexity and customization would lead to more specific direction. This would enable placement of products into the appropriate regions of the map. Scales would enable grouping of products allowing for comparison of factors such as business strategy, product development, and customer engagement.

### *3.1. Modifying a geometric complexity factor to determine levels of complexity*

Several studies have evaluated geometric complexity parameters of manufactured products [28,29,30,31]. Common parameters considered in these studies included geometric volume, surface area, bounding box, number of triangles within the STL file, and number of features contained. Of particular interest is the geometric complexity factor developed for the purpose of categorizing castings [31]. In this study, two families of components with varying levels of complexity are considered, and other parts from the literature are also examined.

The first family is based on a control arm concept described in [32] with digital drawings being created in order to conduct the analysis needed for this project. The second involves the GE engine bracket that formed the basis of an open source design challenge competition in 2013 [33]. In both case studies, the intent is to use complex design to reduce the weight of the part while meeting the same mechanical requirements as the baseline. For the control arm, the baseline part would be manufactured by forging or casting. One approach to reducing the weight of the part would be the machining of a pocket followed by machining of the holes within the pocket. An example of this approach is shown in Fig. 5 and this design resulted in a 16% reduction in weight versus the baseline part. Even greater weight savings can be achieved through incorporating a complex lattice structure into the design. A design incorporating the lattice is also shown in Fig. 5, and results in a 22% reduction in weight. Incorporation of lattice structures would take advantage of AM process capabilities and would be difficult if not impossible to fabricate

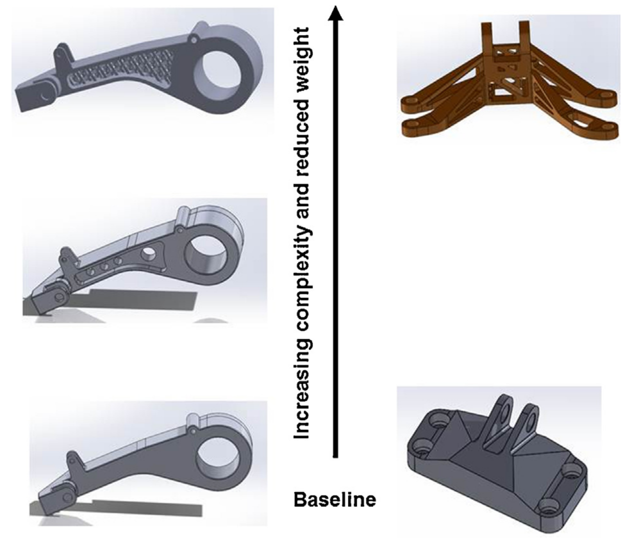


Fig. 5. Two families of parts where increasing complexity leads to reduced weight. On the Left are examples of a control arm. On the right is an engine bracket.

using conventional means. It should be noted that the bounding box is the same for each of the control arms.

For the engine bracket, the baseline part is machined from a plate or forging. As part of the challenge, the redesigned part had to meet four load cases and maintain the same assembly interfaces as the original. The redesigned part analyzed here was designed at Penn State University's Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D) and was provided to the authors for this study. The redesigned part achieved nearly a 90% reduction in weight versus the baseline design. Both the baseline and redesigned engine brackets are shown in Fig. 5.

Additional data can be found in the literature. A study [34] examined the cost of fabricating three metallic parts fabricated using selective laser melting (SLM), a powder bed fusion technology. The study also contained the geometric data for the three parts: a solid pyramid, a pyramid containing a lattice, and a joint [34]. Another study [28] examined the complexity of six highly dissimilar parts. The geometric data for all of the parts considered in this analysis can be found in Table 1.

In order to determine the region best describing a product, the complexity factor model found in [31] will be modified for this purpose. The model presented by [31] was focused on cast parts and included parameters specific to casting such as core volume and depth of mold. However, parameters involving part volume, surface area, and number of holes (number of cores in [31]) will be retained here.

