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ADDING PRODUCT VALUE THROUGH ADDITIVE MANUFACTURING

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ABSTRACT

The term additive manufacturing (AM) refers to layer-based material addition technologies that have extended the approach of rapid prototyping (RP) technologies to end-use products and components. The application of AM technologies for this purpose is still rather limited at present but there are a few widely publicised examples. The authors believe that the wider use of AM is being inhibited by the inability of most designers to fully appreciate the contribution that AM can make to E3 (economic, ecological and experience) product value. Research at (removed for anonymity) has indicated that AM can contribute in each of these areas. This paper defines E3 value and then gives some examples of AM products that demonstrate different means of improving value. The conclusions drawn are that AM has an important role to play in adding E3 value to many products but that designers must be better informed as to how to integrate this added value into their designs.

Keywords: additive manufacturing, product value, design practice, product-service systems

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1 INTRODUCTION

Using the E3 approach, product value can be categorised into economic, ecological and experience value. For a product to be successful in a highly competitive global market, it is necessary to maximise all three of these. There are well established techniques for evaluating and improving E3 values as explained by Kim et al. (2011). However, there are instances when design for manufacture and assembly (DfMA) considerations will limit the designer in his or her pursuit of maximum value. For example, aesthetic appearance may be comprised by the need for an injection moulding split plane. Additive manufacturing (AM), also known as 3D printing, eliminates many of these DfMA considerations and offers the designer unprecedented geometric freedom (Hague et al., 2003). It also removes the requirement for tooling and, in certain circumstances, has been shown to have less environmental impact (Drizo and Pegna, 2006). Although AM processes are expensive to operate, they offer reduction in whole life-cycle costs. These factors rewrite the business case for low production volumes and distributed manufacturing. Some designers, for example Janne Kyttenen (FOC, 2013) and Lionel Dean (FF, 2013), have been very successful in exploiting this enhanced design freedom to create high value added products specifically tailored to AM processes. The authors of this paper believe that there are many more product families that could benefit from the use of AM to enhance their E3 value.

The problem that needs addressing is that there is currently no systematic tool available to designers who want to know how best to improve E3 product value through using AM. Therefore, this paper attempts to demonstrate the need for and potential benefits of such a design tool by giving examples of how AM can add different categories of E3 value to different types of products. It does this firstly by presenting an overview of how this can work, followed by two more in-depth case studies that provide quantitative evidence for this. Future research will concentrate on developing a prototype tool for professional and student designers.

2 PRODUCT SERVICE SYSTEMS AND E3 PRODUCT VALUE

As market competition is getting more intense and technological differentiation becomes difficult, design for new value has been recognized as the emerging paradigm and yet has received attention in research. With the increased attention on human-centeredness, an integrated viewpoint of products and services rather than a product-service dichotomy should be emphasized. Whatever users want should be fulfilled with product or service elements together in the way of a total solution or functional offering. Technological progress such as information and communication technology (ICT) and ecological recognition on sustainability accelerate the integration of products and services as well (Kim et al., 2009).

Value is considered as a complex and ambiguous concept in various research fields. The evolving service centered logic for marketing (Lusch and Vargo, 2006) puts an increased emphasis on value, especially the value perceived by the customer or market. Service centred logic also means that co-creation of value with customers and other stakeholders of the firm through service experiences and relationships is critical. During the design process of products, services, or product-service systems (PSS), value research can help in identifying customer wants and needs early in the ideation or fuzzy front end. It can identify factors or attributes that influence customer judgments, determine the relative importance of value-related attributes, and determine how offerings are viewed on each of these attributes relative to the customer's alternatives (Miller and Swaddling, 2002). E3 is a relatively new value concept that has been conceived to reflect the requirements and needs of the customer. Economic value includes both cost reduction and income enhancement, which can be achieved through product differentiation, market creation, customer acquisition and retention. Ecological value addresses issues such as energy and water saving, dematerialization, reducing hazardous materials, reuse and recycling. Experience value deals with more people-oriented viewpoints including extrinsic and intrinsic aspects (see Figure 1). The contribution that AM can make to each of these is discussed in the following sections.

