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Additive manufacturing and sustainability: an exploratory study of the advantages and challenges

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ABSTRACT

The emergence of advanced manufacturing technologies, coupled with consumer demands for more customised products and services, are causing shifts in the scale and distribution of manufacturing. In this paper, consideration is given to the role of one such advanced manufacturing process technology: additive manufacturing. The consequences of adopting this novel production technology on industrial sustainability are not well understood and this exploratory study draws on publically available data to provide insights into the impacts of additive manufacturing on sustainability. Benefits are found to exist across the product and material life cycles through product and process redesign, improvements to material input processing, make-to-order component and product manufacturing, and closing the loop. As an immature technology, there are substantial challenges to these benefits being realised at each stage of the life cycle. This paper summarises these advantages and challenges, and discusses the implications of additive manufacturing on sustainability in terms of the sources of innovation, business models, and the configuration of value chains.

1. Introduction

The manufacturing landscape is ever-changing. One of the most significant drivers of this change is the emergence of advanced manufacturing technologies that are enabling more cost- and resource-efficient small-scale production. In combination with other prominent trends such as servitisation (Neely, 2008), personalisation (Zhou et al., 2013) and prosumption (Fox and Li, 2012), the emergence of additive manufacturing (commonly known as 3D printing) as a direct manufacturing process is leading companies to rethink where and how they conduct their manufacturing activities.

The adoption of additive manufacturing (AM) and other advanced manufacturing technologies appears to herald a future in which value chains are shorter, smaller, more localised, more collaborative, and offer significant sustainability benefits (Gebler et al., 2014). Additive manufacturing mimics biological processes by creating products layer-by-layer. It is inherently less wasteful than traditional subtractive methods of production and holds the potential to decouple social and economic value creation from the environmental impact of business activities. Among the many potential sustainability benefits of this technology, three stand out:

- Improved resource efficiency: improvements can be realised in both production and use phases as manufacturing processes and products can be redesigned for AM;
- Extended product life: achieved through technical approaches such as repair, remanufacture and refurbishment, and more sustainable socio-economic patterns such as stronger person-product affinities and closer relationships between producers and consumers (Kohtala, 2015);
- Reconfigured value chains: shorter and simpler supply chains, more localised production, innovative distribution models, and new collaborations.

However, despite these prospective benefits, AM has not been sufficiently explored from a sustainability perspective. While it could be an enabler and a driving force for improved industrial sustainability, the consequences of its implementation on the industrial system could lead to an alternative scenario in which less eco-efficient localised production, customer demands for customised goods, and a higher rate of product obsolescence combine to bring about increased resource consumption.

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To date, investigations by researchers into the sustainability implications of AM have either been done at a broad level (Gebler et al., 2014; Kohtala, 2015) or been highly focused on the issue of material and energy consumption (Baumers et al., 2011; Faludi et al., 2015). As a nascent research area in which the impacts of AM on sustainability are unclear, the objective of this paper is to begin to unpack the issues that exist at the intersection of these topics by asking: *How can additive manufacturing enable more sustainable models of production and consumption?*

Exploring the topic of AM through the lens of industrial sustainability provides a more comprehensive understanding of the implications of AM for improving the sustainability of industrial systems. Such systems are *"complex with a large number of actors on a global stage* [in which] … *actors interact with each other in complex, interlinked value chains, exchanging data, goods (raw materials, components and products), services and, of course, money"* (Royal Academy of Engineering (2012)). As they include distributed manufacturing systems within them, industrial systems cover the spectrum of digital manufacturing through to peer-to-peer production, and encompass distributed production modes of mass customisation, bespoke fabrication, mass fabrication and personal fabrication (Kohtala, 2015).

The paper begins by first providing an overview of AM technologies, their characteristics, and a description of their industrial applications. This is followed by a review of previous studies on aspects of the sustainability of AM. The paper then explores examples from current practice. These examples highlight the ways in which firms have already begun to implement AM and the consequences of this technology's adoption on the sustainability within the wider manufacturing system. Using a product life cycle perspective leads to the categorisation of these examples within four main clusters: product and process redesign, material input processing, make-to-order component and product manufacturing, and closing the loop. Building on these insights, the paper discusses how AM creates opportunities for sustainability and the types of organisations that are realising these opportunities, along with potential sustainability benefits that could come in the future through the adoption of new business models and the re-distribution of manufacturing.

2. Additive manufacturing

Among the variety of advanced manufacturing technologies that are currently emerging, additive manufacturing stands out as one with enormous potential for changing the distribution of manufacturing and society as a whole (Huang et al., 2013; Lipson, 2012).

2.1. Review of additive manufacturing technology

The term 'additive manufacturing' covers a broad range of production technologies that fabricate products layer-by-layer, enabling three-dimensional objects to be 'printed' on demand. The ASTM F42 Technical Committee that is responsible for overseeing the development of AM standards defines the technology as *"a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies"* (ASTM, 2012). Some of the most widely adopted AM technologies are fused deposition modelling (FDM), stereolithography (SLA), selective laser melting (SLM), selective laser sintering (SLS) and digital light processing (DLP), but there are a variety of other AM processes too, including polyjet, electron beam melting (EBM) and laminated object manufacture (LOM) (Petrovic et al., 2011). In terms of materials, a variety of polymers, metals, ceramics and composites can be used for AM. The use of these materials is dependent on the type of AM process used (Guo and Leu, 2013).

The first applications of AM were in the area of rapid prototyping and then tooling. These application areas continue to be exploited to the present day but performance improvements to AM technologies mean that they are increasingly being used for direct manufacturing. Certain industries such as aerospace, where the need to produce a small number of highly complex aircraft components makes the application of AM technologies ideal, are already fully aware of their potential and are investing in research to improve their reliability and applicability (Guo and Leu, 2013; Lyons, 2012). In the medical sector highly personalised one-off products are needed. The capabilities of AM make it the ideal technique to address this need. This is exemplified by the manufacturing process for in-ear hearing aids which has almost entirely shifted to AM (Sandström, 2015), while other applications in orthodontics, prosthetics, orthotics, implants and replacement organs are at various stages of maturity and adoption. The pattern of industrial emergence, technology adoption and diffusion can be seen to follow the niche development and speciation that has been observed in previous emerging industries (Ford et al., 2014; Phaal et al., 2011).

In addition to these technical and commercial developments there have been a range of other advances made in cold spray-based AM processes that have not been used as prototyping methods (Sova et al., 2013). Although these have not traditionally been considered as AM, they are being promoted as such and fit within the ASTM definitions of AM.

Alongside the advances that have been made in AM in the industrial market, a variety of consumer grade '3D printers' have proliferated on the market. The majority of these home 3D printers (e.g. RepRap, Makerbot, Ultimaker) are based on the fused deposition modelling (FDM) technology originally developed by the US firm Stratasys. Their commercialisation was made possible following the expiry of the first patents protecting this technology, an open source movement that saw hobbyist activity around the technology, and crowdfunding through platforms such as Kickstarter and Indiegogo. These machines offer the promise that individual consumers will be able to design and produce personalised products at their convenience (Lipson and Kerman, 2010).

A list of the current characteristics of AM is provided in Table 1, describing both the advantages of this manufacturing technology relative to established subtractive and transformative methods, and the challenges to its development and wider adoption.

2.2. Additive manufacturing and sustainability

Manufacturing is about converting material input into goods and services. The efficiency of this conversion process is a key determinant of the environmental impact associated with manufacturing (Gutowski et al., 2009). Additive manufacturing has been identified as having the potential to provide a number of sustainability advantages. These advantages include the generation of less waste during manufacturing due to it being an additive process; the capability to optimise geometries and create lightweight components that reduce material consumption in manufacturing and energy consumption in use; the subsequent reduction in transportation in the supply chain; and inventory waste reduction due to the ability to create spare parts on-demand (Chen et al., 2015; Mani et al., 2014). Overall *"AM is expected to become a key manufacturing technology in the sustainable society of the future"* (Huang et al., 2013, p. 1201).

There are currently few studies investigating and analysing the degree to which these potential advantages are being realised. The majority of academic studies have focused on the energy

Table 1
Advantages and challenges of additive manufacturing (adapted from Berman (2012); Chen et al., 2015; Huang et al., 2013; Petrick and Simpson (2013); Petrovic et al. (2011)).

Advantages	Challenges
● Small batches of customised products are economically attractive relative to traditional mass production methods ● Direct production from 3D CAD models mean that no tools and moulds are required, so there are no switch over costs ● Designs in the form of digital files can be easily shared, facilitating the modification and customisation of components and products ● The additive nature of the process gives material savings, as does the ability to reuse waste material (i.e. powder, resin) not used during manufacture (estimated at 95–98% recyclability for metal powders) ● Novel, complex structures, such as free-form enclosed structures and channels, and lattices are achievable ● Final parts have very low porosity ● Making to order reduces inventory risk, with no unsold finished goods, while also improving revenue flow as goods are paid for prior to being manufactured ● Distribution allows direct interaction between local consumer/client and producer	● Cost and speed of production ● Changing the way that designers think about and approach the use of additive manufacturing ● Removing the perception that AM is only for rapid prototyping and not for direct component and product manufacture ● Development and standardisation of new materials ● Validation of the mechanical and thermal properties of existing materials and AM technologies ● Development of multi-material and multi-colour systems ● Automation of AM systems and process planning to improve manufacturing efficiency ● Post-processing is often required. This may be due to the stair stepping effect that arises from incrementally placing one layer on top of another, or because finishing layers are needed ● Support structure materials cannot be recycled so need to be minimised through a good build-up orientation ● Intellectual property issues, particularly regarding copyright ● Deficits in designers and engineers skilled in additive manufacturing ● Non-linear, localised collaboration with ill-defined roles and responsibilities ● Continuously changing set of competitors

consumption of AM, with research assessing either the relative energy performance of different types of AM or comparing AM with other manufacturing techniques such as injection moulding (Baumers et al., 2011; Chen et al., 2015; Franco and Romoli, 2012; Le Bourhis et al., 2013; Sreenivasan et al., 2010; Yoon et al., 2014). The overall results from these studies vary widely and remain inclusive. From these studies it is difficult to generalise whether AM has a lower environmental impact than other manufacturing techniques because the life cycle impact of parts made with AM is highly dependent on machine utilisation (Faludi et al., 2015), the specification of each piece of AM equipment, and how the material input is processed. Calls for further studies into this area have been made (Huang et al., 2013). It is clear however that increasingly machine utilisation through machine and tool sharing is key to reducing the environmental impact of AM.