The first parameter will be the part volume ratio ($C_{PR}$) which incorporates the ratio of the volume of the part, $V_p$, to the volume of the bounding box, $V_b$. This parameter is expressed as:

$$C_{PR} = 1 - \frac{V_p}{V_b} \quad (1)$$

The next parameter is the area ratio ($C_{AR}$). This parameter involves the ratio of the surface area of a sphere with equivalent volume to the manufactured part, $A_s$, to the surface area of the

Table 1
Geometric data for the products included in this study.

| Part | Surface area (mm$^2$) | Volume (mm$^3$) | Number of facets | Number of holes | Bounding box (mm) | Block volume (mm$^3$) |
|---|---|---|---|---|---|---|
| Control arms | | | | | | |
| Baseline | 23,084 | 102,164 | 11,310 | 4 | 158 × 71 × 53 | 594,554 |
| Machined part | 26,228 | 85,709 | 12,420 | 8 | 158 × 71 × 53 | 594,554 |
| Lattice | 30,719 | 79,581 | 16,402 | 80 | 158 × 71 × 53 | 594,554 |
| Engine brackets | | | | | | |
| Original GE design | 59,464 | 463,262 | 87,176 | 6 | 179 × 108 × 63 | 1,217,916 |
| PSU final design | 34,374 | 56,535 | 128,318 | 17 | 164 × 101 × 63 | 1,043,532 |
| From Ref. [34] | | | | | | |
| Pyramid | 4912 | 14,650 | 6924 | 0 | 42 × 48 × 51 | 102,816 |
| Pyramid lattice | 18,767 | 4900 | 224,468 | 234 | 42 × 48 × 51 | 102,816 |
| Joint | 1783 | 2020 | | 4 | 12 × 42 × 10 | 5040 |
| From Ref. [28] | | | | | | |
| Prism | 110 | 63 | 8 | 0 | 5 × 5 × 5 | 125 |
| Rib | 94,353 | 79,042 | 340 | 0 | 83 × 60 × 180 | 8,964,000 |
| Plug | 12,850 | 27,056 | 3372 | 1 | 35.5 × 62.3 × 35.3 | 78,071 |
| Housing | 2486 | 1833 | 10,302 | 2 | 33 × 10 × 21 | 6930 |
| Holder | 51,103 | 89,139 | 33,622 | 1 | 213 × 180 × 57 | 2,216,160 |
| Wheels | 96,585 | 168,157 | 584,962 | 10 | 93 × 111 × 93 | 960,039 |

part, $A_p$. A sphere has the minimum surface area as compared to any other geometry of equivalent volume. In general, the higher the surface area, the higher the complexity of the part and the associated manufacturing cost. The area ratio is expressed as the following:

$$C_{AR} = 1 - \frac{A_s}{A_p} \tag{2}$$

Finally, the number of cores parameter ($C_{NH}$) found in [31] will here represent the number of holes $N_H$ in the part or slots that could require a core in casting of a part.

$$C_{NH} = 1 - \frac{1}{\sqrt{(1 + N_H)}} \tag{3}$$

The contribution of each parameter to complexity must be weighted and create the following Modified Complexity Factor (MCF) relationship where $w_i$ represents the weighted factor:

$$\text{MCF} = w_0 + w_1 C_{PR} + w_2 C_{AR} + w_3 C_{NH} \tag{4}$$

A multiple regression analysis involving 40 cast parts of varying complexity was used in [31] to determine the weights of this equation. The analysis included weights for the terms not represented in the modified equation shown. The resulting weights are:

$$\text{MCF} = 5.7 + 10.8 C_{PR} + 18.0 C_{AR} + 32.7 C_{NH} \tag{5}$$

Table 2 contains geometric complexity data for the fourteen parts from the part families and the literature components described above. Based on inspection, products with a modified complexity factor value greater than 44 are determined to fall into the "High Complexity" region of the complexity-customization-production volume model. Additive manufacturing is likely to be cost effective for parts with MCF values greater than 44. It may still be competitive for values less than 44 if time is critical, or the cost of tooling for low volume applications is prohibitive. Of the fourteen parts, six were determined to be "High Complexity" or for low production volumes: Region 3. The reminder would be considered "Low Complexity" or Region 2 for low production volumes.

It should be noted that increasing the ratio of the surface area to the geometric volume does not necessarily correlate to increased complexity. While [28] suggests using the number of triangles contained in an STL file mesh as a measure of complexity, the utility of such a measure is limited given that the mesh density can be varied by processing software or user input.