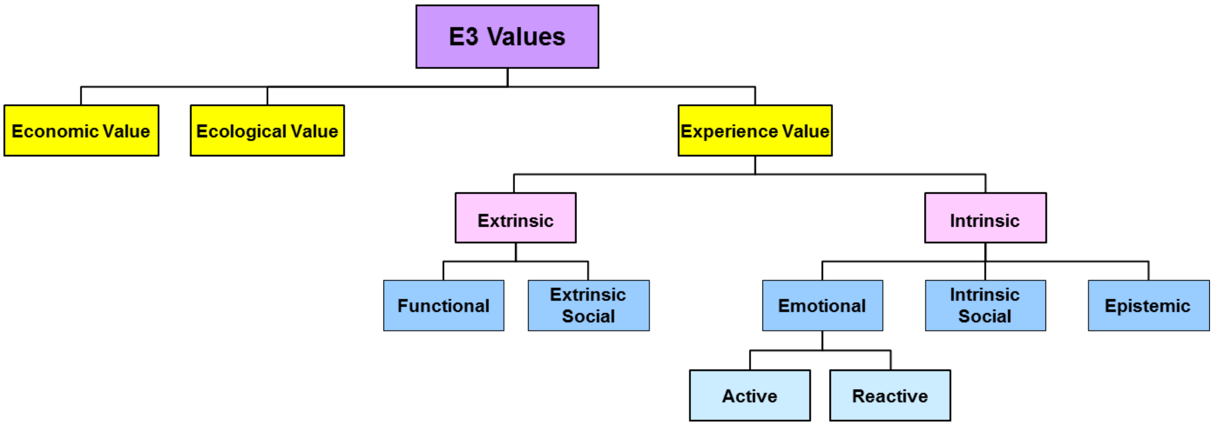

Figure 1. Different categories of E3 values (Cho et al., 2010)

3 USING AM TO ADD ECONOMIC VALUE

AM can contribute to both cost reduction and income enhancement.

3.1 Cost reduction

AM has a contribution to make in terms of reduced product cost in at least two ways. Firstly, where a large percentage of the product cost comes from multiple assembly operations, AM can be used to reduce component count. Assembly is often a labour-intensive process that adds substantially to the overall manufacturing cost. On top of this, the cost of storing and administering separate components is a wasted expenditure. Therefore, there is a great drive to reduce component count where possible. Conventional design for assembly (DfA) thinking indicates that separate components are needed when there is relative movement between parts, different materials are needed or to provide access for assembly or disassembly operations, e.g. a cover that is attached once all the internal components have been inserted. However, the lowest possible number of components is often not reached because design for manufacturing (DfM) considerations point towards less geometrically complex components with fewer functions.

AM has the ability to create virtually any geometry, which means that more complex shaped components, performing multiple functions, can be produced. Such components can replace a number of simpler components held together with multiple fasteners. An example of this is the tractor control pod casing shown in Figure 2. The new AM casing design was a single component design whereas the previous design had a separate lifting handle, armrest, sub-frame and three outer covers.

Figure 2. Single component tractor control pod casing (Burton, 2005).

AM can also produce “ready assembled” products. That is, internal components within an assembly can be produced simultaneously with the external casing, even if they have relative movement. Therefore, an extra cover component is not required to “close-up” the product after assembly. This is acceptable in single-use, no maintenance products but where future access for servicing or replacing components, this would not be advisable. Multi-material AM is growing in capability, e.g. components with stiff regions similar to an engineering plastic and flexible regions similar to an elastomer. Such parts are currently only suitable for prototypes but will eventually be suitable for production. This could eliminate the need for separate seals around a component. Multiple metal or metal/ceramic AM is also being researched which could lead to further component consolidation. Provided the reduction in component count did not adversely affect customer satisfaction in any way, a less expensive to make assembly could be sold for the same price.