The economic and environmental performance of manufacturing systems are strongly intertwined and this also applies to AM (Chen et al., 2015). Currently available AM techniques can be economically convenient and compete with traditional processes for small to medium batch production of metal parts. The machine cost per part is a major component of total cost. Machines and materials for AM are still expensive but the cost of these will decrease as AM becomes a more commonly used production technique. Furthermore, AM is expected to become more cost effective as larger production volumes become more economically feasible than at present.

The design freedoms offered by AM allow product and component redesign. Using additive techniques, several parts made of the various material can be replaced by one integrated assembly, which will reduce or eliminate cost, time and quality problems resulting from assembling operations. Assembly cost is minimised or even cut out through part consolidation. Redesign can result in an optimum strength-to-weight ratio able to meet functional requirements while minimising material volume. Life cycle analyses have shown that the adoption of AM could have significant savings in the production of goods. Savings are estimated at $113–370 billion by 2025, with these arising from reductions in material inputs and handling, along with shorter supply chains (Gebler et al., 2014).

The economic benefits due to efficiency and process improvements in design, testing and manufacturing are greater than the benefits from the avoidance of investment in tooling (Atzeni and Salmi, 2012). In addition, once the part design is released, the production begins immediately. Reducing the time delay between design and manufacturing results in cost savings. Further cost reductions can be realised if the component shape is modified to fully exploit AM potentials. Using additively manufactured components can also lead to cost savings in the use phase. Lightweight components will reduce energy consumption and could deliver savings of $56–219 billion by 2025 (Gebler et al., 2014).

Despite the potential increase in recycling rate, materials used for AM are not necessarily greener than materials used in traditional manufacturing. The one exception may be the bio-polymer polylactic acid (PLA) (Faludi et al., 2015). Potential material savings may be partially offset by the relative toxicity of the material used for AM (Faludi et al., 2015) and the impact of energy usage for producing the input material as well as the processing itself. Thus the full environmental performance of AM must take into consideration the energy demand from a system perspective and not just the process itself (Faludi et al., 2015; Hao et al., 2010; Reeves, 2008; Sreenivasan et al., 2010).

On the social sustainability front, the social impact of AM is also still poorly understood. The most detailed study concerning social issues focuses on work condition and worker's health as social indicators (Huang et al., 2013). AM may have health benefits when compared to conventional manufacturing processes as it allows workers to avoid long-term exposure to harsh and potentially hazardous work environments. However, little research has been made on the toxicity and environmental potency of AM processes and materials. Such impacts may exist during the processing and disposing of the materials used in AM processes. A second social dimension relates to the democratisation of production that direct digital manufacturing technologies such as AM provides. The combination of ICT, widely available CAD software and 3D printers is changing consumption patterns. Rather than being entirely passive consumers, users are becoming empowered to also produce themselves, becoming prosumers within a global manufacturing community (Chen et al., 2015). While some pro-environmental subgroups of prosumers that make use of shared maker facilities are aware of the environmental implications of AM practices, the majority remain unaware and sustainability issues are not integrated into their practices (Kohtala and Hyysalo, 2015).

This potential for AM to contribute to a more sustainable society is also beginning to be recognised in policy circles. In the UK, the

Additive Manufacturing Special Interest Group that was formed within the Materials Knowledge Transfer Network identified how AM has the potential to support future needs in sustainable, high value manufacturing through a more efficient manufacturing system and new business models (TSB, 2012). Meanwhile, the UK's Government Office for Science expects AM to have "*a profound impact on the way manufacturers make almost any product*", stating that it "*will become an essential 'tool' allowing designs to be optimised to reduce waste; products to be made as light as possible; inventories of spare parts to be reduced; greater flexibility in the location of manufacturing; products to be personalised to consumers; consumers to make some of their own products; and products to be made with new graded composition and bespoke properties*" (BIS, 2013).

3. Research methods

While researchers such as Chen et al. (2015) and Mani et al. (2014) have identified the sustainability benefits of additive manufacturing and Kohtala (2015) the potential threats, it is important to examine how these potential benefits and threats are being implemented in practice. This paper investigates the implications of the adoption of AM by organisations and industries through exploratory case studies (Yin, 2009).

The cases were identified through reviews of industry reports from consultants (e.g. Wohlers, CreditSuisse, PWC), reputable industry news sources (e.g. TCT Magazine, 3D Printing Industry, 3D Print Pulse, 3Ders), and at the suggestion of industry experts. Following the identification of potential cases, a life cycle perspective was used to guide the selection of the cases used in this paper. A theoretical replication logic was adopted to select cases for contrasting results. The novelty of AM technologies at this point in time means that the selected cases are exemplars of the application of AM rather than representative of a larger population.

A case description was created for each example based on the data obtained. This data was directly drawn from company websites and the aforementioned industry news sources. In one case, academic publications were also used to create these descriptions. Selected links to these sources of data are provided in Table 8 in the Appendix. While there is the potential that this company data could mis-represent the magnitude of the sustainability benefits achieved, for this exploratory study it is sufficient to identify the types of benefits being realised rather than quantify them.

A coding process was adopted to extract the sustainability advantages and challenges from the case descriptions, with these analysed within the frame of the product and material life cycles (Fig. 1). This process led to the identification of the sustainability benefits being realised through AM at different stages of the product life cycle (Table 2). The examples in this table are clustered according to the section in which they appear, i.e. the life cycle stage which is the focus of the changes resulting in the adoption of AM. The specific advantages and challenges from each of these cases are described in Section 4 and summarised in Tables 3–6. An overall summary of the observed advantages and challenges across the life cycle stages is provided at the end of Section 5 (Table 7).

4. Additive manufacturing in industry: the sustainability implications

In this section the sustainability implications of AM's adoption begin to be explored. The cases are grouped and discussed across four stages of the product life cycle: product and process design; material input processing; make-to-order component and product manufacturing; and closing the loop.

4.1. Product and process design

AM enables the design of more complex and optimised components thanks to greater freedoms in shape and geometry, along with simpler assemblies comprising fewer parts and fewer different materials. The free-form and lightweight structures that are possible are often inspired by nature and draw on biomimicry concepts. The benefits that can be realised occur over the whole life cycle of the product and its materials, as illustrated in Fig. 1. Examples of product improvements include greater operational efficiency, functionality and durability, and ease of manufacturing and maintenance (Despeisse and Ford, 2015).

4.1.1. Component and product redesign

The new AM design freedoms allow the creation of new material structures such as porous mesh arrays and open cellular foams. Incorporating these novel structures into the core of components can enhance the attributes of the component being fabricated. Possible improvements includes increased strength, stiffness, energy efficiency and corrosion resistance (Guo and Leu, 2013). For

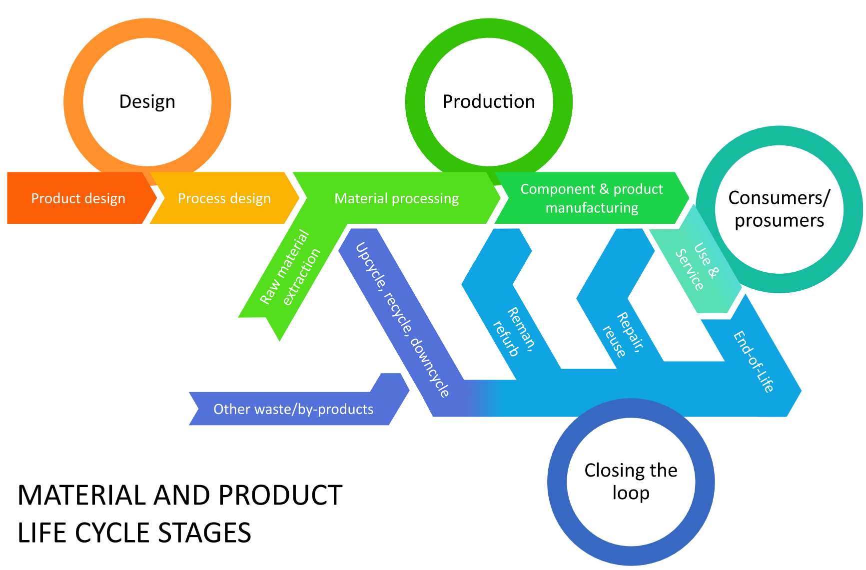

Fig. 1. Life cycle perspective for identifying sustainability benefits of AM.

Table 2
Identified sustainability benefits across various life cycle stages.

