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A Sustainable Innovation for Product Component Prototyping with 3-D Printing Techniques

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Abstract: Transformative innovations has been shaping the manufacturing industry gearing towards sustainable development. One technology gaining traction is the three-dimensional (3-D) printing or additive manufacturing. Industries ranging from aerospace and automotive to healthcare and consumer goods are utilizing this technique to create beneficial product solutions. This paper analyzed the environmental impacts of 3-D printing techniques on product prototyping and compared it to the traditional manufacturing process. Furthermore, the future developments and directions of additive manufacturing are discussed.

Key Words: 3-D printing; Additive manufacturing; Manufacturing; Prototyping; Sustainable development

1. INTRODUCTION

Sustainability has been an emerging topic in discussions of various fields of study, especially in the manufacturing industry. A large and growing number of companies are realizing the financial and environmental benefits of sustainable strategies for their productive systems. The aim is to create products that reduce negative environmental impacts at the same time conserving energy and natural resources. Although, due to innumerable variables that are to be taken into consideration, there is no single solution to answer all of its demands (Guo, Nannan, & Leu, 2013; Houe, Raymond, & Bernard, 2009; Kumar, Sameer, & Valora, 2008). Currently, one of the revolutionary technologies is the three-dimensional (3-D) printing or Additive Manufacturing because it has the potential to eliminate the traditional manufacturing limitations and influence the way people design, produce, buy, and distribute goods. Among other things, additive manufacturing can improve the sustainability of the production processes by more efficient utilization of raw materials, design and manufacturing of lighter and more complex parts, and reduction of intensive supply chain, large inventories and global emissions (Berman & Barry, 2013; Campbell, Williams, Ivanova, & Garrett, 2011a).

One of the unique characteristics of additive manufacturing is the ability to build an object by adding layers of material one at a time unlike the subtractive process, which starts from a large piece of material and is shaped or carved in order to achieve a desired geometry. 3-D printing processes produce less waste material and do not require multiple tools and molds to complete manufacturing (Petrovic et al., 2011).

2. Overview of 3-D Printing

3-D printing is a set of manufacturing techniques utilizing three dimensional Computer Aided Design (CAD) model to fabricate 3-D objects. As aforementioned, these techniques slice the object into layers and build the object by depositing one layer of material on top of another until the entire model is constructed. The generalized steps are shown in Figure 1.

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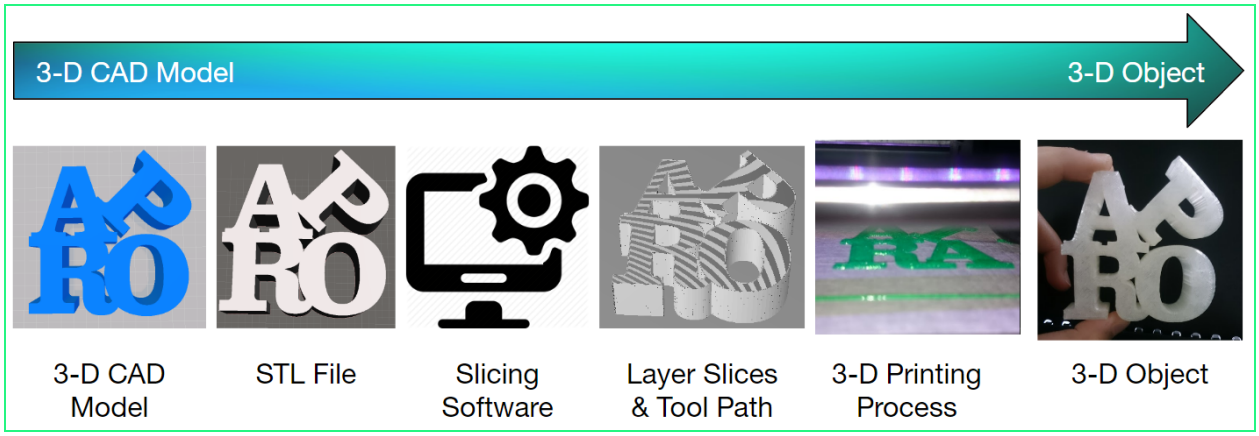