3.2 Income enhancement

In terms of income enhancement, AM's main contribution is towards product differentiation and, to some extent, market creation. It does this through its ability to replace mass produced parts with batch production where batch size can be as low as one. This enables manufacturers to create many different versions of their products aimed at different markets and to facilitate product customisation (perhaps creating new niche markets). In general, customisation can be thought of as the process of taking a general product design concept and tailoring it to the needs of a specific customer. However, there are different types of customisation and consequently, different methods of achieving it. At one extreme there is the notion of producing a bespoke product that has been designed from its outset with one customer in mind and aims to satisfy the requirements of that individual and no others. An example of this could be a uniquely commissioned piece of jewellery that will never be replicated. At the other extreme is the modification of one feature of an otherwise standard product. Somewhere between these two extremes will be the method of modularisation where a highly customised product can be generated by selecting from several ranges of available options. The relationship between the type of customisation and number and range of available options is shown in Figure 3.

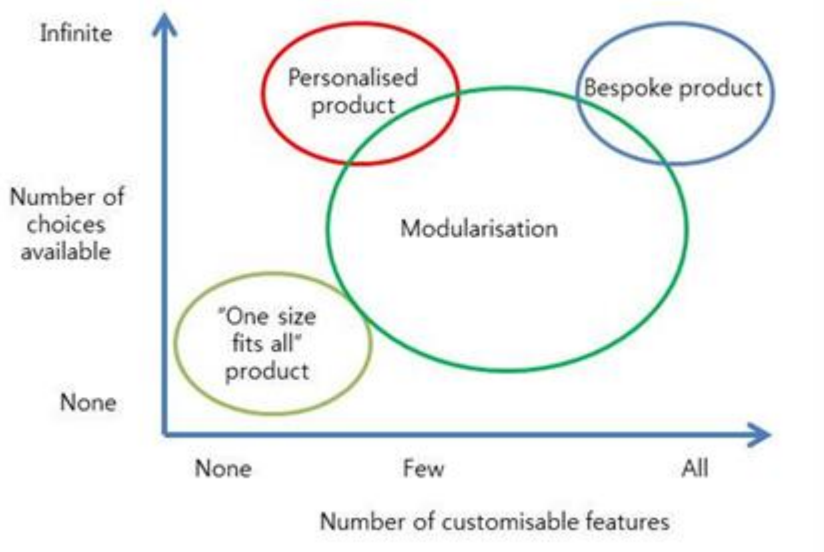

Figure 3. Different types of customisation.

Additive Manufacturing lends itself to all types of customisation but is perhaps best suited to creating an infinite number of choices for one or a few features, which could be termed "personalisation". The customisation of the product could be in terms of different functionality, different aesthetics, different user-fit, etc. Every product made using AM would be unique in some way. This effectively means that manufacturing would be on a "batch size of one" basis, something that AM can handle more easily than conventional manufacturing processes. This does not necessarily imply that products would be made one at a time, but rather that many variations of the product could be made simultaneously. The geometry of some of the product's components would be changed in response to customer requirements. For components that were not to be customised, e.g. for safety reasons, these could be made in larger batches and assembled with the AM components to produce the final product. Product value would be added through the fact that customers will often pay a premium price for a product that they know is uniquely theirs. Perhaps the best known example of is the production of customised hearing aids using AM . This application uses an imprint of the individual's outer ear together with reverse engineering to produce a uniquely shaped hearing aid design. This is then built directly using

AM technology. The end result is a product that fits the user’s ear exactly. It is estimated that over 10 million of these products have been made using AM (Materialise, 2012). This application is successful for two reasons. Firstly, the small size of the product means that many can be built at the same time and therefore manufacturing costs are reduced (particularly since no tooling is required). Secondly, most customers are prepared to pay a premium for such a “tailor-made” device. Both of these reasons contribute to the product having a higher added-value than a conventionally manufactured item.

4 USING AM TO ADD ECOLOGICAL VALUE

To establish sustainable development and sustainable consumption, many governments have given guidance to companies or consumers by enforcing regulation or through information campaigns (Cho et al., 2010). AM can help manufacturers to increase a product’s ecological value in a number of ways. The fundamental working principle of most AM systems is that they only use the amount of material actually needed for part fabrication with little or no material wastage, unlike subtractive processes which create chips or swarf. Unused material in the build chamber can often (but not always) be recycled for future use. A further material saving can be made through component shape optimization, which enables the same function to be undertaken using less material. An example of is the diesel fuel pump housing shown in Figure 4 where the ghosted outline is the original design and the solid outline is the optimised shape. (An added improvement is the optimised shape of the flow channels which would also improve pumping efficiency – see section 5.1). Such a complex shape would be difficult to manufacture using conventional processes, e.g. casting, but with AM is entirely feasible. The reduced weight of the component would also result in less fuel being used throughout the lifetime of the vehicle on which the pump is mounted, yielding a further ecological benefit.