Section	Example	Product and process design	Material processing	Component and product manufacturing	Use and service	Repair and reman	Recycling
4.1.1	SAVING project			✓	✓		
Component and product redesign	Rolls-Royce			✓		✓	
	GE			✓	✓		
4.1.2	Salcomp			✓			
Process redesign	Construction			✓			
4.2	Metalysis		✓				
Material input processing	Filabot		✓				✓
	EKOCYCLE Cube		✓				✓
	Bewell Watches		✓				✓
4.3	Kazzata	✓				✓	
Make-to-order component	Siemens			✓		✓	
and product manufacturing	Home 3D printers	✓		✓			
	3D Hubs			✓			
4.4	PPP		✓				✓
Closing the loop	Caterpillar				✓	✓	
	HMT			✓		✓	

example, the strength of an EBM-fabricated component using a Ti6Al4V open cellular foam can be up 40% greater than a full density EBM-fabricated component (Murr et al., 2010).

Components and products can be redesigned to take advantage of AM's beneficial properties. Examples from the UK-funded SAVING (Sustainable product development via design optimization and AdditiVe manufacturING) project include the redesign of belt buckles on aeroplanes in order to reduce weight; heatsinks to improve airflow and thermal efficiency; and heat exchangers that provide improved efficiency within constrained geometries.

Aerospace is one sector in which AM has found particular application given its high performance needs and relatively low scale of production. Aside from the significant environmental impacts of the airline industry, the manufacturing of aero engine components itself has a high impact on the environment. Substantial waste arises from the manufacturing process. Typical buy-to-fly material ratios of 4:1 (input material to final component) are common using traditional 5-axis milling processes, with some components having a ratio as high as 20:1. The EU FP7 MERLIN project sought to address this environmental impact through the application of AM technologies in civil air transportation. The project involved a number of leading European aerospace organisations, including Rolls-Royce, Turbomeca and MTU, as well as researchers at the Fraunhofer ILT. One of the results of this project was an improved AM process, Laser Material Deposition (LMD), for the manufacture of bladed disks ('blisks') used in aero engines. The benefit of this manufacturing process is that it avoids the generation of waste ('swarf'). The majority of this swarf material cannot be recycled; when it can be it is usually done much lower down the value stream and consumes a similar level of energy to the manufacture of the original material. Early demonstrators developed at the Fraunhofer ILT show that the LMD process can achieve material savings of approximately 60%, along with time savings of 30%.

The most noteworthy product redesign to date is that achieved by GE for its LEAP engine that launches in 2016. After several years developing capabilities in AM, GE will include nineteen additively manufactured fuel nozzles in the new engine. Designed for additive manufacture, the new fuel nozzle is five times stronger to aid durability and has been designed in order to provide the best fuel flow geometry to improve combustion efficiency. Furthermore, GE has been able to realise a significant weight reduction of 25% relative to the existing nozzle. Part of this reduction has been achieved through simplification; the existing design had 20 separate components while the new design is a single component.

4.1.2. Process redesign

Just as improvements can be made to product design, so too can improvements be made to the production process design. Through incorporating AM-produced components (e.g. moulds, tooling) that make use of forms only possible through AM, the production process can become more energy and resource efficient (Chen et al., 2015).

An example of this can be seen at the Finnish company Salcomp, a world leader in the production of electrical plugs and power supplies for mobile phones. In this high volume industry, cost and efficiency are the major driving forces for maintaining competitive position. Seeking to improve the production efficiency of its Chennai plant, Salcomp identified that the cooling time in its injection moulding process was a limiting factor. Working together with EOS, a German developer of direct metal laser sintering (DMLS) AM technology, Salcomp engineers were able to redesign the vent structure of the moulds used so that heat would be dissipated more quickly. These moulds were then produced using the DMLS AM technology. The main benefit of this redesign was that cooling time was reduced from 14 s to 8 s, enabling 56,000 more units to be produced each month. A secondary benefit was an improvement to quality, with rejection rates reduced from 2.0% to 1.4%.

Current AM systems remain far from automised and need to become so if they are to become more integrated into manufacturing systems and realise resource efficiency improvements. Part of the need for automation arises from the requirement for post-processing to eliminate the 'stair stepping' effect that results from the incremental layer-by-layer build-up of material. In other cases post-processing may be required to achieve a particular aesthetic finish. Applying hybrid manufacturing techniques could be one solution to these problems. Such techniques have existed for a long time, e.g. ultrasonic assisted mechanical machining (Colwell, 1956; Markov and Neppiras, 1966). Hybrid manufacturing processes offer a number of advantages such as improved finish quality, shorter production time, and reduced tool wear. The integration of AM with traditional subtractive, joining and transformative processes into these hybrid manufacturing techniques can also realise these advantages.

The potential for process redesign extends beyond traditional manufacturing into other sectors. One example is the construction sector, which as a major material, energy and water consumer presents significant opportunities for resource efficiency improvements (Buyle et al., 2013). Demonstrations of in-situ construction, such as the MX3D bridge, 3D Print Canal House and 3D printed apartment buildings in China, show what is becoming

Table 3
Summary of observed sustainability advantages and challenges at the design stage.

Example	Advantages	Challenges
SAVING project	• Material and energy savings in the production of high value products • Improved product functionality and efficiency in use	• Educating manufacturers about the potential uses and benefits of AM
Rolls-Royce	• Lower energy intensity and waste avoidance in the manufacturing process • In-situ repair for maintenance and extended product life	• Process scale-up • Implementation of distributed maintenance system • Certification of repair process
GE	• Improved durability for extended product life • Improved fuel efficiency during product use • Simplification and dematerialisation of the product	• Certification of new components • Capturing and replicating learning in future applications
Salcomp	• More energy efficient production process • Improved quality reduced rejection rate	• Capturing and replicating learning in future applications
Construction	• In-situ manufacturing process generates less waste • Transportation of more basic materials simplifies supply chains	• Limited and uncertain performance due to low maturity of the technology for large-scale structures • Requirement for standards and regulations

possible using AM approaches in this industry. These early examples demonstrate that the environmental impacts of logistics can be reduced through additively manufacturing using basic materials. This means that fewer materials can be brought to and from the construction site, also reducing waste overheads. However, the construction industry is highly conservative and slow to change, with this conservatism arising from the longer life cycle of infrastructure and concerns about safety and liability. Demonstration of the infrastructure is needed over a longer timeframe than in other industries in which product life cycles are shorter and includes process and material certification.

4.1.3. Benefits and limitations

The above examples demonstrate the potential of AM redesigns to improve the overall sustainability performance of products and processes. Material and energy efficiency can be improved through dematerialisation and reducing energy consumption during processing. Moreover, the adoption of AM may result in reconfigurations to the value chain. Redesign of products and components can lead to simpler products that require fewer components, materials, actors, stages and interactions. Thus improving the performance of products through simplification can reduce the scale of material flows and lead to a reduction in the environmental impact over the whole supply chain. The shift from a centralised system of manufacturing to a more decentralised one implies that the environmental impact of transportation will be reduced while at the same time supporting and empowering local communities (Chen et al., 2015).

However, there are also barriers and challenges to fully exploiting these potential benefits. Firstly, current perceptions of AM technology by designers and engineers are biased by its original application being limited to rapid prototyping and tooling, and thus not being considered fit for purpose for direct component and product manufacture. Secondly, there are limitations to the performance of AM technologies. While novel forms can be created through AM, new functionality such as microelectronics cannot be embedded yet into components and products. AM technologies need further development to become sufficiently advanced to enable the integration of these types of new functionalities during the manufacturing process. Changing mindsets and improving the technical performance of AM technologies is needed to harness the full benefits of AM at the design stage.

4.2. Material input processing

The materials that are used as inputs to AM provide opportunities for sustainability improvements. Just as there are a variety of AM technologies, so too is there significant variety in the materials used as inputs. The nature of the material is dependent on the specific type of AM process used. The four major categories of material are liquid, filament/paste, powder and solid sheet (Guo and Leu, 2013).

During the raw material processing stage, there is the potential to rethink how certain raw materials are processed to minimise the resources needed to bring them into a usable form as inputs for manufacturing processes. Metal powders used in laser sintering and melting approaches, along with electron beam melting, are one such case. Significant energy is expended during the process of refining and processing the metal ores in preparation for manufacturing. One company that is addressing the high energy consumption of refining metal ores is the UK-based firm Metalysis, which has commercialised a process for producing titanium powder directly from titanium ore (Lubik and Garnsey, 2016). This process, the FFC process, requires significantly less energy to produce the titanium powder than the established Kroll process (Mellor et al., 2015). Furthermore, the process uses a non-toxic

Table 4
Summary of observed sustainability advantages and challenges at the material input processing stage.

Example	Advantages	Challenges
Metalysis	• Lower environmental impact of titanium powder production through lower energy consumption • Process reactants are non-toxic and can be recycled locally	• Material and process standardisation • Process scale-up for new materials
Filabot	• Democratised material recycling • Localised material recycling	• Limited to polymer filament • Possibility of colour and material contamination
EKOCYCLE Cube	• Diversion of PET waste streams into new applications • Input recycled materials are from larger-scale recycling systems, potentially more efficient than local recycling systems	• Limited material options • Limited percentage of recycled content • Compatibility of proprietary non-standard material input format
Bewell watches	• Diversion of by-product from waste stream • Upcycling	• Limited recyclability of product at its end-of-life due to mixed materials

reactant, calcium chloride, during refinement and any leftover CaCl can be reused. However, the relative immaturity of the technology means there are currently few materials for which such novel processing techniques have been developed. For those that have, there has yet to be standardisation. To identify the most resource efficient standards and enable this standardisation to be achieved, further research is required to explore and validate the mechanical and thermal properties of AM technologies and materials.

