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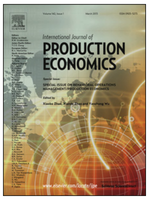

Additive manufacturing: A framework for implementation

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ABSTRACT

As mass production has migrated to developing countries, European and US companies are forced to rapidly switch towards low volume production of more innovative, customised and sustainable products with high added value. To compete in this turbulent environment, manufacturers have sought new fabrication techniques to provide the necessary tools to support the need for increased flexibility and enable economic low volume production. One such emerging technique is Additive Manufacturing (AM). AM is a method of manufacture which involves the joining of materials, usually layer-upon-layer, to create objects from 3D model data. The benefits of this methodology include new design freedom, removal of tooling requirements, and economic low volumes. AM consists of various technologies to process versatile materials, and for many years its dominant application has been the manufacture of prototypes, or Rapid Prototyping. However, the recent growth in applications for direct part manufacture, or Rapid Manufacturing, has resulted in much research effort focusing on development of new processes and materials. This study focuses on the implementation process of AM and is motivated by the lack of socio-technical studies in this area. It addresses the need for existing and potential future AM project managers to have an implementation framework to guide their efforts in adopting this new and potentially disruptive technology class to produce high value products and generate new business opportunities. Based on a review of prior works and through qualitative case study analysis, we construct and test a normative structural model of implementation factors related to AM technology, supply chain, organisation, operations and strategy.

1. Introduction

Additive Manufacturing (AM) is defined as “the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining” (ASTM Standard). Synonyms found in the literature include additive processes, additive techniques, additive layer manufacturing, layered manufacturing, and freeform fabrication. There is now a large number of technologies which employ this method of manufacture, some of the more widely used include stereolithography (SL), fused deposition modelling (FDM), selective laser sintering (SLS) and 3D printing (3DP). Since the development of many of these technologies has occurred simultaneously, there are various similarities as well as distinct differences between each one (Kulkarni et al., 2000). Reviews of the numerous AM technologies have been performed in previous works (Gibson et al., 2010; Groover, 2007; Hopkinson et al., 2006).

With over 20 years of history, in its early years AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP). These prototypes were most commonly used as communication and inspection tools, producing several physical models in short time directly from computer solid models helped to shorten the production development steps (Santos et al., 2006). RP remains the dominant application of polymer AM processes and is well established in the market. Many of the aforementioned technologies are limited to Rapid Prototyping as they do not allow common engineering materials to be processed with sufficient mechanical properties (polymers, metals, ceramics, and composites thereof) (Kruth et al., 2007). The concept of Rapid Manufacturing (RM) – “the production of end-use parts from additive manufacturing systems” (Hague et al., 2004) – is emerging today; though its economic impact remains modest (Levy et al., 2003). There are few-large scale applications of RM, many of which are for producing personalised products in the medical field (Strategic Directions, 2008). Ruffo et al. (2007) provided a summary of the pitfalls which exist for companies looking at the use of RM as a solution for current manufacturing problems or wishing to take advantage of this emergent technology, suggesting they are concentrated in three specific areas:

- manufacturing processes and materials,
- design,
- management, organisation and implementation.

These issues are inter-related and this study centres on the third of these areas, specifically focusing implementation of AM technologies for production applications. It is inevitable that some

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of the factors critical to the implementation of AM technologies are also important to the adoption of other manufacturing technologies. However, it is not the aim of this study to rediscover these issues, rather this paper seeks to build on this, adding insights into factors that are specific, or of particular importance to AM technologies due to their unique characteristics, resource requirements, benefits and tradeoffs and so on. The remainder of the paper is organised as follows. In the next section, a short overview of AM technology and applications is presented along with an introduction technology implementation theory. Then the research framework is presented with a detailed description of the constructs and supporting literature. The data collection process is then described and the results of the framework test are described. Finally, the paper closes with conclusions, limitations of the study and suggestions for future research.

