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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 cm³ 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. ■ Ability to flexibly manufacture low quantities of products, down to a single unit, afforded by the absence of costs relating to tooling and changeover.	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. Tailoring products to individual applications, or users, effectively produces highly differentiated products which provide more utility to end-users (Wong and Evers, 2010).
Limitations (Ruffo and Hague, 2007)	Economic effect (constraints)
■ Limited palette of build materials (Goodridge et al., 2012). ■ Slow process speed. ■ Poor dimensional accuracy compared to some conventional processes. ■ Rough surface finish. ■ Problems with process predictability and repeatability. ■ Cost effectiveness.	The use of non-standard materials produces an extra cost, either through intrinsic material properties or through price (Hague et al., 2004). Increased indirect (time dependent) costs (Ruffo and Hague, 2007). Potentially significant and expensive post-processing requirements. As previous, potentially significant and expensive post-processing requirements. Increased costs associated with build failure and quality (Bourell et al., 2009). Unfavourable processes economics at medium to high production volumes (Ruffo and Hague, 2007; Hopkinson and Dickens, 2003).

the manufacture of end-use products. It is argued in this paper that the associated change of innovation context boosts the importance of unit costs and has a number of consequences for related issues such as new technology development strategy and business model innovation.

To inform this analysis, this paper establishes a detailed technical understanding of the determinants of manufacturing cost by comparing two different technology variants, Electron Beam Melting (EBM) (Arcam AB, 2013) and Direct Metal Laser Sintering (DMLS) (EOS GmbH, 2013). Table 2 summarises the two platforms analysed for this paper.

Belonging to the class of powder bed fusion processes (ASTM, 2012), both platforms are aimed at the production of end-use metal components and are used within the manufacturing industry for this purpose (Wohlers, 2012). This paper concentrates on these particular process variants for the following three reasons:

- polymeric and metallic powder bed fusion systems are seen as the most widely used additive platforms for the manufacture of highly engineered end-use products (Stucker, 2012; Ruffo and Hague, 2007);
- as opposed to several polymeric powder bed fusion systems, metallic processes such as EBM or DMLS are capable of generating material properties that match or even exceed their conventional manufacturing counterparts (Krishnan et al., 2013; Fachini et al., 2009), ensuring that material properties are sufficient for end-use applications;
- constituting metallic powder bed fusion processes that operate according to different operating principles, the technical closeness of EBM and DMLS lends itself to an assessment of two platforms featuring varying levels of productivity while maintaining similar target applications.

This paper is organised as follows: subsequent to the introduction, Section 2 briefly presents the methodology used to experimentally measure build time and energy consumption on the two assessed AM systems. Section 3 outlines a suitable cost modelling technique which is followed by a presentation of the model results in Section 4. Section 5 discusses the results reached by this inter-process comparison in the context of surrounding topics. Conclusions are drawn and recommendations for further research are expressed in Section 6.

2. Experimental measurement of build time and energy consumption

In the context of the assessment of the economic performance of AM processes, special significance is attached to the fact that the technology is capable of producing multiple, potentially unrelated parts in parallel (Ruffo and Hague, 2007). This is due to the observation that an incomplete use of the available build volume may lead to inefficient machine operation (Baumanns et al., 2011b).

To avoid such inefficiency, commercial operators of such technology in practise try to insert as many parts as possible into individual batches, or “builds” (Ruffo and Hague, 2007). Therefore, the analysis of the economic performance of such processes requires an approach based on data originating from build configurations in which the available capacity is utilised fully. To achieve this, this paper employs a computational build volume packing algorithm developed for previous research (Baumanns et al., 2013), as summarised graphically in Fig. 1. This ensures that the build operations providing the data are performed with a sufficient and consistent degree of efficiency.

To populate the build, the algorithm draws parts from a basket of representative test parts. These five test geometries, as presented in Fig. 1, have been designed to be representative of parts manufactured using metallic processes such as EBM or DMLS. It is important to point out that while the basket of parts contains digital 3D CAD designs, the actual physical parts are built using two differing processes and materials. This may lead to unintended variation in terms of mechanical performance and geometric tolerances.