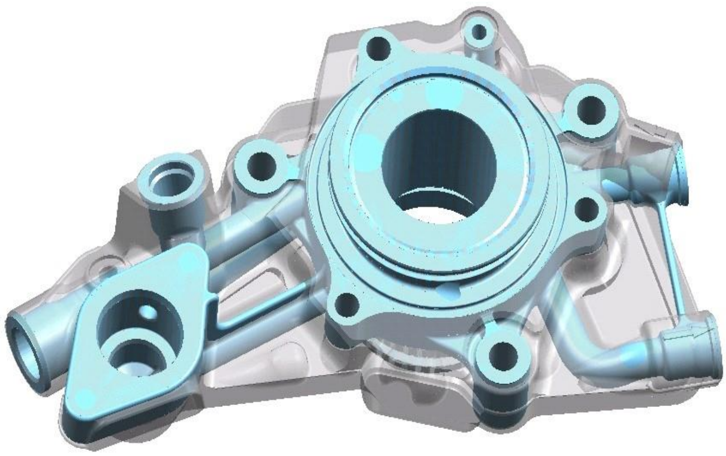

Figure 4. Shape optimization for AM (Hague, 2005).

As well as offering a saving in energy during the use of a product, some AM systems have also been shown to use less energy overall than conventional manufacturing processes, particularly for low volume production (Telenko and Seepersad, 2012). This is because the high level of energy going into the production of tools is avoided, since AM requires no tooling. However, as the size of the production run increases, so the impact of the tool energy decreases and the energy consumption of AM becomes less favourable.

5 USING AM TO ADD EXPERIENCE VALUE

According to a recent special report on service design, people are becoming less interested in “stuff” alone – products or commodities – and far more interested in an all-embracing experience as they interact with a product or service (Guardian, 2010). Pine and Gilmore (1998) argue that experiences represent the next step in the evolution of economy as products and services become more commoditized. Creating value in such an environment requires staging memorable experiences that unfold over time. Experience can be characterized by a more dynamic use environment, customer participation and social interaction. Therefore, designing the experience should be focused on how participation and interaction can be enhanced to create a successful experience by designing activities, physical layout, and social interaction (Gupta and Vajic, 1999). As previously mentioned, such an experience will have both extrinsic and intrinsic values.

5.1 Extrinsic experience value

AM can have most influence on the extrinsic experience value of a product through improving its functionality, i.e. making it perform better. In the field of mechanical engineering, the functionality of a product is often directly related to its shape. A prime example of this is turbine blades within a jet engine. The gas flow is determined by the exterior blade profile and the temperature resistance by the shape of the internal cooling cavities. With conventional manufacturing processes, component shape is often constrained by the capability of the particular process used. This is especially true for complex internal geometries. However, with AM there is far less restriction in the shape that can be produced. As a result, the geometry can be fully optimised for functionality rather than comprised by the need for design for manufacture. So, in the case of the aforementioned diesel fuel pump, the internal flow passages could be made more efficient with curved corners rather than sharp changes in direction as in the original design. Another aspect of AM that could lead to increased product functionality is the ability to produce components with variable material composition. At the simplest level, this could be a variation in porosity of AM parts. Parts would be densest where strength is most required and elsewhere the lower densities would yield a weight saving. At a more advanced level, different combinations of materials could be used in different parts of a component. For example, one section of a metal part could be enriched with copper to aid heat conductivity whereas another section could have a ceramic added to improve wear resistance. This is known as functionally graded material (FGM) composition and is not yet widely implemented within AM. However, if successfully introduced in a commercial AM system, it could revolutionise the manner in which components are designed to meet specific functional requirements.