### 3.2. Determining the level of customization

Customization is approached from the perspective of discrete levels. The customization levels were determined from literature and online searches of customized products. Products considered included monogrammed shirts, personalized bracelets, computer box frames, water bottles with customized text and geometry, anatomically customized wet suits, customized running shoes, and a printed jaw implant. Attributes of each of these products were recorded. Similar parts were grouped together. The following levels based on increasing level of customization were created from this process:

**Level 0**: No customization. This level defines products where the customer has no input into customizing the product. Commodity products would be described by this level.
**Level 1**: Pre-defined options. Here, customization is limited to a few pre-defined options. For example, the customer is allowed to choose the color of a laptop's anodized case.
**Level 2**: Limited customization/many restraints. This is the entry into the high levels of customization; a product described by this level has only one feature that is customizable. This feature is not predefined by the manufacturer. An example would be text incorporated into the geometry of the part (i.e., not

Table 2
Geometric complexity data including the modified complexity factor. Assuming low production volumes and low level of customization, map regions are shown.

| Part | Number of facets/volume | Surface area/geometric volume ($mm^2/mm^3$) | Modified complexity factor | Map region (Low volume/High volume, low customization) |
|---|---|---|---|---|
| Control arms | | | | |
| Forged or cast part | 0.11 | 0.23 | 42.5 | Regions 2/1 |
| Machined part | 0.14 | 0.31 | 48.3 | Regions 3/4 |
| Lattice | 0.21 | 0.39 | 56.9 | Regions 3/4 |
| Engine brackets | | | | |
| Original design | 0.19 | 0.13 | 42.0 | Regions 2/1 |
| PSU final design | 2.27 | 0.61 | 55.2 | Regions 3/4 |
| From Ref. [34] | | | | |
| Pyramid | 0.47 | 0.34 | 22.4 | Regions 2/1 |
| Pyramid lattice | 45.81 | 3.83 | 63.2 | Regions 3/4 |
| Joint | | 0.88 | 40.4 | Regions 2/1 |
| From Ref. [28] | | | | |
| Prism | 0.13 | 1.75 | 16.5 | Regions 2/1 |
| Rib | 0.00 | 1.19 | 31.8 | Regions 2/1 |
| Plug | 0.12 | 0.47 | 34.2 | Regions 2/1 |
| Housing | 5.62 | 1.36 | 40.2 | Regions 3/4 |
| Holder | 0.38 | 0.57 | 40.2 | Regions 2/1 |
| Wheels | 3.48 | 0.57 | 52.7 | Regions 3/4 |
| From Ref. [31] | | | | |
| Average cast part | | | 33.2 | Regions 2/1 |

cosmetic surface coating) that could be defined by the consumer as compared to pre-defined words. There may or may not also be other features with pre-defined options.

**Level 3**: Greater freedom of customization. Within this level, there are an increasing number of features that are defined by the customer. However, this would not be a random level of customization.

**Level 4**: Truly Unique. For a product to be truly unique, it would require random customization such as for a human or animal anatomy, where each part is unique in design features and overall geometry. This represents the upper limit of customization within our product map. The Invisalign® brace molds are an example of this type of customization.

Levels 0 and 1 above correspond to the "Low Customization" Regions 1 through 4 of the map. Products within those regions have no customization or the customer can only choose from pre-defined options. The level of engagement with the customer is minimized.

Regions 5 through 8 of the map include products of "High Customization". Here, at least one aspect of the product (i.e. features, geometric shape, materials) must not be predefined and it must be unique. From a conventional manufacturing standpoint, this provides a challenge because tooling and fixturing will likely need to change to accommodate the customization, and since this is not-predefined the manufacturer will not have needed tooling readily available – unless one can print the tooling.

Customized products are not new. The challenge in conventional manufacturing is the cost of tooling, fixturing, and dies for increasing levels of customization and in particular customer-defined features. This is extremely critical since the unit cost is severely impacted with additional tooling, particularly for low volume production. In order to minimize the cost and lead time associated with re-tooling, conventional manufacturing fabricates customized products through using (a) pre-defined options (i.e., Level 1), (b) assembly of Level 1 components into a customized structure such as a customized mountain bike, or (c) costly and time consuming fabrication to achieve uniqueness such as hand-crafting and artisanship. When it comes to additive manufacturing, complexity is free and customization is also free.