On both investigated powder bed fusion systems, the inserted parts must be connected to the systems’ build platforms, either by direct placement or through sacrificial anchor structures (Mumtaz and Hopkinson, 2011). Hence, the employed packing algorithm was configured to a packing mode arranging parts on the X/Y plane of the build platform. The anchor structures were designed before the builds by the system operators in a platform-specific automatic process.

The presented cost model is based on the actual weight of the parts generated during the build experiments on the DMLS system; hence the material consumed to create the anchor structures is taken into account. Fig. 2 shows the packing configurations generated for both systems using the build volume packing algorithm.

Table 2
Specifications of the analysed systems.

	Electron Beam Melting (EBM)	Direct Metal Laser Sintering (DMLS)
System model	S12	EOSINT M 270
Beam type	Electron beam	Yb-fibre laser
Beam power	3500 W	200 W
Build material used for this research	Titanium, Ti-6Al-4 V	Stainless Steel, 17-4 PH
Material density	4.43 g/cm ³	7.78 g/cm ³
Nominal build volume size, X × Y × Z	250 mm × 250 mm × 200 mm	250 mm × 250 mm × 215 mm
Usable build area, X × Y	200 mm × 200 mm	225 mm × 225 mm
Layer thickness	70 µm	20 µm
Process atmosphere	Vacuum (with the addition of Helium)	Nitrogen
Part retrieval	Automatic separation from steel substrate through thermal expansion	Wire erosion
Manufacturer reference	Arcam AB Arcam AB (2013)	EOS GmbH EOS GmbH (2013)

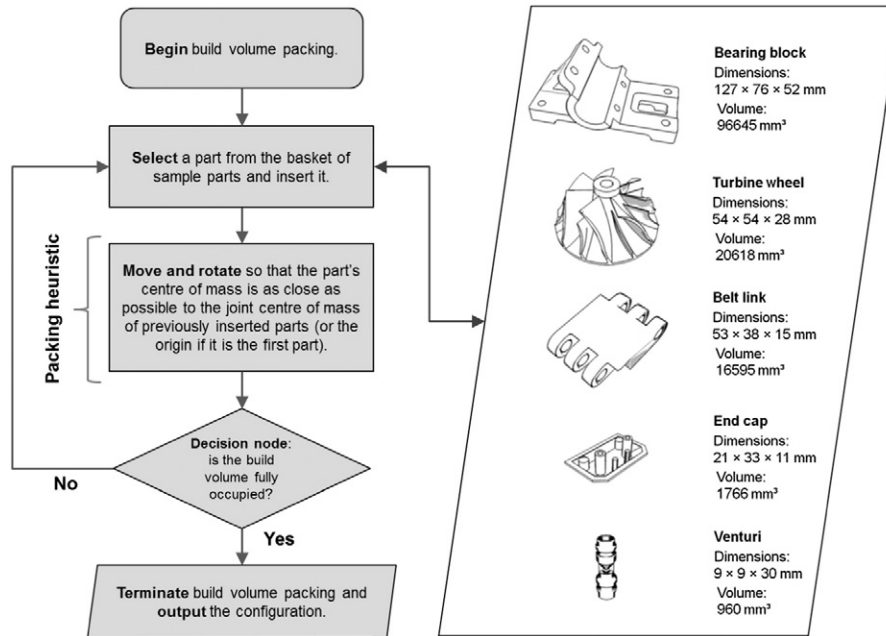


Fig. 1. Flow chart of the packing algorithm and a summary of the test parts, adapted from (Baumers et al., 2013).

Table 3 summarises the composition of the full builds shown in Fig. 2 and indicates packing algorithm performance in terms of the ratio of occupied to available build volume floor area, measured in terms of discrete (5 mm)³ voxel elements. It should be noted that this two-dimensional measure is not reflective of the utilisation of the available build volume cuboid itself. The very similar build volume occupation measures (93.00% vs. 92.59%) indicate that the build volume packing algorithm has exhausted the available capacity almost equally well on both systems.

On the basis of these two build configurations, total build time T_{Build} (including system start up and cool down) and total energy consumption E_{Build} (including process cooling) are experimentally measured for the EBM system using a Yokogawa CW240 digital power monitoring system. The corresponding estimates for the DMLS system are obtained

from the previous study employing the same methodology (see Baumers et al., 2013).

