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A literature review from a design perspective

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Additive manufacturing for circular product design: a literature review from a design perspective

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Abstract
Circular product design is a relatively new approach to design suitable strategies to realize circular products. Additive manufacturing (AM) is seen as a promising enabling production process. It has digital and additive characteristics, which makes AM different from conventional production techniques. However, it is yet unclear how this technique can contribute to circular product design in practice. In this paper, a literature review is placed in context, i.e. the results of a literature review on sustainability opportunities in AM are compared to five typical design cases in a design review.

The outcomes of the literature study reveal the aspects of the digital and additive characteristics of AM, that lead to potential sustainability opportunities. We compared these aspects to the circular design strategies as described by Bakker et al. (2014) and Bocken et al. (2016) in the context of the five selected design projects. Each project is described in terms of circular design strategies and how these were achieved through additive manufacturing.

Using design practice to reflect on the outcomes of the literature review resulted in a better understanding of the potential of additive manufacturing for circular product design. The relation between the sustainability aspects of AM and the circular design strategies were made explicit. AM seems to be especially suitable to customize parts to fit existing products and to contribute to new opportunities regarding material recycling. These findings deserve further exploration in order to understand the motives for implementation in circular product design.

Introduction

Circular product design aims to preserve the economic and environmental value of materials for as long as possible by keeping them in the economic system, either by lengthening their life within products or by 'looping' them back into the system for reuse (den Hollander et al., 2017). This is a relatively new approach to design suitable strategies to realize circular products (Bakker et al., 2014; Bocken et al., 2016).

Additive manufacturing (AM), being a rapidly growing and emerging technique, is seen as a promising enabling production process for the circular economy (Despeisse et al., 2017; Esmaeilian et al., 2016; Huang et al., 2015). It is different from conventional production techniques, like injection moulding or milling, through its digital and additive characteristics. Although literature describes many potential sustainability advantages of additive manufacturing, it is yet unclear how this technique can contribute to circular product design in practice.

We are particularly interested in the way in which designers can use AM to fulfil circular design requirements. Therefore, in this paper a literature review is performed concerning the sustainability aspects of additive manufacturing. The outcomes are compared to circular design strategies in the context of some typical AM product design projects. We will discuss how the additive manufacturing opportunities described in literature can be used in design practice to realize circular product design and move towards a circular economy.

Method

In this paper the state of the art of the field is studied as a foundation for research through design (Horváth, 2008; Koskinen et al., 2011; Stappers, 2007). Therefore, a literature review is placed in context, i.e. the results of the literature review on sustainability opportunities in AM are compared to five typical design cases in a design review.

The literature review is based on the rigorous and evidence focused methodology of Hagen-Zanker & Mallett, (2012). Relevant literature related to AM, circularity or sustainability and product design was collected. Literature was obtained through addition of search strings in Google scholar and snowballing. Search strings consisted of "circular product design" and ("additive manufacturing" OR "3d print*"); "circular economy" and ("additive manufacturing" OR "3d print*") and "product design";

"sustainable design" and ("additive manufacturing" OR "3d print*"). As this study focusses on circular product design, articles and documents focussing on circular business models were considered out of scope. It should be noted that research into the sustainability potential of additive manufacturing is an emerging field and, although rapidly expanding, not yet mature. Many papers are exploratory and propositional in character, often relying on (grey) literature and with only few empirical studies.

The design review describes five product design cases. The projects were selected based on the following criteria: 1) The cases show how 3D printing is implemented by professional designers and 2) how they gave shape to their sustainability ambitions. 3) All projects are conceptual consumer products, which are 4) not older than 5 years (made between 2012-2016), and 5) presented at design related exhibitions, hence fulfilling a pioneering and model role.

Results literature review

The literature study confirms that the digital and additive characteristics of additive manufacturing enable aspects that are considered to support sustainability. Table 1 outlines AM-related aspects resulting from these characteristics and their potential sustainability opportunities as described in literature.

The AM-aspects do not show a clear hierarchy and also in the relation to sustainability opportunities different papers have varying interpretations. Therefore, some of the aspects appear both in the first and second column. For example, "small scale" production is seen by some as an AM-aspect that enables customization and local production, but others consider it a sustainability opportunity that can be enabled through "absence of specialized tooling". Likewise, some consider local production as an AM-aspect enabling several sustainability opportunities, while others consider it as a sustainability opportunity being enabled through e.g. on demand production.