Recycled materials sit alongside virgin materials as inputs into the AM process. An example at the local level can be seen with home 3D printers using fused deposition modelling (FDM) technology. Waste plastic filament, misprints and undesired outputs can be reclaimed and reused. This is achieved through use of equipment such as that produced by Filabot. It first involves grinding the plastic goods into granules and then feeding these granules into a filament producing machine. The main issue with this approach is colour contamination and a reduction in the material properties of the polymer. The latter issue can be overcome through the use of polylactic acid (PLA), a polymer commonly used in 3D printing filament, which has the ability to be recycled with little quality loss.

At the system level this is achieved through the use of commonly recycled materials and their conversion into forms suitable for AM. An example of this can be seen in the EKOCYCLE Cube home 3D printer, which uses recycled polyethylene terephthalate (rPET) in its cartridges. These cartridges currently use 25% recycled PET content and are available in red, white, black and natural colours. Higher recycled percentages are also possible but are limited by the lower aesthetic quality of the resultant polymer. As a collaboration between 3D Systems and the Coca-Cola Company, this initiative seeks to divert used PET bottles, such as those from Coca-Cola, from the waste stream.

Finally, AM can also allow the conversion of waste and by-products into products. There are examples demonstrating that material traditionally considered as waste can be upcycled to manufacture luxury products using AM. Upcycling is advocated by the cradle-to-cradle community (Braungart and McDonough, 2002) and enables value to be created from what would otherwise be considered a waste. One such example from our cases is provided by Bewell Watches. Wood flour and dust is a typical by-product from timber and wood processing, and is considered waste. These wood wastes have found applications as a filler in thermosetting resins, wood-plastic composites and building products. Bewell Watches manufactures customised wood watches using these wood by-products combined with binding agents to create a wood filament for AM, thus diverting material from waste streams and creating value for the company and its customers. There are however limitations on material recirculation due to quality and purity issues which could prevent recycling of the products when they reach their end-of-life. Current technologies for wood-polymer composite recycling are in their infancy and the national infrastructures required for their recycling are missing (Teuber et al., 2016).

4.3. Make-to-order component and product manufacturing

The economics of AM make it ideal for make-to-order component and product manufacturing, allowing production of spare parts for replacement, and lower cost customisation and personalisation. Holding a database of digital designs allows products to be manufactured on demand using AM. Doing so can help eliminate or at least minimise inventory waste, reduce inventory risk with no unsold finished goods, with the potential of improving revenue flow as goods are paid for prior to being manufactured.

Traditionally, when a component in a product breaks the consumer will either discard or repair the product depending on the value of the product and the cost and ease of its repair. Repairing the product usually require obtaining a replacement component from the manufacturer or its distributors. For such organisations maintaining an inventory of replacement parts is costly and there is great uncertainty over future demand for these parts. The alternative, producing one-off spare parts on demand, is prohibitively expensive using traditional manufacturing technologies. However, the economics of AM makes the one-off production of spare parts more cost attractive, with the added benefit that the 3D CAD files containing component designs can be easily shared once they have been created. At present however there is limited access to such files.

Kazzata is a digital repository that provides a selection of 3D CAD files of replacement parts that users can download and manufacture. The number of files available from Kazzata is currently very limited so in addition it provides a service that links consumers with spare part needs to designers who can provide CAD design services. Following the design of the spare part, the consumer can then receive either the 3D CAD file for themselves to manufacture, or the replacement component directly from Kazzata. Similar design and engineering services can be provided by the rapidly growing number of AM service bureaus. Barriers to a wider system of spare parts include component certification and legal issues concerning liability.

In industry, one organisation making the shift towards make-to-order product manufacturing for spare parts is Siemens Power Generation Services (Siemens PGS). As one of the businesses within Siemens AG it provides support, maintenance and repair services to customers operating rotating power equipment such as gas steam and wind turbines, generators and compressors. Having identified

Table 5
Summary of observed sustainability advantages and challenges at the manufacturing stage.

Example	Advantages	Challenges
Kazzata	• Increased access to digital designs for spare parts	• Limited availability of digital designs • Cost of acquiring new digital designs
Siemens	• Novel design made possible through AM • Quicker component repair • Less high-value waste generated • Upgradability of component being repaired • Potential for the on demand manufacture of spare parts	• Capturing and replicating learning in future applications
Home 3D printers	• More localised manufacturing • Simpler supply chains • Democratised design • Raised awareness of manufacturing process and its impacts	• Limited functionality and utility • Reliability and quality of 3D printing process • Limited digital designs available • Encourages materialistic society and consumerism
3D Hubs	• Improved access to equipment • Increased equipment utilisation • More localised production through proximity of producer to customer	• Services are currently fragmented and unevenly distributed • Majority of services are lower-end consumer 3D printers

the combustion system in gas turbines as one particular application whereby AM could improve customer value in spare parts repair and manufacturing, Siemens PGS acquired direct metal laser sintering (DMLS) AM systems from EOS in 2007. Within this combustion system, Siemens PGS has redesigned the burner 'swirler' to make use of the design freedoms afforded by AM. Through using AM the burner tip can be repaired more quickly and with less waste. It is estimated that the repair time is ten times quicker than the previous approach. Less waste is generated as little of the burner is now discarded; only the top 18 mm edge of the burner tip is removed prior to repair. Using AM also allows for much easier upgrading to the latest design and is a step towards the business' future vision of spare parts being manufactured on demand closer to the customer's location.

As described in this section, the configuration of the manufacturing system can change dramatically with the introduction of AM. The shift from traditional mass production methods and economies of scale to small batch production of customised or personalised goods is made possible at a lower cost. The development and diffusion of consumer 3D printers in homes and offices, such as Ultimaker, Cube and Makerbot Replicator, are also blurring the line between consumers and manufacturers. Technology users are playing the role of both producers and consumers, making them prosumers. They can design and manufacture products on-demand to the exact specifications required and at the point of use in space and time. In addition, 3D printers can be combined with Filabot and other in-situ recycling systems to convert waste back into filament and use it as input for 3D printing new products. In this fashion, home 3D printers are beginning to enable more distributed, small-scale and localised manufacturing. Their wider adoption is anticipated to have major effects on the whole supply chain. Logistics are simplified as fewer, more basic material inputs are needed. Furthermore, inventories of components and products can be reduced or eliminated, thus in turn reducing the economic losses and environmental impacts associated with unsold and obsolete components (Chen et al., 2015).

From a sustainability perspective, the additive nature of AM makes it a more resource efficient manufacturing process as less waste is generated compared to subtractive techniques. While it can be argued that AM is more energy intensive per unit produced (relative performance), AM allows units to be produced to exactly match the demand (make-to-order) and thus offers the potential for better absolute performance. Higher raw material utilisation leads to dematerialisation and reduced waste (Chen et al., 2015).

As well as reducing energy and resource consumption, the make-to-order model of distribution also allows direct interaction between local consumers/clients and producers, with collaborative learning and user innovation benefits of this approach (de Jong and de Bruijn, 2013). Networks such as 3D Hubs provide an online platform that links owners of 3D printers with customers. The owners are typically prosumers who have spare printing capacity and want to increase utilisation. This provides access to local manufacturing. It delivers the same benefits as described above but increases equipment utilisation as customers do not need to own and operate their own equipment. The number of hubs in the network is rapidly growing. At the time of writing, there are over 25,000 3D printers accessible within the 3D Hubs network.

The challenge of this distribution model is that non-linear, localised collaboration between actors with ill-defined roles and responsibilities could result in conflicts and incompatibilities (Petrick and Simpson, 2013; Chen et al., 2015). Additionally, a continuously changing set of actors and competitors creates an uncertain investment environment that makes business strategy formulation and competitive positioning difficult. Companies and entrepreneurs entering this market must have extreme resilience, flexibility and responsiveness to rapidly adapt to market changes (Gartner, 1985).

4.4. Closing the loop

Attempts at closing the loop can be achieved at various stages and scales in AM. The highest value recovery possible is achieved locally during the manufacturing process when the unused AM material (powder or resin) is reclaimed. For metal powders it is estimated that 95–98% can be recycled (Petrovic et al., 2011).

At the product end-of-life stage, in-situ recycling systems can be linked to AM, diverting material from waste streams and into new applications. However this links to the material standardisation issue previously discussed. The greater the diversity in materials entering the recycling system then the greater the complexity of processes required during the recycling process, along with the potential for loss of value when materials cannot be separated. This then speak again for the need for the further development and validation of material properties and AM technologies.

The AM process has the potential to increase the value recovered embedded in waste. For instance, the example of reusing the plastics such as PET commonly used in consumer products and transforming them into fashion products. This can be readily achieved with the relatively simple AM equipment that is available to the general public either as products (e.g. EKOCYCLE Cube, Filabot linked to a 3D printer that uses filaments such as the MakerBot) or as services (e.g. 3D Hubs).

Table 6
Summary of observed sustainability advantages and challenges at the use and end-of-life stages.