3. Construction of an AM cost model

As AM is a capital-heavy manufacturing technology, process time forms an important driver of manufacturing cost. Correspondingly, several AM cost models are based on build time estimators (Alexander et al., 1998; Hopkinson and Dickens, 2003; Byun and Lee, 2006; Ruffo and Hague, 2007; Di Angelo and Di Stefano, 2011; Atzeni and Salmi, 2012). Ensuring technical efficiency has been shown to be necessary for models of AM resource consumption (Baumers et al., 2011b). Therefore, the approach used in this research has been augmented by adding build volume packing functionality

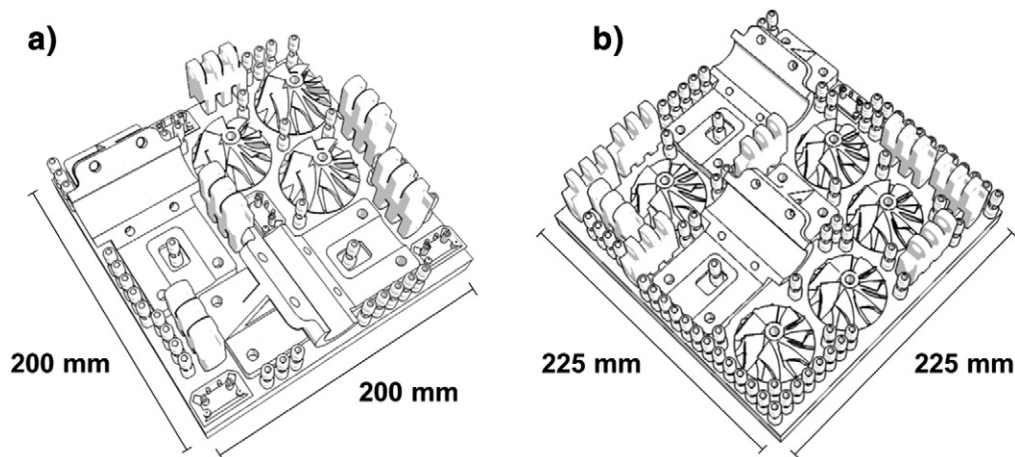


Fig. 2. Full capacity utilisation for EBM (a) and DMLS (b).

Table 3

Composition of the build experiments.

	Total parts contained	Bearing block	Turbine wheel	Belt link	End cap	Venturi	Ratio of occupied build volume floor voxels
EBM (Arcam S12)	53	2	3	5	4	39	93.00%
DMLS (EOSINT M270) (Baumers et al., 2013)	85	2	5	8	1	69	92.59%

to model the technology's industrial usage for the parallel manufacture of multiple, potentially unrelated, products. This is especially relevant when making comparative statements on AM process performance.

The cost model used in this paper draws on two direct costs of manufacturing, raw material cost and energy consumption, which are combined with the total indirect (time-dependent) costs incurred during the build. The total cost C_{Build} of the build can be expressed as:

$$C_{Build} = (\dot{C}_{Indirect} \times T_{Build}) + (m \times Price_{Raw\ material}) + (E_{Build} \times Price_{Energy}) \quad (1)$$

where $\dot{C}_{Indirect}$ is the total indirect cost rate, measured in £/h, T_{Build} and E_{Build} are the estimates of build time and energy consumption respectively, m is the mass of all parts including sacrificial anchor structures, $Price_{Raw\ material}$ is the price of the metal powder, measured in £/kg, and $Price_{Energy}$ is the electricity cost, measured in £/MJ.

Table 4 summarises the published data used in this inter-process comparison. As can be seen, a number of costs are shared between both systems, such as overheads, labour, depreciation periods and utilisation rates. These are viewed as highly similar across both platforms, which is a simplifying assumption. Note that all monetary cost data used in this research are expressed in 2010 pounds sterling (£).

It is also noteworthy that cost models of this type exclusively reflect what can be defined as well-structured costs (Son, 1991). Ill-structured costs relating to quality, build failure and logistics, which may be very relevant within AM (Bourell et al., 2009), are excluded from the analysis.

