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Unlocking value for a circular economy through 3D printing: A research agenda

M. Despeisse [a,*], M. Baumers [b], P. Brown [c], F. Charnley [d], S.J. Ford [a], A. Garmulewicz [e], S. Knowles [f], T.H.W. Minshall [a], L. Mortara [a], F.P. Reed-Tsochas [g], J. Rowley [h]

[a] Institute for Manufacturing (IfM), University of Cambridge, Cambridge, UK
[b] Additive Manufacturing and 3D Printing Research Group (3DPRG), University of Nottingham, Nottingham, UK
[c] Industrial Design Engineering, Delft University of Technology, The Netherlands
[d] Cranfield Centre for Competitive Creative Design (C4D), Cranfield University, Cranfield, UK
[e] Facultad de Administración y Economía (FAE), Universidad de Santiago de Chile, Chile
[f] Fila-Cycle, Sheffield, UK
[g] Saïd Business School (SBS), University of Oxford, Oxford, UK
[h] Digits2Widgets (D2W), London, UK

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ABSTRACT

The circular economy (CE) aims to radically improve resource efficiency by eliminating the concept of waste and leading to a shift away from the linear take-make-waste model. In a CE, resources are flowing in a circular manner either in a biocycle (biomass) or technocycle (inorganic materials). While early studies indicate that 3D printing (3DP) holds substantial promise for sustainability and the creation of a CE, there is no guarantee that it will do so. There is great uncertainty regarding whether the current trajectory of 3DP adoption is creating more circular material flows or if it is leading to an alternative scenario in which less eco-efficient localised production, demands for customised goods, and a higher rate of product obsolescence combine to bring about increased resource consumption. It is critical that CE principles are embedded into the new manufacturing system before the adoption of 3DP reaches a critical inflection point in which negative practices become entrenched. This paper, authored by both academic and industry experts, proposes a research agenda to determine enablers and barriers for 3DP to achieve a CE. We explore the two following overarching questions to discover what specific issues they entail: (1) How can a more distributed manufacturing system based on 3DP create a circular economy of closed-loop material flows? (2) What are the barriers to a circular 3D printing economy? We specifically examine six areas—design, supply chains, information flows, entrepreneurship, business models and education—with the aim of formulating a research agenda to enable 3DP to reach its full potential for a CE.

1. Introduction

1.1. Background

The emergence of new advanced manufacturing technologies creates opportunities for changing how manufacturing activities are organised. Alongside important advances in innovation processes, technologies may affect the distribution of manufacturing and the subsequent flow of materials and goods with many potential sustainability benefits (Gebler et al., 2014). Such benefits include the potential to move towards a Circular Economy (CE), which aims to radically improve the resource efficiency of society by eliminating the concept of waste and leading to a shift away from the linear take-make-waste model.

It is still unclear however what the implications of the value chain reconfigurations caused by those new technologies are, whether they can realistically enable a more circular use of resources, and under which circumstances they are truly beneficial from a sustainability viewpoint. This requires a better understanding of the information flows and the relationships between stakeholders along the product and material life cycles (Evans et al., 2009).

One such advanced technology is 3D printing (3DP, also known in industry as additive manufacturing). The standard definition of 3DP technology is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" (ASTM, 2012). In other words, 3DP allows objects to be fabricated layer by layer in a continuous or incremental manner, enabling three dimensional objects to be 'printed' on demand (Petrovic et al., 2011).

Some of the most widely adopted 3DP technologies are material extrusion, vat photopolymerisation and powder bed fusion. Other technologies available include material jetting, binder jetting, directed

* Corresponding author.
E-mail address: md621@cam.ac.uk (M. Despeisse).

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energy deposition and sheet lamination. These technologies are able to process a variety of polymers, metals, ceramics and composites (Guo and Leu, 2013).

It is widely recognised that 3DP offers significant advantages in terms of design freedoms, mass customisation, co-creation and innovative business models (Berman, 2012; Petrick and Simpson, 2013; Ford and Despeisse, 2016; Rayna and Striukova, 2016).

Current industrial applications of 3DP are already enabling more circular production systems with the use of recycled and reclaimed materials as input for AM processes. For instance, in metal additive manufacturing, more than 95% of the unused powder can be locally filtered and reused directly (Vayre et al., 2012; Faludi et al., 2015a), while the other 5% can be sent to a centralised recycling facility to produce virgin powder. So not only is the process using less material due to its additive nature (i.e. material is added only were needed as opposed to subtractive processes which generate large amounts of material waste) but the system around the process is designed to enable a closed-loop circulation of materials.

Similarly, plastics used in 3DP are commonly recycled plastics, such as ABS, PLA and PET, and the filament itself often has a recycled content, e.g. EKOCYCLE Cube uses 25% recycled polyethylene terephthalate (rPET) in its cartridges[1] and Recyclebot (waste plastic extruder) produces filament from 100% household polymer waste (Baechler et al., 2013). While, plastics are still recycled at low rates in centralised recycling facilities, distributed plastics recycling to produce filament for 3DP could help increased this rate at a lower economic and environmental cost (Kreiger et al., 2014).