Example	Advantages	Challenges
PPP	• Small and simple equipment, quick and easy to use as mobile or small-scale recycling station • Accessible and fun to use for the general public, raising awareness of plastic waste recycling • In-situ recycling of common plastic waste from everyday products and packaging	• Limits on recyclability of plastics due to quality loss • Educating consumers about recycling 3D printed plastics
Caterpillar	• Improved product utilisation • Reduced material consumption • Designed for longevity • Aligned with business model	• Replication of business model to other sectors
HMT	• Automated processes, all process steps integrated into one • High accuracy, thus high quality finish • Potential for high volume • Remanufacturing and repair of high value components at low(er) cost	• Limited integration of AM with other techniques in design and production • Required mindset shift for designers and engineers

Initiatives such as Better Future Factory help raise awareness and educate the public about small-scale plastic waste recycling and AM. Its Perpetual Plastic Project (PPP) investigated the possibilities of using plastic waste as an input for 3D printing. The materials tested are commonly used plastics for everyday products such as plastic cups, bottles, caps and supermarket plastic bags; i.e. polylactic acid (PLA), polystyrene (PS), low density polyethylene (LDPE), polyamide (PA) and polypropylene (PP). While the project found that some plastics are recycled more successfully than others, it also demonstrated the feasibility and relative ease of plastic recycling for 3D printing applications. One such plastic, the bio-polymer PLA, can provide a wide range of material properties and thus substitute for different plastics. Through the greater use of PLA and less diversity in the range of plastics consumed, simpler recycling systems may be realised. In addition, PLA has the ability to be recycled with no quality loss when treated by specialised companies (e.g. Plaxica). It can be fed back into the same system and thus enable a closed-loop circulation of material (Chen et al., 2015).

During repair, maintenance and remanufacturing, the make-to-order model can be applied with the same benefits of minimising the inventory waste as spare parts could be produced locally only when needed, with lower energy intensity processes. This is even more the case with modular and upgradable components, such as that previously described at Siemens PGS. AM repair technologies enable products to be maintained on a more localised basis, potentially in-situ. This is another advantage of the LMD AM technology co-developed by Rolls-Royce. As well as for component manufacture, LMD can also be used for the in-situ repair of damaged blisks. As a result, this technology offers the potential for maximising the use and extending the lifespan of the blisk. The equipment manufacturer Optomec has also commercialised a technology, LENS, that was originally developed at Pratt & Whitney and which can be applied to blisk repair.

Cold spray AM has a long history in its application to remanufacturing. Caterpillar has been using this technology for remanufacturing diesel engines since the early 1970s. During the subsequent four decades, Caterpillar improved and expanded its remanufacturing processes, Cat Reman, by replacing products before they break with a mixture of new and used parts. Over the last five years, they achieved an average of 94% of product end-of-life take back. This resulted in increased profit margins while simultaneously delivering products of the highest quality; remanufactured engines and parts are of the same quality of new ones. Today, 40% of the components in a reman engine are new and could be further reduced to 25% through better quality control, less scrapping of parts that could be remanufactured (i.e. better availability of reman components), new innovative repair techniques and AM. These new techniques can be applied for expensive parts such as metal spraying of the worn surfaces of piston rods followed by machining to obtain surfaces as good as new.

Another application of this technique is the repair of engine heads and blocks with cracks or similar faults by method of milling, metal spraying, grinding and polishing. For Caterpillar, remanufacturing makes both economic and environmental sense. Although the cost of remanufactured engines depends on the number of parts which can be remanufactured, it is estimated that a remanufactured engine costs 60% of the price of a new one, reman parts are sold at the price of 40% of new ones. The opportunity that remanufacturing presents extends beyond Caterpillar. In the UK alone it is estimated that remanufacturing has the potential to create £5.6bn for manufacturers and support the creation of over 310,000 new manufacturing jobs while reducing greenhouse gas emissions (Lavery et al., 2013).

Hybrid technologies combining additive and subtractive processes hold the potential to scale up remanufacturing and repair of high value components. Following the promising results of the Innovate UK RECLAIM project, the spin-out company Hybrid Manufacturing Technologies (HMT) developed the AMBIT™ multi-task system combining laser cladding, machining and inspection. This new hybrid systems addresses the issue of automation as it allows repair/remanufacture in a fully automated manner. This allows the process to be applied more broadly, more accurately and more productively to remanufacture high volume, high value parts at lower cost. As with LMD, this technology has been applied to the repair of turbine blades.

5. AM as part of a transition towards a more sustainable industrial system

The examples in this paper demonstrate some of the ways in which AM is beginning to transform the industrial system and enable improvements to resource efficiency and new models of sustainable production and consumption. These examples provide some initial insights in response to the question asked at the outset of this paper: *how can additive manufacturing enable more sustainable models of production and consumption?* The following sections build on observations from these examples with a discussion of how AM is creating opportunities for improved sustainability, who is realising these opportunities, and the effect of AM on business models and the distribution of manufacturing.

5.1. AM opportunities for enabling sustainability

Taking a product life cycle perspective, this paper has principally considered the opportunities through which AM could contribute towards sustainability. AM is an emerging manufacturing process and its adoption has direct impacts at this stage of the product life cycle. What is apparent from this study is that it is also beginning to deliver sustainability benefits at other stages of the product life cycle. The examples in this paper illustrate some of the nascent benefits which are slowly being realised, with the pace of adoption and diffusion varying across the different stages.

While AM can be considered as a direct substitute for traditional manufacturing processes, its primary economic benefits lie in the production of customised single or small batches of goods. As technology and market demonstrations of these advantages are being made, a growing number of organisations are adopting the technology or drawing on the offerings of service bureaus. In its current manifestation, AM will be a direct substitute for some organisations but for many it will be complementary to existing production, or a means of market entry because of the way that it lowers the cost of small-scale customised production.

A second major benefit of AM is the design freedoms it allows. The examples illustrate the potential sustainability improvements that can be made from the redesign of components, products and the process itself. Thus while AM can be used to directly replicate and produce existing components and products, this fails to take full advantage of these freedoms. Being able to take advantage of AM's design freedoms requires design for AM skills and competences that individuals and organisations cannot attain overnight. It requires that national policies be implemented to initiate educational programmes so that designers and engineers are acquiring the skills needed in industry, and that organisations invest in acquiring AM competences. For those organisations that have experience in the use of AM for rapid prototyping, this competence development may be more readily achieved as it makes the transition towards direct digital manufacturing.

Developing these organisational competences in design for additive manufacture enables digital designs to be produced and retained so that spare parts can be produced on demand when repairs are required. Coupled with modular design, repair, remanufacturing and refurbishment approaches will enable product life extension and enhancement. The relatively ease and affordability of producing such spare parts and integrating modular upgraded components may lead companies to rethink their business model, an issue that is discussed further in Section 5.3.

5.2. Realising AM opportunities for sustainability

As social constructions, technologies are developed and adopted within the complex network of existing infrastructure, technologies, behaviours, norms and attitudes of its constituents (Bijker and Law, 1992; Metcalfe, 1998). The social construction of technology tell us that history matters and that the investments made by individuals and organisations in hard and soft technology lead complex systems to exhibit path dependence (David, 1985; Shapiro and Varian, 1999). Within these complex systems, asynchronies between supply and demand create opportunities for value creation and capture (Ford et al., 2014; Metcalfe, 1998).

The type of value that can be created or captured varies. In the case of AM there are clear resource efficiency benefits that are being realised that have both economic and environmental benefits. These are most notable in aerospace where the use of high value materials and the high degree of waste generated during production provides strong economic incentives for adopting the new technology. For companies competing in this space, the economic motive is primary, with the environmental benefits being a positive side-effect. While behaviours may be most often motivated by the creation or capture of economic value, there are also cases where behaviours are motivated by social or environmental values. Such is the case for cleantech ventures such as Filabot, which have the direct aim of commercialising technologies to reduce negative environmental impacts. Through taking something considered as waste, Filabot's products can add value by supporting localised polymer recycling.

The examples in Section 4 show how some of the opportunities that AM technologies create for more sustainable production and consumption are beginning to be realised. The ability of an organisation or entrepreneur to respond to such opportunities is dependent on organisational antecedents, resources and cognitive capabilities (Eckhardt and Shane, 2003; Short et al., 2009). These factors help to understand who responds to opportunities, why they do so and where innovations may be expected to originate in the future.

Sometimes the innovators are established companies who already have achieved and maintained competitive positions in their markets. While possessing greater resources than new entrants, such companies face the ambidexterity challenge of continuing to exploit their existing technologies while concurrently exploring new technological domains and markets (March, 1991; Tushman and O'Reilly, 1996). Constrained by the existing capabilities they have developed and the need to serve existing customers, established organisations can be slower to respond to opportunities that may appear financially unattractive and without the growth prospects that their investors expect (Christensen, 1997; Leonard-Barton, 1995). In comparison, although entrepreneurial ventures possess far fewer resources, their relative advantages lie in having fewer sunk investments and the flexibility to experiment with novel product–market combinations and business models (Lubik and Garnsey, 2016).

Although the examples explored in this paper are just a small sample they indicate that for established companies such as GE, Rolls-Royce and Siemens, adopting AM provides a means through which they can serve their existing customers in new ways and attempt to retain or improve their competitiveness. How these three companies built their competences is illustrative. In the case of GE it first entered into a partnership with Morris Technologies to explore the potential of AM. Then when it began to see the direct benefits that could be achieved it realised that it needed to acquire Morris Technologies and the tacit knowledge and skills possessed by its employees. In contrast, Rolls-Royce acquired competences through collaboration with other aerospace companies, universities and AM equipment suppliers in an EU-funded consortium, while Siemens did so through direct interaction with its equipment supplier, EOS. In each there were transfers of AM knowledge that allowed the companies to begin to integrate AM into their activities.