4. Presentation of experimental results

This section presents the results of the build experiment on the EBM system and compares them to matching data generated during previous research on the DMLS platform (Baumers et al., 2013). Details of the build time and energy consumption elements are shown in Table 5, together with estimates of the full costs of the two builds, calculated according to the above cost model (Eq. (1)). Note that despite the EBM system's substantial warm up and cool down procedure, which the DMLS platform does not require, the total build time T_{Build} measured on the EBM system was much shorter (25.65 h vs. 107.79 h). Corresponding to this, the total energy consumed, E_{Build} , during the full build experiment was also significantly lower (200.80 MJ vs. 917.10 MJ).

EBM's advantage in process speed leads to a shorter build time, 20.97 h vs. 107.77 h, and results in a higher build rate, 15.63 cm³/h vs. 4.83 cm³/h. This can be identified as the central reason for the lower total cost and energy consumption estimates.

Two further technical remarks should be made at this point. Unlike the DMLS system, EBM does not require an ancillary wire erosion process to remove the parts from the substrate after the build is complete. In EBM, the titanium parts separate from the steel build plate during cool down due to differences in thermal expansion behaviour. Moreover, the low density of the Ti-6Al-4 V material used ($\rho = 4.43$ g/cm³, see Table 2) has also led to comparatively moderate raw material costs, despite the high specific cost of the material (156.97 £/kg, see Table 4).

Fig. 3 breaks down the total cost of both full build experiments in graphical form, illustrating the dominance of machine costs for both systems, which are build-time dependent.

Table 4

Data used in the cost model.

	EBM	DMLS
<i>Production overhead*</i>		
Rent, building area cost	4.53	£/h
<i>Administration overhead*</i>		
Hardware purchase	1,670.27	£
Software purchase	1,670.27	£
Hardware cost/year	334.05	£
Software cost/year	334.05	£
Consumables per year	1,113.52	£
Total administration overhead	0.31	£/h
<i>Production labour*</i>		
Technician annual salary	25,165.45	£
Employer contributions	22.00	%
Total production labour	6.14	£/h
<i>Utilization*</i>		
Utilization rate	57.04	%
Annual machine operating hours	5,000.00	h
<i>Equipment depreciation*</i>		
AM equipment and wire eroder	8	Years
Hardware and software	5	Years
<i>Machine costs</i>		
Machine purchase	348,772.73	£
Machine purchase cost per year	43,596.59	£
Maintenance per year	27,758.69	£
Consumables per year	5,783.06	£
Wire erosion machine purchase		55,000.00
Total wire erosion costs per year		8,165.00
Total machine costs per year	77,138.34	£
Total machine costs	15.43	£/h
Total indirect costs per machine hour ($\dot{C}_{Indirect}$)	26.41	£/h
Direct cost for build material powder ($Price_{Raw\ material}$)	156.97	£/kg
Direct electricity costs ($Price_{Energy}$)	0.018	£/MJ

*Adapted from Ruffo et al. (Ruffo and Hague, 2007), converted into 2010 pounds sterling (£).

Table 5

Build time, energy consumption and cost results.

Category	Break down	unit	EBM	DMLS Arcam (2013)
Build time	Warm up (h)	h	1.69	0.02
	Build time (h)	h	20.97	107.77
	Cool down (h)	h	2.99	N/A
	Total build time, T_{Build} (h)	h	25.65	107.79
Energy	Energy consumed, E_{Build} (MJ)	MJ	200.80	917.10
	Production overhead	£	116.19	488.27
	Administration overhead	£	7.95	33.41
	Production labour*	£	157.49	661.81
	Machine costs	£	395.78	1511.75
	Wire eroder costs	£	N/A	176.02
	Raw material costs	£	278.78	328.40
Direct costs	Electricity costs	£	3.61	16.51
	Total cost of build, C_{Build}	£	959.81	3218.87

*Assuming 100% operator attendance during the build process (Ruffo and Hague, 2007).

As a summary metric for the comparison of manufacturing cost, the total cost per cm^3 of material deposited is useful. This specific cost metric can be calculated by attributing total cost, C_{Build} , to the total volume of manufactured parts, net of anchor structures. The build experiment performed on the EBM system resulted in a total specific cost of 2.39 £/cm^3 which is far lower than the result for DMLS of 6.18 £/cm^3 .