Aspects of additive manufacturing	Could result in sustainability opportunities	Literature
Design for customization and personalization	Extended product life through increased product desirability and attachment	Diegel et al., 2016; Diegel, 2010; Ford & Despeisse, 2016; Kondoh et al., 2017; Loy et al., 2016; Loy & Tatham, 2016; Nagarajan et al., 2016
Design for co-creation	Minimization of environmental impact (co-creation of sustainable solutions)	Kohtala, 2015; Reay & Withell, 2011
	Creation of individual meaning, leading to product attachment	Loy & Tatham, 2016
On-demand production	(in-situ) repair (production of spare parts)	Diegel et al., 2016; Ford & Despeisse, 2016; Mani et al., 2014; Matsumoto et al., 2016a; Mcintyre et al., 2016; Prendeville et al., 2016; Van Wijk & Van Wijk, 2015
	Supporting local production	Chen et al., 2015; Esmaeilian et al., 2016; Ford & Despeisse, 2016; Mcintyre et al., 2016; Singh Srai et al., 2016
	Reducing inventories (only producing when needed)	Esmaeilian et al., 2016; Huang et al., 2015; Kai et al., 2016; Loy & Tatham, 2016; Olson, 2013
	Digital storage (reducing inventories, eliminating storage)	Ford & Despeisse, 2016; Mohr & Khan, 2015
Small scale production	Supporting customization and personalization	Ford et al., 2015; Gebler et al., 2014; Hao et al., 2010; Huang et al., 2013
	Supporting local production	Despeisse et al., 2017; Kohtala, 2015
Local production (distributed manufacturing)	Localised repair (eliminating supply chains and logistics)	Despeisse et al., 2017; Ford & Despeisse, 2016; Freitas et al., 2016; Mançanares et al., 2015; Mcintyre et al., 2016; Van Wijk & Van Wijk, 2015
	Efficient use and/or recycling of local material	Despeisse et al., 2017; Kobayashi, 2016; Kreiger et al., 2014; Loy et al., 2016
	Shortened supply chain and reduced transport	Chen et al., 2015; Ford & Despeisse, 2016; Freitas et al., 2016; Gebler et al., 2014; Hao et al., 2010; Huang et al., 2013; Mançanares et al., 2015; Prendeville et al., 2016
	Empowerment of local communities	Chen et al., 2015; Ford & Despeisse, 2016; Loy et al., 2016; Prendeville et al., 2016
Absence of specialized tooling, i.e. no moulds required	Supporting small scale/customized production	Chen et al., 2015; Despeisse & Ford, 2015; Huang et al., 2015; Kondoh et al., 2017
	Less resources spent on fabrication (no mould, etc.)	Chen et al., 2015; Hao et al., 2010; Kondoh et al., 2017
Increased design flexibility enabling design for optimized geometries and/or lightweight products	Optimized material usage	Ford & Despeisse, 2016; Mançanares et al., 2015; Nagarajan et al., 2016
	Assembly simplification (fewer parts, materials)	Ford & Despeisse, 2016; Huang et al., 2013
	Increased product functionality	Nagarajan et al., 2016
	Supporting repair (e.g. less expensive, add on new material on existing surfaces)	Bertling et al., 2014; Diegel et al., 2016; Ellen MacArthur Foundation, 2013; Matsumoto et al., 2016b; Tang et al., 2016
	Reduced energy consumption	Ford & Despeisse, 2016; Hao et al., 2010; Kondoh et al., 2017; Mançanares et al., 2015; Mani et al., 2014; Nagarajan et al., 2016

Table 1. Aspects of AM that are considered to result in sustainable opportunities as obtained from the literature review. The appearance of Ford and Despeisse in the references is striking, which results from their work that describes overviews of AM and sustainability, as well as circular economy.

In addition to the sustainability opportunities outlined in Table 1, also challenges and uncertainties are noted. The additive character of AM allows for fabrication of complex parts, unable to be created in different ways (Lipson, 2012), resulting in optimized geometries and lightweight components. This is achieved through layer-by-layer building, instead of subtracting material, and is therefore expected to reduce production waste (e.g. Diegel, 2010; Ford & Despeisse, 2016; Kondoh et al., 2016). However this is criticized by others, because of the need for support material (Almeida & Correia, 2016; Bertling et al., 2014).