### 3.3. Continuous scales for customization

The primary role of this study is to categorize products into the eight regions of the complexity, customization, and production volume model. Future work could explore the development of continuous scales customization. A continuous scale could lead to parametric cost analysis providing a simple tool for early development milestone decision making. A qualitative example is shown in Fig. 6 based from [13] where a break-even point

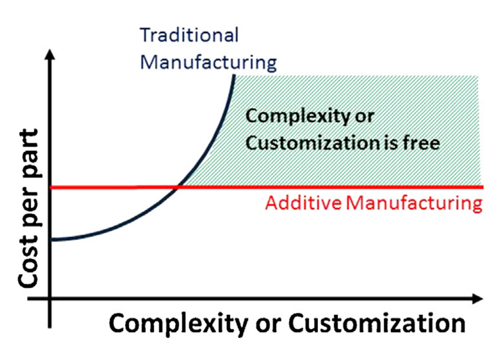


Fig. 6. In conventional manufacturing, increasing complexity and/or customization leads to increased cost. With additive manufacturing, complexity or customization becomes free.

Table 3
Geometric data for the products included in the case studies.

| Part | Surface area ($mm^2$) | Volume ($mm^3$) | Number of holes | Bounding box (mm) | Block volume ($mm^3$) | Modified complexity factor |
|---|---|---|---|---|---|---|
| Lever | 3894 | 4300 | 1 | – | 7106 | 31.6 |
| Dental brace mold surrogate | 12,373 | 58,109 | 0 | 158 × 71 × 53 | 128,910 | 19.1 |
| Suspension | 21,373 | 44,021 | 13 | 37.6 × 47.7 × 164 | 294,609 | 51.8 |

in cost is shown when comparing cost per part and complexity. For complexity levels greater than that of the break-even point, it is more cost effective to manufacture using additive manufacturing. This is known as "complexity is free". However, this relationship should also be true of customization as well leading to "customization is free" in AM. As demonstrated in [10,11], there is a break-even cost point between conventional and additive manufacturing when comparing cost per part and production volume. Based on these relationships, one should be able to plot a break-even surface in three dimensional space when the complexity, customization, and production volume are defined.

One can also envision a continuous customization factor similar to Eq. (4) above that would include weighted parameters including the number of pre-defined options and number of customer defined options.

### 3.4. Manufacturing process selection case studies

#### 3.4.1. Region 1 and 2: lever

Consider for example a series of products with very different attributes as shown in Tables 3 and 4. The first is the lever first described in [10] and also contained in [11]. The lever is made of a polymer. For conventional processing, the fabrication method is injection molding using polycarbonate. The additive manufacturing method studied in both [10,11] is laser sintering, a powder bed fusion process in this case using nylon as the material. Two production volumes are considered: 1000 parts and 18,000 parts. Using the part volume found in [10], the bounding box from [11], and the surface area estimated from a similar lever [35], the Modified Complexity Factor is 31.2 which would be considered low. The part is not customized and all parts within the 1000 and 18,000 part production runs are the same, so the customization considered low. Arbitrarily taking 10,000 as the division between high and low volume, we consider the lever with a production volume of 18,000 parts to be within Region 1 whereas the lever with a production volume of 1000 parts to be within Region 2. Cost analysis are found in both [10,11] with slightly different results for the laser sintering as the studies used different models. Within region 1, injection molding shows a clear advantage over additive manufacturing in cost per part and total manufacturing cost (€1.75/part [10] for injection molding versus €2.20/part [10] to €3.44/part [11] for laser sintering). The faster cycle times of the injection molding system make up for the non-recurring costs of the tooling which is amortized over many parts. However, at the lower volume, there are fewer parts over which to amortize the cost of injection molding tooling while additive manufacturing shows a clear cost advantage (€27.59/part [10] for injection molding versus €2.20/part [10] to €3.59/part [11] for laser sintering).

The study in [10] also considered material extrusion in the form of Fused Deposition Modeling (FDM) and vat polymerization in form of SLA. The authors in [10] printed the FDM lever with ABS as the material although the technology is capable of printing in polycarbonate. The SLA used an epoxy photopolymer. The cost of printing the lever using FDM was €4.47/part and for SLA was €5.25/part. As with laser sintering, FDM and SLA are at a disadvantage compared to injection molding in Region 1, but are more competitive in Region 2.