In this context, a crude, yet interesting, measure illustrating the two technologies' efficacy in turning raw material and energy into products is the ratio r of all direct costs over total cost, C_{Build} , which can be obtained at follows:

$$r = \frac{(w \times \text{Price}_{\text{Raw material}}) + (E_{\text{Build}} \times \text{Price}_{\text{Energy}})}{C_{\text{Build}}} \quad (2)$$

For the experimental results reached on the EBM platform, the result is $r = 0.42$, suggesting that for every pound spent for this processes, raw materials and energy worth £0.42 are converted into products (and anchor structures). This ratio appears less favourable for DMLS, at $r = 0.12$, suggesting that

DMLS is less effective in the conversion of raw materials and energy into products. This result matches data available for the same DMLS machine (Atzeni and Salmi, 2012), indicating that approximately 10% of component cost is attributable to raw material.

Thus, the presented results show that system productivity has a very significant effect on the cost performance of the assessed AM processes. Noting that two different build materials are used, the mass-based material deposition rate observed on the S12 EBM system (69.24 g/h) is 84% greater than that observed on the M270 DMLS system (37.58 g/h). This demonstrates that system productivity is a central driver of manufacturing cost on these variants of AM technology. This result is supported by data available for more up-to-date versions of the surveyed AM systems (Rengers, 2012).

5. Contextualisation of the experimental results

After assessing the build speed and cost performance of two major AM platforms, it is now interesting to put these results into the context of the wider literature. Three themes of particular interest have been identified for this research: i) system productivity as a main driver of cost, ii) the evidence for process-borne economies of scale and iii) the importance of the concepts of technology-push and demand-pull innovation for the further emergence of the AM industry.

5.1. System productivity as a driver of cost in AM

The inter-platform comparison between EBM and DMLS has provided evidence that system productivity is a main driver of manufacturing cost. Deposition rates of 37.58 g/h (DMLS) and 69.24 g/h (EBM) were measured, resulting in mean cost estimates of 6.18 £/cm^3 (DMLS) and 2.39 £/cm^3 (EBM). For conventional manufacturing processes such as machining or injection moulding, Gutowski et al. (2009) report typical process rates of well over 100 kg/h . Acknowledging the substantial difference between AM and conventional processes, it has been argued (AM Platform, 2013) that due to

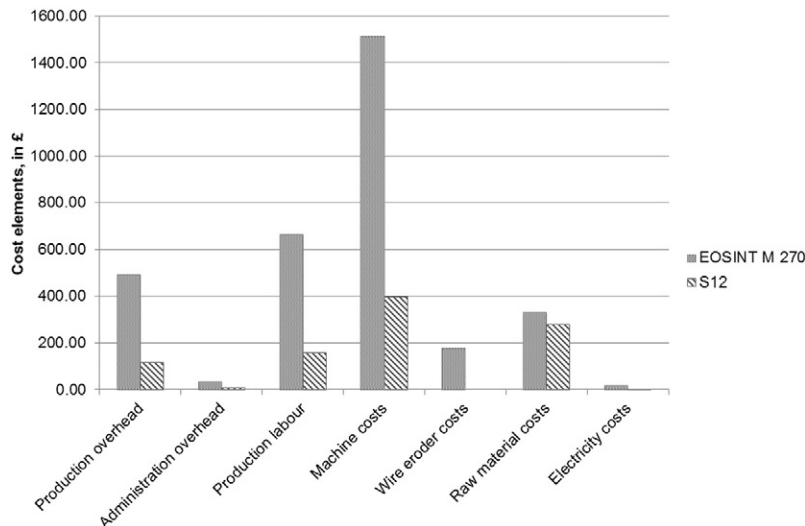


Fig. 3. Costs of EBM (S12) and DMLS (EOSINT M 270) broken down.

productivity limitations, current AM systems are almost in all cases unable to support high-volume production.