These examples are showing that 3DP can facilitate the implementation of circularity concepts by directly using reclaimed and recycled materials, but also with more sustainable materials—"ones which are renewable or abundant, non-toxic, recyclable or compostable, and which have little embodied energy or resources" (Faludi et al., 2015b). In addition, due to the digital nature of the fabrication process, the designs can be modified and shared easily. As its technical performance improves, the potential to use 3DP as a direct manufacturing process is gradually being realised in sectors such as aerospace, automotive, construction, pharmaceuticals and healthcare where personalisation is key, e.g. hearing aids, orthodontics, prosthetics, and implants. These are at various stages of maturity and adoption, and new applications continue to be found as the technology further develops.

1.2. Research aim and objectives

Among the variety of advanced manufacturing technologies that are currently emerging, 3DP stands out as one with significant potential for changing the distribution of manufacturing and society as a whole (Huang et al., 2013; Lipson, 2012). To date, investigations by researchers into the sustainability implications of 3DP have looked at the potential impact at a broad level (Gebler et al., 2014; Kohtala, 2015; Ford and Despeisse, 2016) and have focussed on the issue of material and energy consumption (Baumers et al., 2011; Faludi et al., 2015a). This paper brings together academic and industry experts in the field to construct a research agenda for exploring the means through which 3DP can enable more sustainable modes of production and consumption, and unlock value in the CE, doing so through investigating the following overarching questions:

- How can a more distributed manufacturing system based on 3D printing create a circular economy of closed-loop material flows?
- What are the barriers to a circular 3D printing economy?

Starting from the cross-disciplinary palette of questions identified by Ford et al. (2016), this paper derives research questions specific to the CE. Given the geographic location of the authors, these questions are approached from a UK perspective but are considered to be more widely generalisable.

2. Research programme

The issues covered within this paper are diverse and span the entire product and material life cycles (Fig. 1). The sections below explore six areas of research identified as critical to understand how 3DP can enable the move towards a CE, namely: (1) product, service and system design, (2) material supply chains, (3) information structure and flows, (4) entrepreneurial responses, (5) business model transformations, and (6) education and skills development. Accordingly, exploring these research areas requires a multidisciplinary approach and a systems-level perspective.

2.1. Product, service and system design

Designing for a CE requires a monumental shift in the way that organisations, designers and entrepreneurs develop, exploit and obtain value from products (Charnley et al., 2011; Bakker et al., 2014). There is an urgent need not only to address production processes, products and the provision of services, but to also redesign the patterns of consumption or lifestyles, as well as the institutions that underpin them (Vezzoli et al., 2015). However, the redesign task is not a simple one as there are strong interdependences between design, process and material selection. Manufacturing processes are not interchangeable as they usually require design adaptation and validation. The redesign also needs to account for the operational characteristics of the new manufacturing process, such as effective build volume utilisation and handling, variations in finish quality and material properties. This can be partly addressed through education (discussed in Section 2.6) and design software supporting optimisation for 3DP.

Design is particularly influential in how the entire value chain is configured in both forward and reverse processes (Schenkel et al., 2015). However, designers cannot wait for the development of a remanufacturing, reuse and/or recycling infrastructure and other alternative business models before they start to design for the CE; they must anticipate and prepare for the alternative economy, particularly where there is a long product lead time from initial concept to shop floor (Andrews, 2015).

3DP is proposed as a tool to enable design for a CE, but without a comprehensive understanding of the characteristics of the technology and resulting products that can align with CE principles, its use could be ill fated. Most existing approaches to design for a CE involve recovery at product and/or component level, where the implementation of maintenance, refurbishment and remanufacturing into industrial processes has been proposed as a means to extend the life of valuable components such as electrical and electronic goods and motor vehicles (Parker, 2010; Ellen MacArthur Foundation, 2013; Stahel, 2013). Consequently, design guidelines, principles and tools to support remanufacturing and refurbishment have been a fruitful topic for research, where many researchers have tried to improve ease of disassembly, material and component separation and reassembly for circular products (Sherwood and Shu, 2000; Sundin et al., 2012; Go et al., 2015).

Several sources also highlight the importance of accurate material selection during design, either purposeful to generate an additional benefit during or at end of life (Braungart and McDonough, 2002) or preventive, to reduce the environmental impact related to product creation (Allwood et al., 2011). However only the latter has been truly explored from a design perspective (Whalen and Peck, 2014; Peck et al., 2015).

In summary, the literature describing design guidelines suitable for a circular economy suggests necessary changes to incorporate the application of materials suitable for end-of-life and the technical characteristics of modularity, disassembly and repair-friendly features into products. This would appear to still be a limited approach as the value

[1] Information available from http://www.3dsystems.com/shop/support/ekocycle/faq.