#### 3.4.2. Region 5: customized lever

Now consider the situation where the lever has one feature (not predefined by the manufacturer) that can be changed by the customer. 1000 customized parts are desired. The customization becomes Level 2 which is considered a high level of customization. This feature does change the part geometry but for the example here it does not significantly change the geometric complexity of the part. As such there is little change in the value of the Modified Complexity Factor meaning a low level of complexity. The product is in map Region 5. The cost of the

Table 4
Map regions (complexity, customization, production volume) and cost data for the case studies.

| Part | Process | Material | MCF | Customization | Production volume | Map region | Cost per part |
|---|---|---|---|---|---|---|---|
| Lever | Injection molding | Polycarbonate | 31.6 | Level 0 | 18,000 | 1 | € 1.75 |
| Lever | Laser sintering | Nylon | 31.6 | Level 0 | 18,000 | 1 | € 2.20–3.44 |
| Lever | Injection molding | Polycarbonate | 31.6 | Level 0 | 1000 | 2 | € 27.59 |
| Lever | Laser sintering | Nylon | 31.6 | Level 0 | 1000 | 2 | € 2.20–3.59 |
| Lever | Injection molding | Polycarbonate | 31.6 | Level 3 | 1000 | 5 | € 27,300 |
| Lever | Laser sintering | Nylon | 31.6 | Level 3 | 1000 | 5 | € 2.20–3.59 |
| Braces Mold | Stereolithography | Photopolymer | 19.1 | Level 5 | 17,000,000 | 6 | <$400 |
| Suspension | 4-Axis CNC (RP) | Ti-6Al-4V | 51.8 | Level 0 | 4 | 3 | $1358.25 |
| Suspension | Electron beam melting | Ti-6Al-4V | 51.8 | Level 0 | 4 | 3 | $1254.65 |

tooling for the injection molding is €27,360. If one takes the approach tooling must be changed for each customized part, the cost per part becomes €27,360 as the cost of material per part is merely €0.23 for the injection molding case. Alternatively, one could have a fabricated for an injection molded workpiece that is then machined into the various customized geometries, but this post-processing will be costly as well. Meanwhile, the part cost for using laser sintering would remain between €2.20/part to €3.59/part. It should be noted that these are just fabrication costs and do not reflect the additional costs of design, tracking, and logistics for customized parts that would be required regardless of manufacturing method.

### *3.4.3. Region 6: customized tooling for dental appliances*

The example of the customized lever provides insight into the manufacturing process selection used to fabricate molds for Invisalign® braces. Since the Invisalign® molds are proprietary; a surrogate STL file is used to obtain the complexity factor based on a dental impression [36]. The MCF value for the dental brace mold is 19.1. The braces are customized for human anatomy (nearly random) and as such would be considered Level 5 or high customization. The production volume of molds is 17,000,000 as noted in [23]. This would therefore be located in Region 6 of the map. Based on the customized lever analysis above, there is no advantage to use a conventional process to fabricate the molds, only an additive process would be considered. Although the fabrication cost per part is proprietary, Invisalign® advertises that a series of five braces (requiring five molds) can cost $2000. Therefore, the cost of fabrication must be less than $400 per mold [26].

### *3.4.4. Region 3: suspension component*

The final case study involves a suspension part found in [37]. The part material is Ti-6Al-4V. Since the geometry of the part is long with a smaller cross-section, it is ideally suited for a subtractive process called CNC-RP [38]. The workpiece is a Ti-6Al-4V rod which is held by chucks in a 4-axis CNC machine. Arguably, this is the best case geometric scenario for machining given that no fixturing is necessary and when the ratio of starting rod stock to final material mass (buy-to-fly ratio) is relatively low. A powder bed fusion (specifically Electron Beam Melting) is the additive process considered in [37]. Laser based powder bed fusion can alternatively be used to process the same part. The Modified Complexity Factor is 51.8 which would be considered high. The production volume is four parts. The parts are not customized (Level 0). This combination of attributes places the suspension part into Region 3. The cost analysis in [37] shows a cost of $1358/part for the subtractive fabrication and $1255/part for fabrication by EBM. It should be noted that the complexity of the part design, requirement of cutting tools, loss of material through scrap and machining chips, and machinability could be attributed to using additive method in this part.