In contrast, the entrepreneurial ventures described in this paper are involved in niche exploration, assuming risk and mobilising resources in order to develop products and services in response to perceived opportunities. This covers a range of niches that haven't yet been exploited by larger companies. They include the development of new material inputs (Metalysis), using a new material input arising from a waste by-product (Bewell Watches), launching consumer 3D printers (e.g. Makerbot, Ultimaker), growing a two-sided network of 3D printers (3D Hubs), or launching equipment for localised polymer filament recycling (Filabot). The market entry of these and similar ventures contribute to the AM ecosystem in ways that would not be done by established companies requiring larger revenue streams. Through experimenting in these niches, these ventures are helping the industry emerge and transition the manufacturing system towards one in which production is more localised and closed-loop material flows are achieved.

Given these market dynamics, these patterns can be expected to continue. Established firms will take the relatively lower-risk approach serving existing customers through component and product redesign, and the provision of spare parts and repair services. Sustainability benefits will be realised from these activities while there continues to be alignment between economic and environmental goals. Meanwhile entrepreneurial ventures will experiment by introducing new products and services into new market niches, thereby bringing wider system change. This experimentation will be closely monitored by established firms. The latter can employ a 'watch and see' approach as the niches are occupied by the risk-taking new ventures, then acquire those ventures demonstrating growth prospects or that have established a strategic position (Christensen and Raynor, 2003). Such was the approach adopted by the leading AM firm Stratasys when it acquired Makerbot in 2013.

5.3. AM and (sustainable?) business models

The business model is concerned with how companies create value, who they create value for, and how they capture that value (Andries et al., 2013). It is a *"structural template of how a focal firm transacts with customers, partners, and vendors. It captures the pattern of the firm's boundary spanning connections with factor and product markets"* (Zott and Amit, 2008, p.5). As described in Section 5.1, adopting AM could cause established companies to reconsider their business models, which in turn may change the sustainability impacts of their practices. One of the areas in which AM creates new business opportunities is in repair, refurbishment and remanufacturing. Companies are beginning to discover the implications of using AM technologies on extending product life cycles and closing the loop. It is proposed that the availability of AM technologies for repair, refurbishment and remanufacturing, and the subsequent extension to product life cycles, will create incentives for companies to adopt product-service business models.

The examples in this paper begin to show the forms of product-service business models that are arising. Such business models can be classified as being product-, use- or result-oriented (Gaiardelli et al., 2014). Of these, product-oriented and result-oriented business models are apparent around the adoption and application of AM. Product-oriented business models can include a number of product-related services. In the AM service space these services include spare parts and consumables delivery; updates/upgrades; remanufacturing, refurbishing, cleaning, safe keeping; recycling and take back; repair and maintenance. These services are being provided as part of the product-service business models of companies such as Caterpillar, GE and Siemens, through their remanufacturing, maintenance and upgrade services respectively. Pay-per-use services are becoming available within the result-oriented service space. Here Rolls-Royce is famed for its “Power by the Hour” pay-per-use approach. Extending the product life cycle of blisks through AM could enhance this offering, allowing repairs to be conducted more locally, quickly and cost effectively, and satisfying its customers' needs for a high level of flight utilisation. For both these product-oriented and result-oriented product-service business models, it is anticipated that providing these product-services will extend product life cycles and give rise to slower, less resource-intensive consumption. Further investigations are required into how product-service business models align business and sustainability interests, and whether they decouple the social and economic value created from the environmental impacts of production and consumption.

Outsourcing services are another type of result-oriented product-service business model. 3D Hubs, Kazzata and other service bureaus provide such services. Outsourcing allows customers to access AM without the high investment costs of capital. As a consequence it lowers the barriers to entry for prosumers and entrepreneurs. The availability of these services provides sustainability benefits in the form of increased equipment utilisation. Other utilisation improvements could be realised through use-oriented product-services, in the form of sharing, pooling or renting. The economic viability of providing these types of services is currently limited however by the need for skilled machine operators.

5.4. Re-distributed manufacturing

Along with creating opportunities for innovation and new business models, AM is reconfiguring the distribution of manufacturing activity. From the Industrial Revolution onwards, manufacturing has progressively become more centralised. However, the emergence of advanced digital manufacturing technologies such as AM is creating opportunities for manufacturing to become de-centralised. In this sense manufacturing activity that was once distributed is now being re-distributed as more localised manufacturing becomes economically realisable (Pearson et al., 2014).

An AM-based vision of the future may be one in which: “*The factories of the future will be more varied, and more distributed than those of today* […] *The production landscape will include capital intensive super factories producing complex products; reconfigurable units integrated with the fluid requirements of their supply chain partners; and local, mobile and domestic production sites for some products. Urban sites will become common as factories reduce their environmental impacts. The factory of the future may be at the bedside, in the home, in the field, in the office and on the battlefield*” (BIS, 2013).

In such a world, more localised manufacturing could radically transform supply and distribution networks. The greater application of AM and other digital manufacturing technologies means that “*logistics may be more about delivering digital design files – from one continent to printer farms in another – than about containers, ships and cargo planes*” (PWC, 2014). This shift towards the delivery of digital files and basic materials rather than complex assembled products implies that AM will have substantial positive effects on the environmental impacts of transportation. Product and component redesign will amplify these effects. For example, simplifying complex multi-component products into single-component products will in turn simplify the complex value chains associated with them, with value chains becoming less hierarchical and having fewer production stages. Such changes to the structure of value chains will be slow as change is first dependent on companies engaging in component and product redesign. Change will slowly filter through the production system as companies first engage in component and product redesign and then afterward begin to re-negotiate their position in the value chain. Furthermore, localised manufacturing using basic materials may also allow the material inputs to be sourced more locally, also resulting in shorter supply chains with lower transportation costs.

Although conceptually such changes suggest that environmental benefits will arise from these reconfigurations, questions arise regarding the relative resource efficiency of centralised mass production versus de-centralised, localised small-scale production (Kohtala, 2015). Using principles of lean production and eco-efficiency, larger factories have evolved to become more resource efficient. In the near-term, the resource efficiency of small-scale production may be less resource efficient as the lack of automation and lower equipment utilisation will not allow scale efficiencies to be realised. This may be an intermediate state as the technology is adopted and becomes better understood. However, the current lack of understanding about how AM-based production systems and value chains will affect overall resource consumption indicates that further studies are required if a more informed view of the sustainability impacts of AM implementation is to be obtained. These should go beyond studies that focus solely on the use of a single piece of equipment but consider the wider production network and life cycle analyses of components and products manufactured within these networks.

5.5. Sustainability advantages and challenges of AM adoption

Drawing on prior literature and the analysis and discussion of the cases in the previous sections, Table 7 provides a summary of the observed sustainability advantages and challenges arising from the adoption of AM. The advantages listed are ones that have been demonstrated for particular applications. However, due to the immaturity of AM technologies for direct manufacturing, their wider adoption and the realisation of these benefits is contingent on overcoming the significant challenges highlighted. As an exploratory study, this table provides a starting point for identifying the positive contributions that AM could bring across the product life cycle and the challenges ahead. However it is not a comprehensive listing of advantages and challenges. The rapid pace of change in this industry means that it is highly likely that new applications of AM with further sustainability benefits will soon be created.

While the concept of sustainability covers the environmental, social and economic, the use of the product and material life cycles as a conceptual framework has meant that environmental aspects of sustainability have emerged most prominently in this study. While some aspects of social sustainability have also emerged, these are relatively few. Employment and the distribution of labour, health and safety, ethics, quality of life, creativity and self-expression are just some aspects that are not featured in this study. It is clear that further investigations into the social sustainability of AM are needed that build upon and complement those previously conducted (Huang et al., 2013; Kohtala, 2015).

Table 7
Summary of observed sustainability advantages and challenges of AM adoption.