Another possible drawback of additive manufacturing is the high energy demand, when compared to conventional production processes. Although some life cycle analysis studies can be found concerning this topic, literature is too limited to draw firm conclusions, since the outcome depends heavily on the way of usage (Faludi et al., 2015; Huang et al., 2013). Pre-heating and the processing of raw materials are mentioned as energy intensive activities. However, AM is also mentioned as less energy intensive for small production volumes and in case of shortened supply chains (Almeida & Correia, 2016; Diegel et al., 2016; Freitas et al., 2016; Prendeville et al., 2016)

Repair reappears several times in table 1, as it is widely recognized in literature that additive manufacturing can support repair of products. Through local and on-demand production repair is thought to become more accessible and cheaper, e.g. no stock of spare-parts is needed because of digital storage. However, component certification and liability issues are currently a drawback for acceptance of AM in repair (Ford & Despeisse, 2016). This is not only the case for the production of spare parts,

but also for new parts, e.g. local printing and co-creation lead to new questions about product liability and intellectual property (Diegel et al., 2016).

Design review

In this section we will compare the potential contribution of additive manufacturing in sustainable product design, as discussed above, to the circular design strategies as described by Bakker et al. (2014) and Bocken et al. (2016). A summary of the strategies can be found in figure 1.

This comparison of literature review and circular design strategies is placed in context by the five selected design projects. Below, each case is described in terms of circular design strategies and how these were applied through additive manufacturing.

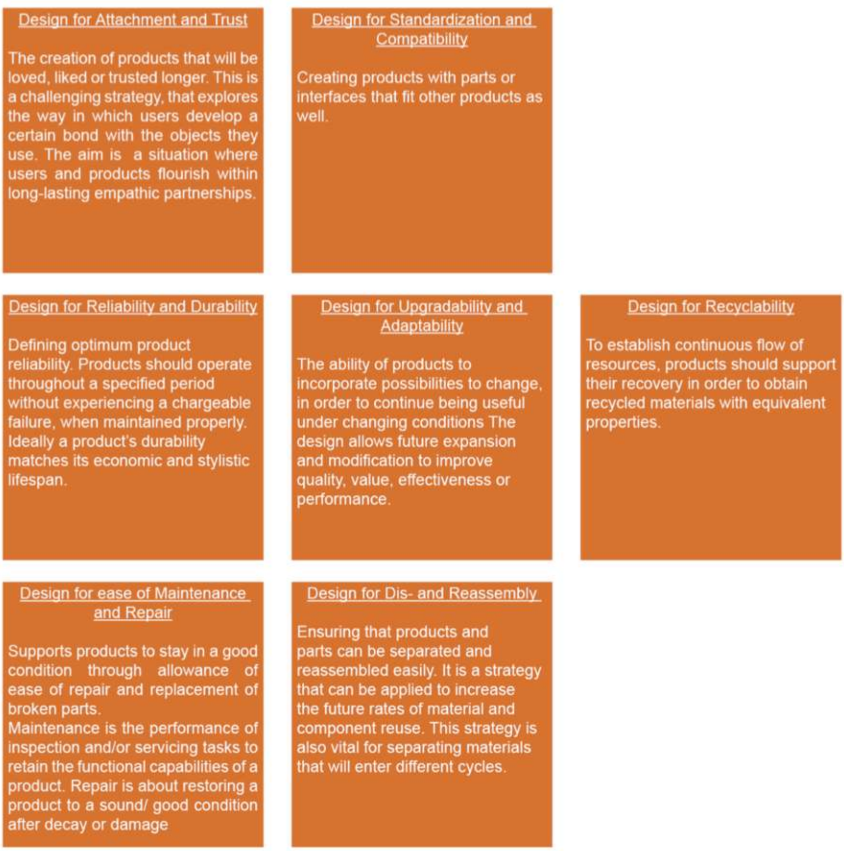

Figure 1. Circular design strategies (Bakker et al., 2014; Bocken et al., 2016).