## 4. Results and discussion

Table 4 lists a summary of the results described in the previous section. The case studies provide insight into the suitability of manufacturing products using AM depending on which region of the model the product occupies.

As hypothesized earlier in this paper, Region 1 (Mass manufacturing) is a region where special purpose conventional mass manufacturing equipment can fabricate low complexity and low customization products more cost effectively than AM. The case study involving the lever at a volume of 18,000 parts demonstrates this as injection molding is shown to be more cost effective at fabricating the lever than AM.

In Region 2 (Manufacturing of the few), AM will be the manufacturing method of choice only if it provides the lowest cost or the shortest production time. Again, in the case study of the lever when the production volume was only 1000 parts, AM was more cost effective than injection molding because it was not necessary to spend cost or time fabricating tooling prior to production. However, AM is not always the process of choice for Region 2. During a recent discussion on 3D printing of sand molds and cores, a foundry shared an example of a particular casting. This foundry had built a business model around low volume manufacturing with short lead times. The foundry showed a low complexity casting that only took 30 min using conventional methods to create the mold and core for sand casting. In this case, the advantage would not be using AM but rather using conventional milling and hand labor to fabricate the mold. Within Region 2, it is not guaranteed that AM is the most cost effective and/or most rapid means of manufacturing.

It is only when the level of complexity and/or customization are increased that there is a higher degree of confidence that AM has the advantage. In the case of the lever with a production volume of 1000 parts, AM becomes much more attractive from a cost standpoint when there is one geometric feature defined by the customer and not the manufacturer (Region 5). Moving into Region 6 with the customized molds for fabricating dental appliances, AM enabled tooling becomes the only way to fabricate truly unique parts in production volumes of millions.

The suspension part had a Modified Complexity Factor value of 51.8 and a volume of four parts placing it in Region 3. As anticipated, the high level of complexity of the suspension part makes machining more challenging requiring longer tool paths and additional steps. As shown in the case study, AM provides a more cost–effective means of manufacturing.

After reviewing the results from the case studies, we can now use the model to understand the rationale of each of the CEOs introduced earlier in this paper. At the time the statement was made [2,3], Terry Gou believed additive manufacturing was not relevant to Foxconn because the company was focused on mass manufactured consumer electronics (Region 1). However, recent developments may make 3D printing more relevant to Foxconn. One of his major customers, Apple, has since filed a patent to print antennas on 3D structures [39], which would be an example of increased complexity. At the same time, his competition is starting the development of customized printed smartphones. Google and Motorola have teamed with 3DSystems to develop a continuous 3D printer for smartphones [40]. Their approach involves a modular, "plug-and-play" printed smartphone structure enabling users to add or remove functionality during the life of the phone. Motorola has already invested in the web-based infrastructure for customization with its Moto Maker website and marketing campaign. Given that there were 968 million smartphones [41] sold worldwide in 2013, the production volume for customized cellphones would mean the product would be located in Region 6 or it would be in Region 8 if the complexity is high. It only makes sense to utilize AM for producing smartphones if the customization or complexity is high enough.

Jeff Immelt has confidence that 3D printing is a good fit for GE. Building on the success of the LEAP engine fuel nozzles (Region 3), GE Aviation is looking at replacing forged and machined titanium leading-edge blades covers with printed ones in order to reduce the costs due to scrap and lead time [19]. This would be a Region 2 application. GE is combing through other product families throughout the company's portfolio seeking similar opportunities for additive manufacturing. GE also sponsored an open-source competition demonstrating the weight savings resulting from complex design. Participants in this competition demonstrated taking a product originally in Region 2 and redesigning it into a Region 3 product. Considering all of these factors, Jeff Immelt finds additive manufacturing to provide a competitive advantage.