5.2 Intrinsic experience value

An important aspect of intrinsic experience value is emotional value. The present E3 value framework divides emotional values into ‘active’ and ‘reactive’ emotions in accordance with Holbrook’s classification of active and reactive values (Holbrook, 1999). Active emotions can be further divided into such value themes as happiness, anger, love, fun, relief, achievement, control/power and trust while reactive emotions can be in reaction to aesthetics and elegance. Reactive emotional values frequently pertain to products or services, while active emotional values are more related with the customer’s intention and concern. Something that looks good, feels good, or sounds good would provide reactive emotional values, whilst pride and achievements are active emotional values themes. Within this context, AM can contribute to improved emotional value by giving the designer more freedom for aesthetic exploration. The need to compromise aesthetics to make manufacturing easier is removed. An excellent example of this is the jewellery designs created by Lionel Dean (FF, 2013). Dean uses the geometric freedom given by AM to create pieces, which might be possible with conventional processes but would be prohibitively expensive (see Figure 5). The result is an aesthetic that generates strong emotions within the customer and a high level of desirability for the product. Such products can usually command higher prices than those with simpler geometries.

6 CASE STUDIES

Having provided an overview of how AM can increase E3 Product value, there now follows two detailed case studies where a quantifiable increase in value has been demonstrated.

6.1 Laser sintered electronics enclosures

Laser sintering is one of the most commonly used AM processes (Wohlers 2012) and can be used with a range of materials including metals and thermoplastics. Laser sintering works through the fusion of powdered material into solid parts, one layer at a time. Unlike many AM systems, laser sintering does not require extra supports (at least when used or polymers) and therefore lends itself to creating highly complex part geometries. This is because the unfused powder in each layer is left in place and forms a supportive matrix around the finished parts. In this work, laser sintering of polyamide was used to create a new range of electronics enclosures for use with a motion capture and analysis system (Campbell and de Beer 2008). The use of AM was particularly appropriate because the company making the parts had a relatively small market (hundreds of parts per year) and there was a great need to reduce assembly costs, possibly by using a smaller number of more complex components. Figure 6a shows one such enclosure attached to a human leg for the purpose of walking gait analysis.

Figure 5. Example of Lionel Dean jewellery design (FF, 2013).

Figure 6. Electronics enclosure for motion capture and analysis system.

The range of enclosures was designed with many intricate features that reduced the need for assembly by including a greater number of functions within each part. These included integral ball-joints, internal wiring channels, snap-fits, integral hinges and numerous undercuts and overhangs that would be difficult to make with conventional processes such as injection moulding (see Figure 7).

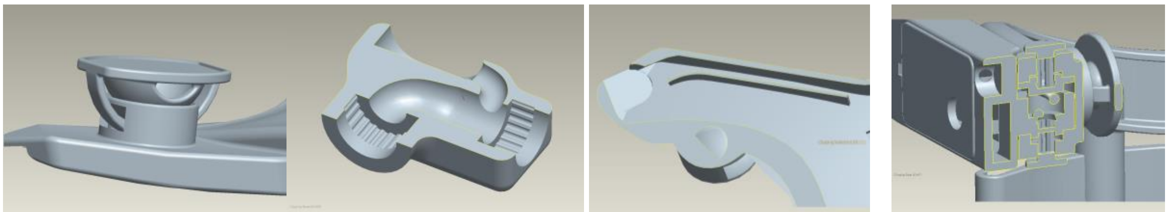

Figure 7. Examples of "designed for AM" features.

As a result of these design changes, the new range of enclosures was radically different to the current design being used by the company. In order to evaluate the impact that these design changes upon E3 product value, the old and new ranges were quantitatively compared across a number of criteria. The results shown in Table 1 verify that both the direct component cost and assembly costs were reduced.

However, the additional benefit of weight saving means that there was also an increase in extrinsic experience value since an improvement in product performance was realised.