Fig. 1. General 3-D Printing Procedure

Table 1. Additive Manufacturing Processes

ADDITIVE MANUFACTURING PROCESS	3-D PRINTING TECHNIQUE/S	DESCRIPTION
Vat photopolymerization layer	Stereolithography (SLA), Digital Light Processing (DLP)	Uses light source to achieve photo polymerization, binding resins together.
Powder bed fusion	Selective Laser Sintering (SLS), Selective Laser Melting (SLM), Selective Heat Sintering (SHS) Electron Beam Melting (EBM), DirEct Metal Laser Sintering (DMLS)	Utilizes two (or three) powder beds filled with powder that will be wielded as product material.
Material Extrusion	Fused Deposition Modeling (FDM)	Deposits layers of melted thermoplastic on top of one another
Material Jetting	PolyJet, MultiJet Modeling	Uses an inkjet head to selectively deposit product material, which are cured with a pass of UV light
Binder jetting	Binder jetting	Utilizes thin layers of powdered material to build up an object and glues the layer together using a binding agent extruded from a nozzle.
Sheet lamination	Laminated Object Manufacturing (LOM), Paper Lamination Technology (PLT), UltrAsonic Additive Manufacturing (UAM), Selective Deposition Lamination (SDL)	Creates a layer by cutting the contours of the layer from the material bonded in place.
Direct Energy Deposition	Sciaky's Electron Beam Additive Manufacturing	The apparatus is usually attached to a multi-axis robotic arm and focused thermal energy is used to fuse materials by melting as the material is being deposited

According to the the American Society for Testing and Materials (ASTM) group, the additive manufacturing processes are categorized into seven, which differ mainly in the manner of creation of each layer, which are summarized and shown in Table 1. These 3-D printing techniques have already been utilized throughout the industrialized world, especially for manufacturing products and components with complex geometries that are difficult or uneconomical through other methods. Also, it enables users to make physical objects rapidly and relatively low-cost as a final product or a prototype. Some of the benefits/ uses of product models as a tool by both the designer and the client are:

- Convert 3-D CAD images into accurate physical models at a fraction of the cost of traditional methods since there are no tooling costs
- Generate visual and tangible models for market research, publicity, packaging, etc.
- Improve design communication and help eliminate design mistakes
- Reduce time to market for a new product
- Generate customer goodwill through improved quality
- Reduce the cost and fear of failure

2.1. 3-D Printing Industry

Worldwide, 3-D printing industry is expected to grow this year, 2016, by 7.3 billion from $3.07B in revenue in 2013 to $12.8B by 2018, and exceed $21B in worldwide revenue by 2020, as shown in Figure 2 (Wohlers Report 2015: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report, 2015). By 2025, the mid-term global market potential is estimated at $230–550 billion (Manyika et al., 2013).

It is approximated that the 3-D printing industry grows by 25-30% per year. However, the application 3-d printed technologies in the developing world is not as great, though many perceive that is has tremendous potential for impact, such as the ability of the technology to decentralize manufacturing, to create manufacturing jobs, and to lower the costs of certain products (Gebler, Malte, Uiterkamp, & Cindy, 2015; R.Ishengoma, Fredrick, & Mtaho, 2014).

According to the report, two thirds of manufacturers are already using 3-D printing in their production systems, and 25% plan to implement the technology in the future. Currently, additive manufacturing captures only 0.04% of the global manufacturing market. Wohler's and Associates forecasts that 3-D printing will adopt 5% of the global manufacturing capacity, which would obtain 3-D printing a $640 billion industry (Wohlers Report 2015: 3-D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report, 2015).