1. "Project RE_": Samuel Bernier (2012)

Project RE_ explores 3D printing as do-it-yourself tool for reuse of products. Samuel Bernier expands the functionality of used cans and jars through the addition of customized lids. Fourteen new objects were designed, e.g. piggybank, pencil holder, orange press (figure 2)(Bernier, 2012). Additive manufacturing enabled this project for several reasons. Direct fabrication from the CAD model allows for adaptation to the different packaging materials through small-scale production and the absence of specialized tooling. In this way the circular design strategy for adaptability and upgradability is adopted. Following the open-source character of 3D printing (Kohtala, 2016; Tymrak et al., 2014; Van Wijk & Van Wijk, 2015), Bernier shares his files online, allowing his customers to adjust and print the objects themselves, leading to design for attachment and trust, i.e. the person-product relationship is strengthened through effort investment during the personalisation process (Mugge et al., 2009).

Figure 2. Objects belonging to "Project RE_" from Samuel Bernier

2. "Screw it": David Graas (2013)

David Graas designed connectors that transform old PET bottles and their lids into e.g. a vase (figure 3) (Graas, 2013). Although "Project Re_" and "Screw it" both increase longevity of packaging, AM is used in different ways. Graas uses additive manufacturing primarily as production technique to enable small-scale production. Due to the absence of specialized tooling, investment cost are reduced and this lowers the barrier to bring products to the market (Chen et al., 2015; Despeisse et al., 2017; Tang et al., 2016). Besides this, the stock is digital and products are only produced on-demand when ordered, eliminating inventory and reducing investment costs. The connectors are designed for standardization and compatibility, as well as dis- and reassembly, allowing different kind of PET bottles to finish the product. When screwed into the connectors the bottles are upgraded into a new and longer lasting product.

Figure 3. The "Screw it" vase from David Graas.

3. "Value added repair": Marcel den Hollander and Conny Bakker (2015)

In this project the lifespan of existing products is increased through repair, using the flexible design aspect of additive manufacturing. The design flexibility allows the creation of a component that fits the broken product, but also to adapt it. The central idea is that through customization of the broken part, a repair cannot only restore the product, but can add value in addition (figure 4). The improvement of the old product, by introducing extra functionalities, adds an extra dimension to repair. It supports design for "attachment and trust" and "upgradability and adaptability" can only be realized, because of absence of specialized tooling and small scale and local production.

Figure 4. Some examples of "Value added repair" from Marcel Den Hollander and Conny Bakker.

4. "BIOMIMICRY soft seating": Lilian van Daal (2014)
Van Daal designed a seat fabricated in one print, but expressing different material properties through different local structures (figure 5) (Daal, 2014). The chair is a good example of the design abilities of additive manufacturing to support design for recyclability. It represents the ability of AM to create complex shapes, leading to several benefits. In this case the variation of local structures makes 'assembly of parts' redundant; the seat is fabricated with only one material, enhancing not only recycling, but also simplifying the supply chain (Despeisse et al., 2017; Prendeville et al., 2016). This augments the ability of local recycling, which can lead to avoidance of information loss and a higher efficiency rate. Kreiger et al. (2014) found that distributed recycling could save up to 80% embodied energy for HDPE filament in areas with a low-density population.

Figure 5. "BIOMIMICRY soft seating" from Lilian van Daal.

5. "Standard Products": Jesse Kirschner and Jesse Howard (2016)
In "Standard Products" joints are 3D printed to create furniture from wood (e.g. stool, cupboard) (figure 6) (Kirschner & Howard, 2016). This project shows the ability of AM to combine design for standardization with design for adaptability. Several standard designs are offered, but through the digital customization, joints can be adjusted to local standards or personal preferences. For example, customers can adjust their product online from a stool into a bench and order the joints on-demand. By simply dis- and reassembling of parts, a better suiting piece of furniture is created and thus the lifespan can be increased. In addition, users can choose whether they prefer the digital file, the printed joints or the complete product (figure 6). In other words, they can decide on the degree of co-creation and local production. Through the availability of the digital files of the joints, parts can easily be replaced and products repaired when broken.