Further refinement to this point can be added by arguing that even if the average unit cost of the output could be depressed by reducing the system purchase price, rather than increasing system productivity, the overheads resulting from running a large number of unproductive systems may result in prohibitive total expenditure. For this economic barrier to be overcome, it is therefore suggested that the deposition rates exhibited by AM systems should be closer to those found in conventional manufacturing (AM Platform, 2013).

This points to the conclusion that as long as deposition rates are high enough to amortise the machine costs over a sufficiently large number of units, the purchase price of an AM system is not of primary importance. Therefore, in the development of next-generation production-ready AM systems, the focus should lie on reducing the various operating costs rather than on the purchase cost of the AM equipment itself. This statement is supported by results on the effect of system upgrades on the cost performance of a polymer jetting-based AM platform (Baumers et al., 2014), concluding that deposition speed and build volume size increases would yield the greatest cost reducing effects.

5.2. Process-borne economies of scale

Economies of scale are defined as situations in which businesses are able to decrease the average unit cost by increasing total output. On the level of manufacturing processes, such economies can arise for two reasons (Haldi and Whitcomb, 1967): i) there are indivisibilities of individual items of equipment or workers and ii) throughput may more than proportionately increase if systems are physically scaled up, or alternatively, if their throughput is increased (Pine, 1993).

Unlike AM, the cost structure of conventional tooled manufacturing processes is often shaped by tooling expenses that are amortised over production runs (Ruffo and Hague, 2007; Atzeni and Salmi, 2012). This produces economies of scale arising from indivisibilities. As AM processes never employ tooling, cutting implements, moulds or dies, such process-borne scale economies based on the use of dedicated tooling are absent.

Moreover, as such tooled processes are mostly confined to large and centralised manufacturing plants, it has been argued that the wide-scale adoption of AM would diminish the importance of such economies of scale and enable the decentralisation of manufacturing to points of consumption (D'Aveni, 2013; Petrick and Simpson, 2014). However, it has also been suggested that the appropriate extent of supply chain decentralisation, and with it the degree of supply chain innovation, will be the results of strategic deliberation by the adopter (Cotteleer and Joyce, 2014).

Using experimental data collected for two AM process variants, this paper demonstrates that, while sunk tooling costs are indeed absent, more productive platforms exhibit lower average unit costs. Further, it must be expected that increasing the dimensions of the available build volume is likely to result in lower average cost as certain fixed process elements, for example warm-up or cool down, can be amortised over a larger build volume (Baumers et al., 2014). This point is supported by the recent commercialisation of AM systems with larger capacity (see, for example, Arcam AB, 2013; EOS

GmbH, 2013; ConceptLaser GmbH, 2014). In addition, AM processes currently under development aim to further increase productivity by making the build process more continuous (Project Ara, 2014; TNO, 2011) or even deposit build material on multiple layers simultaneously (Silverbrook Research, 2010).

This research demonstrates clearly that economies of scale are a reality in AM through increased machine throughput or physical scaling-up. This is an important issue for the diffusion of AM into higher volume applications and expected to be especially relevant within industries marked by the dominance of high fixed costs (Christensen, 2001) and the existence of significant economies of scale which drive down unit costs and deter new market entrants. Among these are the automotive industry (Husan, 1997), consumer goods (Hughes, 1999) and logistics (Cullinane and Khanna, 1999). Therefore, speculation that AM processes may intrinsically be at a disadvantage in high-volume industries appears premature. It is also imaginable that the elimination of tooling resulting from the adoption of AM removes significant front end fixed costs associated with the introduction of new products, thereby promoting product innovation.

5.3. Demand-pull versus technology-push innovation

According to Hull (2012), the first variant of additive technology, stereolithography, was developed in response to the clearly identified market need to speed up the creation of design prototypes. Such explicit needs form a central characteristic of the demand-pull mode of innovation (Martin, 1994). With a narrow aim on automating the prototyping process, the technology, known then as Rapid Prototyping, quickly gained market share in these applications.

The following major step in the evolution of the AM industry was the introduction of the notion that these new technologies could be used as manufacturing processes for end-use products (Rudgley, 2001; Hopkinson and Dickens, 2001). Proposing additive techniques for the manufacture of final products had two consequences: Initially, this greatly expanded the potential market in which AM could be adopted, promoting a specific process for prototyping applications to (in principle) almost limitless applications as a general purpose manufacturing technology.