Advantages	Challenges
Product redesign	
• Design freedoms • Use of biomimicry concepts • Optimised geometries and performance to meet functional requirements • Product dematerialisation • Simplified assemblies, products and components • Reduced cost, time and quality problems through simplified assemblies • Reduced time between design and manufacturing • Improved product functionality • Improved product durability • Upgradability through modular design • Democratised design process	• Educating designers and engineers about the potential uses and benefits of AM • Supporting the skills development of prosumers, designers and engineers • Integrating sustainability considerations using Design for Environment or eco-design principles • Certifying new components • Capturing and replicating learning in future applications
Material input processing	
• Improved resource efficiency of raw material processing as AM requires different forms of material inputs • Reduced toxicity of material processing • Localised material recycling • Democratised material recycling • Diversion of waste and by-products from the waste stream • Upcycling of waste materials into new applications	• Resource efficiency improvements and recycling potential limited to certain materials • Scaling-up processes for new materials • Lack of knowledge and understanding of the environmental performance of material processing techniques • Validating material properties • Certifying materials • Standardising materials and processes • Increasing percentage of recycled content in material inputs • Limited recyclability of products at their end-of-life due to mixed materials • Avoiding material contamination • Improving resource efficiency of small-scale local recycling systems
Component and product manufacturing	
• Reduced energy intensity • Reduced waste generation • Improved quality and reduced rejection rates • Improved resource efficiency reduces costs • Make-to-order manufacturing at the point of use in space and time to the exact specifications required • Improved access to digital designs and manufacturing systems enables make-to-order manufacture of components and products • Flexibility through make-to-order manufacturing • Reduced cost of customisation and personalisation • Improved manufacturing process efficiency through AM-produced tools and moulds • Reduced material inputs and handling reduce costs • Reduced inventory waste including unsold and obsolete products • Localised manufacturing through proximity of producers and customers • Simplified assemblies lead to simpler and flatter supply chains • Simplified supply chains through transportation of more basic materials • Raised awareness of manufacturing process and its impacts • Increased equipment utilisation • Improved productivity, cost and resource efficiency using hybrid technologies • Automated manufacturing processes using hybrid technologies • Higher quality finish achieved using hybrid technologies	• Limited speed and reliability of AM technologies • Limited quality and aesthetics of products • Improving manufacturing capability of AM to integrate functional materials • High machine costs • Improving cost effectiveness and energy efficiency at higher production volumes • Lack of knowledge and understanding of the environmental performance of AM technologies, supply chains and products made through AM • Educating designers and engineers about the benefits of integrating AM into hybrid technologies • Integrating AM with hybrid technologies in design and production • Limited automation • Certifying manufacturing processes • Requirements for standards and regulations • Quality control in distributed networks • Maximising machine usage within distributed networks • Maximising machine usage in the home by prosumers • Optimising AM build process • Limited availability of digital designs • Cost of acquiring new digital designs • Fragmentation and uneven distribution of current AM services • Potential for AM to contribute to a materialistic society and consumerism • Individual prosumers may over-produce and over-consume leading to irresponsible prosumption • Capturing and replicating learning in future applications
Product use	
• Lightweight products • Improved operational efficiency • Improved functionality and durability • Component upgrade for product life extension	• Uncertain performance of products and components due to low maturity of technology • Uncertain performance of products and components over extended lifespan
Repair and remanufacturing	
• Reduced waste generation during repair process • Reduced process time for repair • Improved product utilisation through repair and remanufacturing • In-situ repair and remanufacturing enabled by availability of digital designs • In-situ and spot repair extends product life • Component upgrade during repair process • Product-service business models for repair and remanufacturing align business and sustainability interests	• Replicating business models in other sectors • Implementing distributed maintenance systems • Certifying repair and remanufacturing processes • Certifying spare parts to overcome liability issues • Benefits of AM-based product-service business model have yet to be demonstrated
Recycling	
• Improved material efficiency through recycling • Use of recycled materials and waste by-products as inputs • Simplified assemblies with less material diversity improves opportunities for recycling • Localised recycling systems • Raised awareness of material recycling • Increased acceptance of recycled material content • Democratised material recycling	• Limited recyclability of plastics due to quality losses • Non-recyclability of AM-produced multi-material goods • Educating consumers about recycling AM plastics • Incompatibility between non-standardised, non-recyclable materials

6. Conclusions

This paper has considered the ways in which AM can enable more sustainable models of production and consumption. Investigating AM's adoption through a life cycle perspective, four major categories have been identified in which AM is enabling sustainability benefits to be achieved: product and process redesign; material input processing; make-to-order component and product manufacturing; and closing the loop. This has led to the identification of the sustainability advantages that AM brings across the product and material life cycles, along with the challenges that must be overcome if these benefits are to be realised.

Given the advantages that AM seen in examples, it is clear that AM will play a part in the transition towards a more sustainable industrial system as the application of AM technologies creates opportunities for more sustainable production and consumption. Lessons from past studies of organisational behaviour and entrepreneurship suggest that established companies will primarily focus on serving existing customers and apply AM technologies in the redesign of components and products, while entrepreneurial ventures explore and develop the niches that emerge in the AM business ecosystem. AM also provides opportunity for organisations to experiment with their business models. The transition to direct digital manufacturing will lead to digital designs being kept on file; the ability to reproduce these files as spare parts for repair and remanufacturing will enable product life extension and provides incentives for product-service business models. The exploitation of these opportunities will lead to changes in the distribution of manufacturing and the reconfiguration of value chains. However, significant changes do not appear imminent as change is contingent on organisations first redesigning components and products to have fewer subcomponents, with this simplification subsequently leading to simplified supply chains.

Given its additive nature, AM is inherently a technology that will support sustainable production and consumption. How significant a part AM will play in the transition towards a more sustainable industrial system remains unclear however and there are dangers that unintended consequences with negative sustainability impacts may arise from its adoption and application. While sustainability benefits are evident, substantial challenges also exist (Table 7). It is important that as this technology and associated industrial activity emerges that we as a society understand its potential positive and negative impacts so that positive impacts can be embedded and ensure that AM does not become a missed opportunity for improving sustainability.

A host of further studies are therefore required to investigate these advantages and challenges. At this exploratory stage of research into the implications of AM on industrial sustainability, such studies require deep-dive single case studies and comparative case studies of different sectors, organisations, products and components, along with models of AM-based production systems. Such studies can provide richer insights into the effects of AM on sustainability, including the means through which opportunities are exploited and sustainability benefits are realised, the barriers preventing these benefits from being captured, and the specific contexts within which each of these occur. Furthermore, while this study has emphasised the consequences of AM on environmental sustainability, these future studies should not neglect to analyse the effects of adopting this novel production technology on social sustainability.

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Appendix

Table 8
Selected data sources for the examples used in this study.

Example	Data sources
3D Hubs	https://www.3dhubs.com/ http://www.solidsmack.com/cad-design-news/3d-hubs-co-founder-brian-garret-discusses-the-companys-20000th-3d-printer-milestone/
Bewell watches	http://www.bewellwatch.com/ http://www.abnewswire.com/pressreleases/designing-team-from-poland-create-newly-wooden-watches-by-3d-printing-technology_21711.html
Caterpillar	http://www.caterpillar.com/en/company/sustainability/sustainability-report.html http://www.product-life.org/en/archive/case-studies/caterpillar-remanufactured-products-group http://www.ellenmacarthurfoundation.org/case_studies/caterpillar
Construction	http://mx3d.com/projects/bridge/ http://3dprintcanalhouse.com/ http://3dprint.com/38144/3d-printed-apartment-building/ http://www.theguardian.com/cities/2015/jan/31/chinese-firm-creates-worlds-tallest-3d-printed-building
EKOCYCLE Cube	http://cubify.com/en/Ekocycle http://www.coca-colacompany.com/cokestyle/ekocycle-transforming-3d-printing-using-recycled-plastic-bottles
Filabot	http://www.filabot.com/ http://www.wired.com/2013/01/filabot-plastic-recycler/ https://www.kickstarter.com/projects/rocknail/filabot-plastic-filament-maker
GE	http://www.gereports.com/post/102897646835/ http://www.gereports.com/post/80701924024/
HMT	http://www.hybridmanutech.com/technology.html http://qm.the-mtc.org/downloads/qM-Q4-2014.pdf (Value Reclaimed, pp.10–14) https://www.catapult.org.uk/-/leading-a-remanufacturing-revolution
Home 3D printers	http://www.makerbot.com/ https://ultimaker.com/en/products
Kazzata	http://www.kazzata.com/ http://3dprintingindustry.com/2014/05/21/kazzata-first-marketplace-3d-printed-spare-parts/
Metalysis	http://www.metalysis.com/transforming-metals Lubik and Garnsey (2016); Mellor et al. (2015)

(*continued on next page*)

Table 8 (*continued*)

Example	Data sources
PPP	http://www.perpetualplasticproject.com/ http://www.betterfuturefactory.com/work/perpetual-plastic-project-ppp
Rolls-Royce	http://www.merlin-project.eu http://www.ilt.fraunhofer.de/en/publication-and-press/annual-report/2011/annual-report-2011-p82.html http://www.optomec.com/3d-printed-metals/lens-emerging-applications/blisk-repair/
Salcomp	http://www.eos.info/press/customer_case_studies/salcomp
SAVING project	http://www.manufacturingthefuture.co.uk/case-studies/
Siemens	http://www.siemens.fi/pool/cc/events/elp14/esitykset/navrotsky.pdf http://www.eos.info/press/customer_case_studies/siemens https://www.youtube.com/watch?v=VyEgbyNg0Q8

References

Andries, P., Debackere, K., Van Looy, B., 2013. Simultaneous experimentation as a learning strategy: business model development under uncertainty. Strateg. Entrep. 7 (4), 288–310.

ASTM, 2012. ASTM F2792–12a: Standard Terminology for Additive Manufacturing Technologies. ASTM International, West Conshohocken, PA.

Atzeni, E., Salmi, A., 2012. Economics of additive manufacturing for end-usable metal parts. Int. J. Adv. Manuf. Technol. 62 (9–12), 1147–1155.

Baumers, M., Tuck, C., Bourell, D.L., Sreenivasan, R., Hague, R., 2011. Sustainability of additive manufacturing: measuring the energy consumption of the laser sintering process. Proc. of the IMechE Vol. 225 Part B: J. Eng. Manuf. 2228–2239.

Berman, B., 2012. 3-D printing: the new industrial revolution. Bus. Horizons 55, 155–162.

Bijker, W.E., Law, J., 1992. Shaping Technology/Building Society: Studies in Sociotechnical Change. MIT Press, Cambridge, MA.

BIS, 2013. Future of Manufacturing: a New Era of Opportunity and Challenge for the UK – Summary Report.

Braungart, M., McDonough, W., 2002. Cradle to Cradle: Remaking the Way We Make Things. North Point Press, New York.

Buyle, M., Braet, J., Audenaert, A., 2013. Life cycle assessment in the construction sector: a review. Renew. Sustain. Energy Rev. 26, 379–388.

Chen, D., Heyer, S., Ibbotson, S., Salonitis, K., Steingrímsson, J.G., Thiede, S., 2015. Direct digital manufacturing: definition, evolution, and sustainability implications. J. Clean. Prod. 107, 615–625.

Christensen, C.M., 1997. The Innovator's Dilemma: when New Technologies Cause Great Firms to Fail. Harvard Business School Press, Boston, MA.