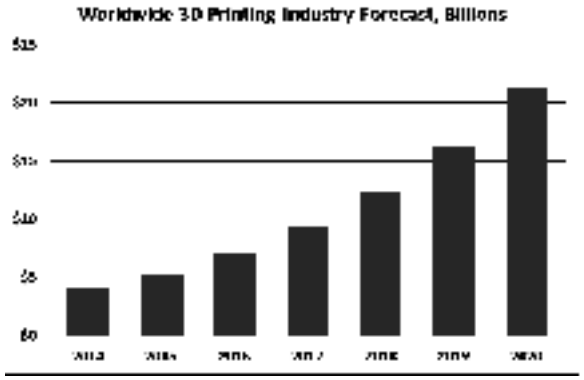

Fig. 2. Worldwide 3-D Printing Industry Forecast. Adapted from (Heller, 2016)

3-D printers are used in a range of industries – from automotive, to toy manufacturing, jewellery making and plastic packaging. The main identified markets are the consumer products and electronics, biomedical, and transportation (Yeh & Chin-Ching, 2014). Today, the three most common applications are for prototyping (25%), product development (16%), and innovation (11%). Primarily, industries have used 3-D printing technology for rapid prototyping to evaluate product design before production, rather than to create final consumer products. Some of the leading qualities of 3-D printing technology includes manufacturing advantages for small batches, cost efficiency for certain applications, unprecedented flexibility in new markets, and improvement of quality through lighter parts, better ergonomics and more design freedom.

One of the main limitation of 3-D printing is its production speeds, which makes it primarily applicable in small-scale production, customized products and/or high-value products (Berman & Barry, 2013; Hopkinson, Hague, & Dickens, 2006).

2.2. 3-D Printing Ecosystem

So far, prototyping has driven the adoption of 3-D printing. Future opportunities 3-D printers chiefly used for prototyping. Figure 3 shows the current percentage of 3-D printer models manufactured. Majority of 3-D printers work with only one kind of material, either plastic, metal, ceramic, wood, or a biological material. The cost to produce a 3-D-printed part is directly dependent on the amount of filament used as energy costs vary nearly linearly with the volume of filament (Kreiger, Mulder, Glover, & Pearce, 2014).

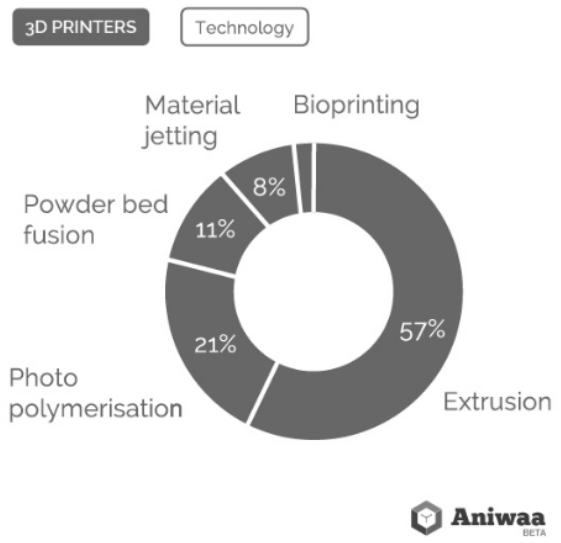

Fig. 3. Percentage of 3-D Printer Models Worldwide. Adopted from ("3D Printing Market Watch - Q4 2015 - Aniwaa," 2015)

As reported, additive manufacturing has shifted the supply chain from production-distribution-retail model toward a model where the consumer utilizes the electronic negotiation to order the personalized or customized product, then initiating production and distribution to the client (Reeves, 2008) as shown in Figure 4.

Additive manufacturing limits the amount of energy used in manufacturing since it has the potential to replace conventional processes like casting or molding.

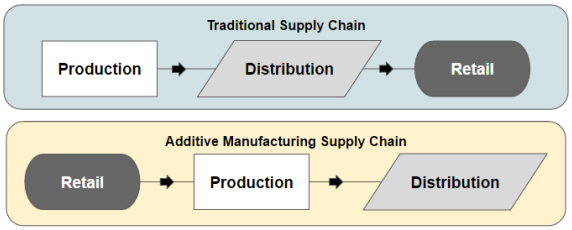

Fig. 4. Traditional vs. Additive Manufacturing Supply Chain.

