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The cost of additive manufacturing: machine productivity, economies of scale and technology-push

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ABSTRACT

As part of the cosmos of digital fabrication technology, Additive Manufacturing (AM) systems are able to manufacture three-dimensional components and products directly from raw material and 3D design data. The layer-by-layer operating process of these systems does not require the use of tools, moulds or dies.

Technology observers speculate that AM will have a profound economic impact on the manufacturing sector and indeed on wider society. By constructing a model of production cost for two different AM systems used commercially for the manufacture of end-use metal parts, Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS), this paper performs an inter-process comparison of cost performance. High specific costs, measured at £2.39 and £6.18 per cm^3 of material deposited respectively, are identified as a central impediment to more widespread technology adoption of such additive systems.

The research demonstrates differing levels of system productivity, suggesting that the observed deposition rates are not sufficient for the adoption of EBM and DMLS in high volume manufacturing applications. Despite the absence of amortisable tooling costs, the analysis also reveals that economies of scale are achievable in AM. The results reached are further discussed in the light of the varying strategic requirements posed by the market-pull and technology-push modes of innovation which are both found in the AM industry.

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1. Introduction

A key role in the emergence of new industries attributed by Porter (1980) is technological uncertainty, which is especially applicable to industries created on the basis of technological innovations (Abernathy, 1978). However, making business decisions and obtaining a competitive advantage within such emerging industries requires a robust understanding of further technological development and its future impact (Walsh, 2004). As noted by Schnaars (1989), technological predictions are "one of the most difficult kinds of forecast to make accurately. There are so many unknowns, and so many possible outcomes, that errors appear everywhere".

As part of the cosmos of digital fabrication technology, a new industry based on Additive Manufacturing (AM) technology is emerging (Wohlers, 2012). Also referred to as 3D Printing, AM technology is defined by the ASTM (2012) as capable of "joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". Several process variants exist within AM, these systems differ in terms of the raw material used and the technical principle employed to deposit the layers (ASTM, 2012), thereby gradually building up three-dimensional (3D) product geometry, entirely without tooling, moulds or cutting implements.

Technology observers and the media speculate that AM will have a profound economic impact on the manufacturing sector

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and indeed on wider society (Koten, 2013; Foroohar et al., 2013; The Economist, 2013; Von Rosenbach and Schulz, 2012). However, attempts to make predictions regarding the likely economic impact and concrete returns to technology adoption in various settings do not feature prominently in the literature. A review by Huang et al. (2013) suggests that research on the impact of the technology has so far concentrated on three aspects:

- impact on health and physical well-being;
- energy consumption and the environment;
- opportunities for manufacturing supply chain improvements.

Perhaps contrasting this, there is a consensus that technological changes, particularly those leading to measurable advances in worker productivity, are central for improvements in overall wealth and societal wellbeing (Krugman, 1999; Carlaw and Lipsey, 2003) and thereby have fundamental social impact. There is also a consensus that the principal driver behind the adoption of new technologies among the community of potential users is the net benefit resulting from the use of the new technology (Stoneman, 2002a; Foster and Rosenzweig, 2010), which may be directed to develop or sustain competitive advantage (Walsh, 2004). Applied to the commercial manufacturing sector, technology procurement activity is targeted at enhancing profits obtained by private firms (Foster and Rosenzweig, 2010; Hurkens and Wynstra, 2004). In this context, it is worth noting that the current technological status quo often exerts a significant inertia: to motivate the adoption of AM, it has been speculated that an increase in revenue of at least 30% to 40% must be projected (Bourell et al., 2009).

To obtain a broad overview of the economic benefits and disadvantages of AM adoption in the context of the manufacturing industry, it is highly instructive to consider the generic advantages and limitations associated with AM, relative to other (more conventional) manufacturing technologies (Tuck et al., 2008; Ruffo and Hague, 2007). Among such substitute technologies are injection moulding processes (Ruffo and Hague, 2007; Hopkinson and Dickens, 2003) and machining approaches (Morrow et al., 2007). Table 1 presents a set of generic advantages and limitations and associates these with likely economic effects on the firm-level. As can be seen, each generic advantage and limitation resulting from AM adoption can be associated with a value-enhancing or cost-increasing effect. Such impacts shape the technology's value proposition to the adopter and also to the community of AM product users.

This research is based on the premise that a systematic analysis of the monetary cost associated with the operation of AM, as one of the critical determinants of the net benefit obtainable from the technology's use, forms an excellent starting point for future analyses of the economic impact of AM adoption. Thus, the question leading to this paper can be posed: how does the cost structure associated with AM processes affect the development, future diffusion and wider societal impact of the technology?

An assumption that shapes much of the debate on impact of AM (see, for example, D'Aveni, 2013) is that it does not exhibit the economies of scale which form a central feature of traditional mass manufacturing approaches (Pine, 1993). This effectively characterises AM as a technology that is able to operate without pressure to decrease manufacturing cost by increasing output.

This paper adds structure to this debate. Contributing results from a cost model which satisfies the requirement of technically efficient machine operation, it presents cost estimates that are reflective of machine usage in a cost-minimising manufacturing implementation. Initially, these results can be used to assess the existing consensus that particular AM platforms are not yet able to support high volume production of end-use products (AM Platform, 2013). However, they are also useful in order to establish the cost reducing effects available from improving system productivity, challenging the assumption that economies of scale do not exist in AM.

A further relevant context for the emergence of AM is formed by the opposing concepts of market-pull and technology-push (Martin, 1994). While having its origins in the manufacture of prototypes for design verification, AM is increasingly used for

Table 1
Generic advantages and limitations associated with AM usage.

Advantages (Tuck et al., 2008)	Economic effect (opportunities)
■ Ability to efficiently manufacture geometrically complex components and products, which may exhibit comparatively higher levels of use-phase performance.	Allows the creation of highly functional and complex products (Baumers et al., 2011a; Hague et al., 2004). For end-use parts, which can be defined as durable goods, see for example Waldman (2003), this will create more economically valuable streams of services over the products' useful lives.
■ Ability to flexibly manufacture low quantities of products, down to a single unit, afforded by the absence of costs relating to tooling and changeover.	Tailoring products to individual applications, or users, effectively produces highly differentiated products which provide more utility to end-users (Wong and Eyers, 2010).
Limitations (Ruffo and Hague, 2007)	**Economic effect (constraints)**
■ Limited palette of build materials (Goodridge et al., 2012).	The use of non-standard materials produces an extra cost, either through intrinsic material properties or through price (Hague et al., 2004).
■ Slow process speed.	Increased indirect (time dependent) costs (Ruffo and Hague, 2007).
■ Poor dimensional accuracy compared to some conventional processes.	Potentially significant and expensive post-processing requirements.
■ Rough surface finish.	As previous, potentially significant and expensive post-processing requirements.
■ Problems with process predictability and repeatability.	Increased costs associated with build failure and quality (Bourell et al., 2009).
■ Cost effectiveness.	Unfavourable processes economics at medium to high production volumes (Ruffo and Hague, 2007; Hopkinson and Dickens, 2003).

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