Christensen, C.M., Raynor, M., 2003. The Innovator's Solution: Creating and Sustaining Successful Growth. Harvard Business School Press, Boston, MA.

Colwell, L.V., 1956. The effects of high-frequency vibrations in grinding. Trans. ASME 78 (4), 837–846.

David, P.A., 1985. Clio and the economics of QWERTY. Am. Econ. Rev. 75 (2), 332–337.

de Jong, J.P.J., de Bruijn, E., 2013. Innovation lessons from 3-D printing. MIT Sloan Manag. Rev. 54 (2), 43–52.

Despeisse, M., Ford, S.J., 2015. The role of additive manufacturing in improving resource efficiency and sustainability. In: Proceedings of the 2015 International Conference on Advances in Production Management Systems (APMS 2015).

Eckhardt, J.T., Shane, S.A., 2003. Opportunities and entrepreneurship. J. Manag. 29 (3), 333–349.

Faludi, J., Bayley, C., Bhogal, S., Iribarne, M., 2015. Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment. Rapid Prototyp. 21 (1), 14–33.

Ford, S.J., Routley, M.J., Phaal, R., Probert, D.R., 2014. The industrial emergence of commercial inkjet printing. Eur. J. Innov. Manag. 17 (2), 126–143.

Fox, S., Li, L., 2012. Expanding the scope of prosumption: a framework for analysing potential contributions from advances in materials technologies. Technol. Forecast. Soc. Change 79 (4), 721–733.

Franco, A., Romoli, L., 2012. Characterization of laser energy consumption in sintering of polymer based powders. J. Mater. Process. Technol. 212 (4), 917–926.

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R., Albores, P., 2014. A classification model for product-service offerings. J. Clean. Prod. 66, 507–519.

Gartner, W.B., 1985. A conceptual framework for describing the phenomenon of new venture creation. Acad. Manag. Rev. 10 (4), 696–706.

Gebler, M., Schoot Uiterkamp, A.J.M., Visser, C., 2014. A global sustainability perspective on 3D printing technologies. Energy Policy 74 (C), 158–167.

Guo, N., Leu, M.C., 2013. Additive manufacturing: technology, applications and research needs. Front. Mech. Eng. 8 (3), 215–243.

Gutowski, T.G., Branham, M.S., Dahmus, J.B., Jones, A.J., Thiriez, A., 2009. Thermodynamic analysis of resources used in manufacturing processes. Environ. Sci. Technol. 43 (5), 1584–1590.

Hao, L., Raymond, D., Strano, G., Dadbakhsh, S., 2010. Enhancing the sustainability of additive manufacturing. In: Procedings of the 5th International Conference on Responsive Manufacturing – Green Manufacturing (ICRM 2010).

Huang, S.H., Liu, P., Mokasdar, A., Hou, L., 2013. Additive manufacturing and its societal impact: a literature review. Int. J. Adv. Manuf. Technol. 67, 1191–1203.

Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. J. Clean. Prod. 106, 654–668.

Kohtala, C., Hyysalo, S., 2015. Anticipated environmental sustainability of personal fabrication. J. Clean. Prod. 99, 333–344.

Lavery, G., Pennell, N., Brown, S., Evans, S., 2013. Next Manufacturing Revolution available at: http://www.nextmanufacturingrevolution.org/nmr-report-download/ (accessed 14.04.16.).

Le Bourhis, F., Kerbrat, O., Hascoet, J.Y., Mognol, P., 2013. Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing. Int. J. Adv. Manuf. Technol. 69, 1927–1939.

Leonard-Barton, D., 1995. Wellsprings of Knowledge: Building and Sustaining the Sources of Innovation. Harvard Business School Press, Boston, MA.

Lipson, H., 2012. Frontiers in additive manufacturing: the shape of things to come. Bridge Link. Eng. Soc. 42 (1), 5–12.

Lipson, H., Kerman, M., 2010. Factory @ Home: the Emerging Economy of Personal Fabrication – Overview and Recommendations. A report commissioned by the US Office of Science and Technology Policy.

Lubik, S.J., Garnsey, E.W., 2016. Early business model evolution in science-based ventures: the case of advanced materials. Long Range Plan. 49 (3), 393–408.

Lyons, B., 2012. Additive manufacturing in aerospace: examples and research outlook. Bridge Link. Eng. Soc. 42 (1), 13–19.

Mani, M., Lyons, K.W., Gupta, S.K., 2014. Sustainability characterization for additive manufacturing. J. Res. Natl. Inst. Stand. Technol. 119, 419–428.

March, J.G., 1991. Exploration and exploitation in organizational learning. Organ. Sci. 2 (1), 71–87.

Markov, A.I., Neppiras, E., 1966. Ultrasonic Machining of Intractable Materials. Iliffe, London.

Mellor, I., Grainger, L., Rao, K., Deane, J., Conti, M., Doughty, G., Vaughan, D., 2015. 4 – Titanium powder production via the metalysis process. In: Qian, M., Froes, F.H. (Eds.), Titanium Powder Metallurgy: Science, Technology and Applications, pp. 51–67.

Metcalfe, J.S., 1998. Evolutionary Economics and Creative Destruction. Routledge, London.

Murr, L.E., Gaytan, S.M., Medina, F., Martinez, E., Martinez, J.L., Hernandez, D.H., Machado, B.I., Ramirez, D.A., Wicker, R.B., 2010. Characterization of Ti6Al4V open cellular foams fabricated by additive manufacturing using electron beam melting. Mater. Sci. Eng. A 527 (7–8), 1861–1868.

Neely, A., 2008. Exploring the financial consequences of the servitisation of manufacturing. Oper. Manag. Res. 1 (2), 103–118.

Pearson, H., Noble, G., Hawkins, J., 2014. Re-distributed Manufacturing Workshop Report, 7–8 November, available at: https://www.epsrc.ac.uk/newsevents/pubs/re-distributed-manufacturing-workshop-report/ (accessed 10.12.15.).

Petrick, I.J., Simpson, T.W., 2013. 3D printing disrupts manufacturing: how economies of one create new rules of competition. Res. Technol. Manag. 56 (6), 12–16.

Petrovic, V., Gonzalez, J.V.H., Ferrando, O.J., Gordillo, J.D., Puchades, J.R.B., Grinan, L.P., 2011. Additive layered manufacturing: sectors of industrial application shown through case studies. Int. J. Prod. Res. 49 (4), 1061–1079.

Phaal, R., O'Sullivan, E., Routley, M.J., Ford, S.J., Probert, D.R., 2011. A framework for mapping industrial emergence. Technol. Forecast. Soc. Change 78 (2), 217–230.

PWC, 2014. 3D Printing and the New Shape of Industrial Manufacturing available at: http://www.pwc.com/us/en/industrial-products/assets/3d-printing-next_manufacturing-pwc.pdf (accessed 10.12.15.).

Reeves, P., 2008. Could Additive Manufacturing Contribute towards Environmental Sustainability and Carbon Reduction across the Supply Chain? Econolyst: the 3D Printing & Additive Manufacturing People available at: http://www.econolyst.co.uk/resources/documents (accessed 10.12.15.).

Royal Academy of Engineering, 2012. Industrial Systems: Capturing Value through Manufacturing. Royal Academy of Engineering, London available at: www.raeng.org.uk/indsys (accessed 10.1215.).

Sandström, C., 2015. Adopting 3D printing for manufacturing - evidence from the hearing aid industry. Technol. Forecast. Soc. Change 102, 160–168.

Shapiro, C., Varian, H.R., 1999. Information rules: a strategic guide to the network economy. Harvard Business School Press, Boston, MA.

Short, J.C., Ketchen, D.J., Shook, C.L., Ireland, R.D., 2009. The concept of 'opportunity' in entrepreneurship research: past accomplishments and future challenges. J. Manag. 36 (1), 40–65.

Sova, A., Grigoriev, S., Okunkova, A., Smurov, I., 2013. Potential of cold gas dynamic spray as additive manufacturing technology. Int. J. Adv. Manuf. Technol. 69 (9–12), 2269–2278.

Sreenivasan, R., Goel, A., Bourell, D.L., 2010. Sustainability issues in laser-based additive manufacturing. Phys. Procedia 5, 81–90.

Teuber, L., Osburg, V.-S., Toporowski, W., Militz, H., Krause, A., 2016. Wood polymer composites and their contribution to cascading utilisation. J. Clean. Prod. 110, 9–15.
TSB, 2012. Shaping our national competency in additive manufacturing: technology innovation needs analysis conducted by the Additive Manufacturing Special Interest Group for the Technology Strategy Board, Technology Strategy Board Knowledge Transfer Network Special Interest Group on Additive Manufacturing.
Tushman, M.L., O'Reilly, C.A., 1996. Ambidextrous organizations: managing evolutionary and revolutionary change. Calif. Manag. Rev. 38 (4), 8–30.
Yin, R.K., 2009. Case Study Research: Design and Methods. Sage, London.
Yoon, H.S., Lee, J.Y., Kim, H.S., Kim, M.S., Kim, E.S., Shin, Y.J., Chu, W.S., Ahn, S.H., 2014. A comparison of energy consumption in bulk forming, subtractive, and additive processes: review and case study. Int. J. Precis. Eng. Manuf. Green Technol. 1 (3), 261–279.
Zhou, F., Ji, Y., Jiao, R.J., 2013. Affective and cognitive design for mass personalization: status and prospect. J. Intell. Manuf. 24, 1047–1069.
Zott, C., Amit, R., 2008. Business model design and the performance of entrepreneurial firms. Organ. Sci. 18 (2), 181–199.