3. 3-D Printing for Sustainable Innovation

Environmental considerations for manufacturing processes is associated to energy and resource use, including emissions and waste. In 3-D printing, electricity is the most dominant resource used impacting the environment. In order to achieve sustainability, it is necessary to improve design, manufacturing, and consumption patterns (Melles, Gavin, de Vere, & Vanja, 2011). Small-scale business operations have been demonstrated as an effective means for economic growth and 3-D printing technology is one of the alternatives to enable such development (Birtchnell & Hoyle, 2014; Pearce et al., 2010; R.Ishengoma et al., 2014).

All sustainability concerns are centered on the patterns of production and consumption that humans engage in, and if sustainability is to be achieved, it is necessary to develop more effective ways to provide both goods and services to people worldwide (Castillo et al., 2012). This will come from the efforts of improving design, manufacturing, and consumption patterns (Melles et al., 2011). Designers and manufacturers have a moral and ethical duty to be responsible for the sustainability of their products (Diegel et al., 2013), maximizing a product's value while minimizing the resources the product consumes (Fiksel et al., 1998).

3-D printers are used in a range of industries. Unlike traditional machining, additive manufacturing does not require the utilization of coolants for cutting, which use water resources and produce hazardous industrial waste. The following are some of the advantages over traditional manufacturing:

- Mass customization

- Complex products
- Lead time and speed
- Fixed-cost tooling
- Supply chain simplification
- Waste Reduction

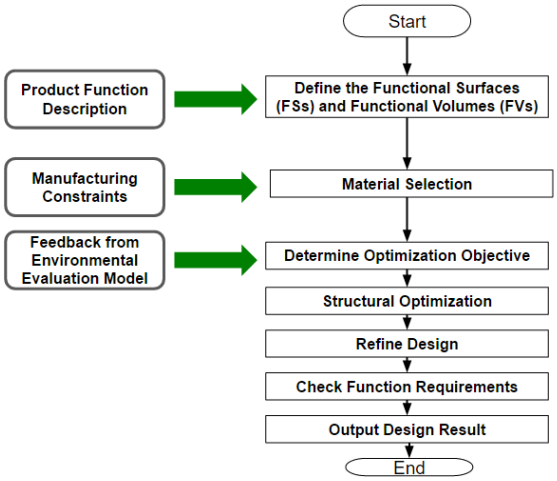

Fig. 5. Workflow of sustainable design optimization for additive manufacturing. Adapte from: (Muthu & Savalani, 2016)

In order to take full advantage of design freedom provided by AM technologies, a general design optimization method for sustainability is proposed in this paper. Based on the design freedom provided by AM processes, this design optimization method will take the environmental impact result as feedback to optimize the product design and reduce its environmental impact design flow of the proposed method is shown in Figure 5.

Feasibility is defined as the ability of the product to be manufactured, produce its intended purpose, and supply its intended benefits. Considerations in manufacturing practice of parts include mechanical requirements, constraints, and capabilities specific to 3-D-printed parts. Various functions, features, and constraints determine whether it is feasible for a product design to be 3-D printed.

These include:

- Geometric complexity,
- customization,
- material properties,
- mechanical properties,
- part sizes, and
- tolerances

4. CONCLUSIONS

3-D printing in manufacturing holds the potential to improve sustainable practices and minimize a product's environmental impact, especially if it becomes applicable in large-scale manufacturing process. With further research and study, this technology can enable product designers to select the most efficient additive manufacturing technology.

It concludes that there is a high possibility that 3-D printing provides more sustainable products to be developed. Although further quantifiable research is needed to allow users to harness better the features of additive manufacturing that can maximize sustainability.

5. FUTURE DEVELOPMENTS AND DIRECTIONS

While most of the applications of 3-D printing are for small-scale markets and prototyping, forecasts predicts that it will further grow in the future. With further research on this technology, this can allow mass manufacturing all over the world (Wohlers, 2012).

As 3-D printing grows, its social and environmental impacts will also grow, having this a critical time to identify this technology's potential challenges and opportunities. Manufacturers, designers, sustainability professionals, and consumers need to understand the potential sustainability impacts of 3-D printing in order to incorporate these considerations into their planning and decision-making.

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