Table 1. Multi-criteria comparison of benefits for new enclosure designs

Criteria	Current Design	AM Design
Relative cost	1	0.95
Component count	>50	40
Assembly time	5 days	2 days
Lead time	2-3 weeks	1 week
Weight	0.8 kg	0.5 kg

6.2 Direct metal tooling with conformal cooling channels

Laser-aided Direct Metal Tooling or simply Direct Metal Tooling (DMT) involves the use of AM to build precisely controlled metal layers for generating full density metallic tools and parts. DMT processes are known by several names, most of which are trademarks of several machine manufacturing companies or research institutions, including Laser Metal Deposition (LMD), Direct Metal Deposition (DMD), Direct Laser Deposition (DLD), Laser Engineered Net Shaping (LENS), Laser Cladding, Laser Deposition Welding and Powder Fusion Welding. These processes promise to take mould making and metalworking in an entirely new direction (Choi and Chang, 2001). They generally involve a laser beam apparatus used to form a melt pool on a metallic substrate, into which powder is fed. The powder melts to form a deposit that is fusion bonded to the substrate or previous layers.The accuracy and surface quality of the DMT parts are generally lower than those of machined parts and so subsequent finish machining operation on final parts may still be needed to achieve tight geometric tolerances. However, DMT can fabricate metal parts with superior material properties such as strong metallurgical bonds, full density, and fine microstructures as well as a greater degree of geometric freedom of manufacturing, which is expected to have the highest potential to revolutionize the way of future manufacturing (Campbell et al, 2011).

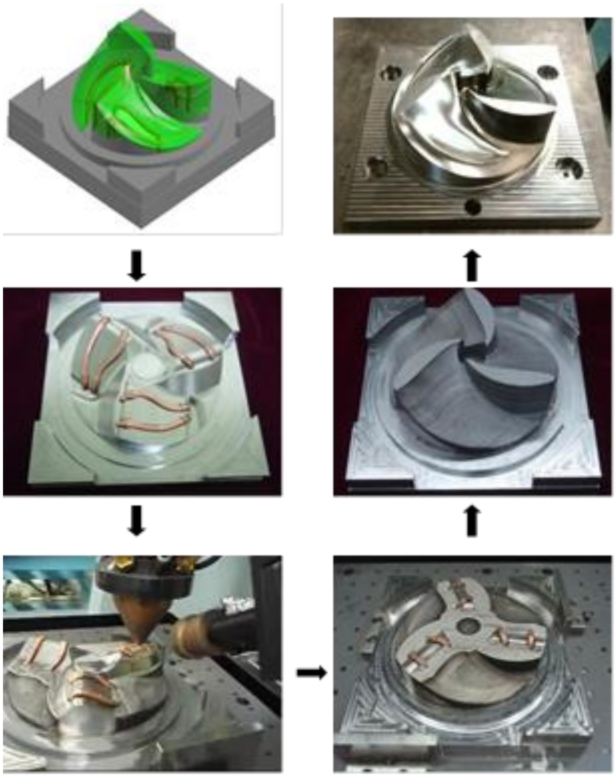

Figure 8. Conformal cooling channel made on a plastic injection mould die using DMT.

DMT was applied to the manufacture of an injection mould tool with conformal cooling. That is, the geometric freedom of the DMT process enabled the inclusion of a cooling channel that smoothly circulated around the mould cavity. Figure 8 shows the various stages of this process, i.e. CAD re-design of the cooling passage is first undertaken, then copper cooling tubes are inserted into the substrate mold part, these are then “buried” using the DMT process to complete the mould die with conformal cooling channels, and finally, the tool is finish machined. This tool design provided more efficient thermal management of the mould die for the plastic part as it was being injected. In the production test results, the total cooling time and production time were decreased by 35% and 25.7% respectively. These improvements contributed directly towards enhanced economic value through reduced part cost and enhanced ecological value through more efficient energy transfer.

7 CONCLUSIONS AND FUTURE WORK

This paper has demonstrated that through its unique geometric capabilities, AM can contribute towards increased economic, ecological and experience value for a range of products. However, the evidence that is available currently is rather anecdotal and there is no systematic design tool available to guide designers on how to routinely achieve this increased value. Such a tool would ideally have the capacity to make value-adding suggestions to the designer and then enable these to be evaluated once embodied into the product design. The designer could then evaluate a range of alternative AM-enabled designs to see which had the highest value and would justify the use of AM. The development of a prototype version of an AM PSS value-adding tool will be the subject of future research collaboration between the authors.

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