Today's businesses recognize that competitive advantage can be transient [42]. Companies need to be agile, seek out and quickly exploit opportunities, while scanning for the next competitive advantage then pivoting to it [42]. The process of reconfiguring assets and organizations to pivot is expensive and lengthy for companies that have conventional manufacturing assets. Additive manufacturing enables agility. The same 3D printer is able to print products within each region representing low and high levels of complexity and/or customization. Unlike conventional manufacturing, there is no need to retool for each product design. In fact, a 3D printer can fabricate products of various regions shown in Fig. 2 at the same time as long as they can be accommodated in the build volume. If there is a need to increase production-build volume, companies can purchase additional 3D printers or they can seek out service providers, participate in regional shared printer consortiums, or (for small items) even order from networks of distributed private printers.

Consider the example of a small metal casting company which is exploring the opportunity of sand mold and core 3D printing. Wanting to establish a customer base prior to purchasing a printer, the company contacts a service provider who has a sand printer or alternatively the company teams with other small businesses and establishes a consortium with a shared printer. In both cases, the foundry does not need to acquire additional assets by itself to get started. Initially, the company considers their traditional low-volume products with low complexity and no customization (Region 2). They would find printing the cores and molds reduces costs by eliminating pattern making and manual preparation of metal flow channels in the sand. 3D printing of sand cores and molds also reduces the time to make the cast part from weeks to days. However, the foundry would also find that many simple castings are best produced by traditional means. New opportunities are realized when the freedom offered by additive manufacturing is used to design complex castings that traditionally would require pain-staking effort to make multiple sand cores but now can be printed as a single core. The company can also offer complex cast part geometries that are impossible to make by hand but are now enabled by printing. These are both examples of Region 3 products. Being in Region 3 opens the door to discussions with customer design engineers to seek improved functionality of cast parts (i.e., lighter weight or improved fluid flow through the part). The company then recognizes an opportunity for a product offering it would have never considered before: customized castings. Engaging a diverse set of potential customers from artists to racing car teams, the company now enters Regions 5 and 7. The company now has the ability to move between four regions of the model able to seize competitive advantage when it presents itself. With enough of a customer base, the company can choose to buy its own printer, or may choose to continue leveraging external assets.

## 5. Conclusions

A product map for 3D printing products provides a reference system for evaluating products and their suitability for printing, gauging the impact of services to support printing, and printing asset access or acquisition decisions. Business leaders can locate their product on the map, determine if it is in a region where additive manufacturing is likely to provide an advantage over conventional manufacturing, and begin the process of creating specific strategies for competitive advantage.

- Manufactured products, regardless of how they are manufactured, can be mapped by their complexity, customization, and production volume.
- A modified complexity factor based on geometric attributes of the product has been developed and demonstrated. This permits determining whether a product has low or high geometric complexity.
- Customization levels are also explored. A product with low customization is one with no customization or has options pre-defined by the manufacturer. On the other hand, if there is at least one option that is defined by the customer, then the product has a high level of customization. The highest level of customization is defined by a random geometry or an anatomical geometry.
- If the product geometry and level of customization is known, it can be placed into a region of the map.
- As shown in the case studies, 3D printing is likely to be more competitive than conventional manufacturing when it comes to fabricating products with higher levels of complexity, customization, or a combination of both (Regions 3 through 8). If a product is identified with higher levels of complexity and/or customization, it is then beneficial to pursue an in-depth cost analysis including other factors not covered here.
- For products having low volume, low complexity and low customization (Region 2) additive manufacturing will be the process of choice only if it provides lower cost and reduced lead times as compared to conventional methods. Manufacturers are encouraged to diversify their product portfolio to include ones outside of Region 2 in order to reduce exposure to

competitive pressure from technologies such as CNC milling machines.
- Additive manufacturing enables product agility. As companies seek transient competitive advantages, they should seek product opportunities in multiple regions of the model rather than be locked into one region as is the case with mass manufacturing.
- Small custom parts such as Invisalign® braces can be produced in high volumes today using custom tooling (e.g., molds) produced through additive manufacturing. More high volume product opportunities will be realized as additive processes evolve to have higher production rates through larger build volumes, faster build speeds, or continuous processes.

In our future studies, we will develop mathematical continuous scales in defining the levels of complexity and customization. Scales will also be refined. For example, complexity scales would also be beneficial to study the grouping of parts from different map regions in a single build envelope and understand the amortization of part costs for high complexity parts. Grouping of products can also be used to determine business strategies for products with similar levels of complexity, customization, and production volume.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.addma.2014.08.005.

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