The second, perhaps more subtle, consequence was that a prototyping technology was now proposed for manufacturing settings for which it was not designed. Differences in the mentality associated with the requirements of prototype creation, rather than finished products, have been emphasised (Bourell et al., 2009). Within AM processes, the 'prototyping mind set' has manifested itself in the observed generic barriers to AM adoption (summarised in Table 1), including lacking cost effectiveness compared to conventional processes.

Where an innovation has been induced by technological capability rather than expressed market need, the concept of technology-push applies (Martin, 1994). This suggests that as Rapid Prototyping evolved into AM, the accompanying mode of innovation rolled over from the demand-pull of the prototyping industry to the conceptual opposite of technology-push in the manufacturing industry. This paper argues that unit cost levels low enough to compete with incumbent high volume conventional manufacturing processes did not feature in the market-pull of prototyping applications. However, following the

Table 6

Consequences of the transition to AM (adapted from Brem and Voigt, 2009).

	Rapid prototyping (demand-pull)	AM (technology-push)
Uncertainty of technology	Low	High
Required R&D funding	Low	High
Duration of R&D programmes	Short	Long
Market related uncertainty	Low	High
Time-to-market	Known	Uncertain/unknown
User integration into R&D	Easy	Difficult
Mode of market research	Verification	New discovery
Need for user business models to adapt	Minimal	Extensive

emergence of the concept of AM, the switch to true manufacturing applications has placed a significant focus on this aspect.

The identification of this pattern leads to the question of whether ongoing AM technology development efforts and accompanying complementary innovation in supporting input markets are appropriate for AM's innovation context. This is of relevance as it has been suggested that such a transition is likely to have significant consequences for various aspects of strategy in an emerging industry (Brem and Voigt, 2009). Table 6 maps out possible consequences for the AM industry.

Due to the large number of potential applications for AM in the general manufacturing sector, this paper takes the position that there is also high market uncertainty once the economic barriers described in this paper have been overcome. According to the framework presented in Table 6, the appropriate response includes investing heavily in background and exploratory research, engaging the future technology users in the innovation process, and to explore novel business models.

6. Conclusions

The cost model constructed in this paper for EBM and DMLS demonstrates that machine productivity forms a main driver of per-unit manufacturing cost. It also suggests that this contributes to a general cost barrier to technology diffusion of AM into mainstream manufacturing. This research has measured low process rates, ranging from 37.58 g/h (DMLS) to 69.24 g/h (EBM), which are substantially lower than those cited for conventional manufacturing technologies (Gutowski et al., 2009).

The observed differences in machine productivity also highlight that economies of scale of the type based on increased throughput are achievable in AM. This forms an important qualification of some of the narratives currently surrounding AM, arguing that economies of scale will cease to exert their competitive pressure after an extensive diffusion of AM technology. Moreover, as part of the emergence of industries, the gradual achievement of economies of scale is a common structural characteristic (Porter, 1980). It is expected that further development of AM technology will enable significant improvements of system productivity and reduced unit costs.

This paper has further argued that the concepts of market-pull and technology-push are helpful in understanding the relationship between Rapid Prototyping and AM. The difference in mode of innovation is relevant for progressing technology diffusion and to enable the manufacturing industry

to successfully capture value from AM. An initial survey of the varying strategic requirements originating from the market-pull and technology-push environments for the innovation process is provided using the framework by Brem and Voigt (2009). This suggests an increase in the technical and market uncertainty resulting from the emergence of the concept of AM.

The economic growth literature (see, for example, Krugman, 1999; Carlaw and Lipsey, 2003) and work on the diffusion of innovations (Rogers, 2003; Stoneman, 2002b) places a great emphasis on the economic impact of new technologies. As this research has only looked at the cost side of a selection of AM platforms, a projection of the technology's overall future impact will also require an analysis of benefits available from novel process/design/material combinations enabled by AM. Such an analysis could be performed through a series of in-depth case studies, including detailed assessments of the functional life-cycle benefits of new product designs. These results could then be generalised to the aggregate levels of the firm, industry and region for an assessment of the likely trajectory of AM technology diffusion and its economic impact.

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