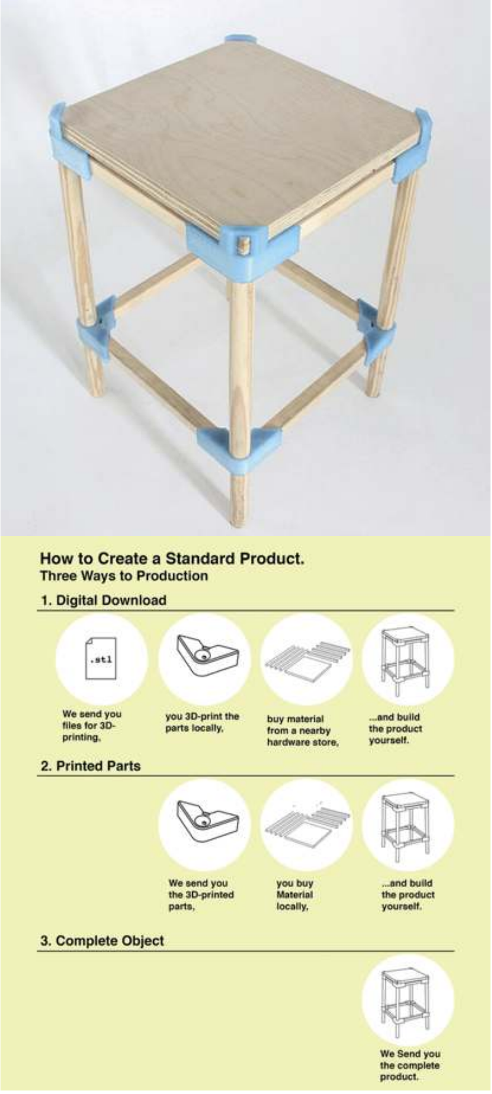

Figure 6. The stool of "Standard Products" from Jesse Kirschner and Jesse Howard.

Discussion and conclusion

Using design practice to reflect on the outcomes of the literature review resulted in a better understanding of the potential of additive manufacturing in relation to circular design strategies. In general, "Project Re", "Screw it" and "Value added repair" are good examples of product life extension of existing products. Parts are added to these products with additive manufacturing, increasing their value. "Standard products" is also an example of product life extension, but seems to be especially designed for it: i.e. instead of adding parts, the design itself consists of values supporting circular product solutions. "BIOMIMICRY soft seating" shows the potential of AM to create products that allow to close the loop through recycling.

In the literature review a number of specific AM-aspects were identified that contribute to sustainability. Table 2 outlines which AM-aspects support a particular circular design strategy based on the insights of this design review. Table 2 shows that design for "ease of maintenance and repair" and "upgradability and adaptability" are well supported by the AM aspects. Literature widely

Circular design strategies \ Sustainable aspects of AM	Design for customization and personalization	Design for co-creation	On-demand production	Small scale production	Local production	Absence of specialized tooling	Flexible design
Design for attachment and trust	3	1		1	1		
Design for reliability and durability							
Design for ease of maintenance and repair	3		5	3,5	3,5	3	3
Design for upgradability and	3,5	5	5	1,3	3,5	1,3	3
Design for standardization and compatibility							
Design for dis-and reassembly							
Design for recyclability					4		4

Table 2. Connection between circular design strategies and AM aspects. Numbers correspond with cases.

recognizes the suitability of AM for repair and this is confirmed by the design cases. Also, the relation with design for "attachment and trust", which is related to personalisation and customization, can be expected. This is mainly considered from the product-user interaction. However, the design cases show that customization is also valuable on product level, i.e. a component can perfectly fit an existing product. The suitability of AM for design for upgradability and adaptability is an interesting outcome, because it enables to extend the life of existing products, as shown by most of the discussed design cases.

Design for recyclability is mainly illustrated by "BIOMIMICRY soft seating" and shows an innovative use of additive manufacturing. This case demonstrates that different mechanical properties can be obtained with a single material, thus revealing opportunities within the relation between materials and products.

However, not all circular design strategies are supported by AM in the five cases. Design for "reliability and durability", "standardization and compatibility" and "dis- and reassembly" are not achieved through directly exploiting one or more of the identified AM aspects. A possible explanation is that these strategies depend highly on design and/or production. "Screw it", for example, evidently supports standardization and compatibility, as well as dis- and reassembly, but this is due to the design as such and not to the specifics of additive manufacturing. The advantages of AM that realize the design do not necessarily contribute to the realization of the circular design strategies; they could have been realized through other manufacturing methods as well. However, the five design cases are not exhaustive, therefore this needs further exploration.

Concluding, this study clearly shows the potential of AM for circular product design. The findings in table 2 deserve further exploration in order to understand the motives for implementation in circular product design. Investigating the strategies through design explorations combined with empirical research seems to be a promising route, because it allows to go beyond analysis, not only gaining knowledge, but also exploring tools for implementation.

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