2. Background

2.1. AM technologies and applications

As previously stated the numerous AM systems share some similarities but have a number of distinctions. The first AM system to be commercialised was SL, whereby a concentrated beam of ultraviolet lamp is used to solidify a liquid photopolymer by tracing a two dimensional (2D) layer in the form of a contour and then an infill. Once the beam has completed a single layer the build platform will then move downward in the *z*-axis, a new layer of photopolymer is distributed and the process is repeated until the final layer is completed. Laser sintering and laser melting processes work in a similar manner, whereby polymer or metallic powders are selectively melted in 2D layers, through high power lasers until a solid part is complete. Another popular process, particularly with hobbyists, is the FDM process. In this method, materials, usually polymer filaments are extruded through a heated nozzle to “print” 2D layers successively, one on-top of another, until the part is complete. Whether through melting of metallic powders or through extrusion of polymer filaments, all AM process share the additive principle of building components. It is possible to identify a number of key steps in the AM process sequence. Gibson et al. (2010) defines eight key steps in the generic process of CAD to part:

- Conceptualization and CAD
- Conversion to STL
- Transfer and manipulation of STL file on AM machine
- Machine setup
- Build
- Part removal and cleanup
- Post-processing of part
- Application

Holmström et al. (2010) suggest the unique characteristics of AM production lead to the following benefits:

- No tooling is needed significantly reducing production ramp-up time and expense.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Allows product to be optimised for function (for example optimised cooling channels).
- Allows economical custom products (batch of one).
- Possibility to reduce waste.
- Potential for simpler supply chains; shorter lead times, lower inventories.
- Design customization.

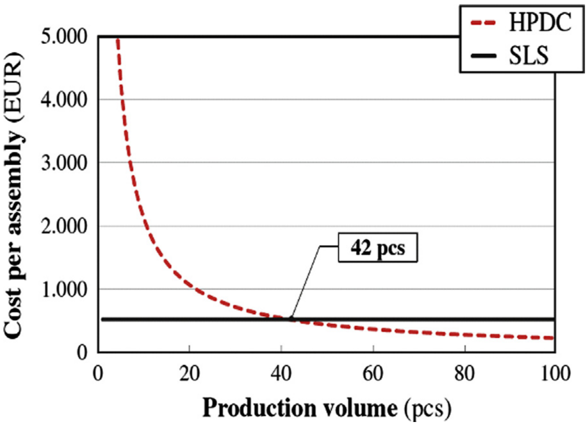

Fig. 1. Breakeven analysis performed by Atzeni and Salmi (2012) comparing HPDC and SLS processes.

These benefits have been captured in a variety of applications spanning a number of industries, and different stages of the product development life cycle. Examples include titanium aerospace parts where only 10% of the raw material is required when compared to the original machined part (The Economist, 2012). Atzeni and Salmi (2012) showed the economics of additive manufacturing for end-use parts through comparing the production of landing gear aircraft assemblies, through high pressure die casting (HPDC) and laser sintering. The authors showed the cost benefit at low to medium production volumes, illustrated in the breakeven analysis shown in Fig. 1. The benefits of AM have been captured in the production of race car gearboxes (The Economist, 2012). AM facilitates the manufacture of smooth internal path ways, providing faster gear changes and reducing component weight by 30%. Similarly, Cooper et al. (2012) illustrate the potential for improved functionality in their study on formula one technology, applying AM to hydraulic component manufacture gaining efficiency of fluid flow of 250%.

As previously stated the current dominant application for AM processes remains RP. Rapid Tooling (RT) also makes up some of the current AM activity which involves the fabrication of moulds and dies. Regarding manufacturing applications of AM processes (RM), notable areas of success include the production of medical devices such as dental crowns and hearing aids, driven by customer requirements for individualised products and AM processes having the benefit of design customization. RM has also been applied to the production of consumer products, including high value lighting goods and electronics. The aerospace sector has also found a number of applications, often driven by the possibility of improving buy-to-fly ratios (as some AM processes have high material utilisation, most notable metal-based process) and reducing the weight of components through design optimisation (Petrovic et al., 2011). Other areas include, automotive, jewellery, architecture and defence applications.

2.2. New technology implementation: theoretical background

Skinner (1984) was one of the first to propose that innovation in production technology can be used strategically as a powerful competitive weapon, suggesting that it can bring to bear many other strategic factors besides achieving low costs including, superior quality, shorter delivery cycles, lower inventories, lower investments in equipment, shorter new product development cycles and new production economics. In Porters (1985) influential work on competitive strategy he suggested technology is perhaps the most important single source of major market share changes

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