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Exploring the potential of additive manufacturing for product design in a circular economy

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Abstract
Additive manufacturing, also known as 3D printing, is acknowledged for its potential to support sustainable design. In this paper, we explore whether the opportunities that additive manufacturing offers for sustainable design are also useful when designing for a circular economy, and to what extent additive manufacturing can support design for a circular economy. We performed a literature review on the sustainability aspects of additive manufacturing and held a series of interviews with designers about their 3D printed design projects to obtain in-depth information. The interviews were analysed using annotated portfolios, a novel analysis method created specifically for this research. This resulted in a visual representation of the outcomes. We found that additive manufacturing supports circular design strategies by creating opportunities to extend a product's lifespan, for instance by enabling repair or upgrades, even if these products were not originally designed for ease of repair or upgrading. However, the use of monolithic structurally complex parts that support design for recyclability may hinder high value product recovery, like repair. Besides this, the current offer of 3D printable materials should be extended with materials developed for durable use, as well as high-value reuse. Concluding, when accounting for these drawbacks, additive manufacturing is able to support multiple product life cycles and can provide valuable contributions to a circular economy.

Keywords: additive manufacturing, circular economy, product design, product life extension, design for sustainability, annotated portfolios

Highlights

- Additive manufacturing creates opportunities for applying circular design strategies
- Sustainable additive manufacturing opportunities should support multiple product lifecycles
- Availability of sustainable materials for additive manufacturing is an issue
- The interview data were analysed with annotated portfolios, a newly developed method

1. Introduction

Additive manufacturing (AM), also known as 3D printing, is a fast-developing collection of production techniques that enable new manufacturing paradigms. Products are manufactured through a digital and additive process in contrast to conventional production methods (Esmaeilian et al., 2016). The contribution of AM to sustainability is gaining attention in the literature; recently several special issues on this topic were published (e.g. Lifset, 2017; Muthu & Savalani, 2016). AM is considered to be promising for sustainable production because the additive and digital nature provides opportunities to save resources. This additive and digital nature enables, for instance, on demand production of spare parts for repair (Matsumoto et al., 2016) or avoids material losses when compared to subtractive technologies such as milling (Mani et al., 2014). These aspects may also offer new opportunities when designing products for the circular economy.

Design for a circular economy has recently come into focus as a new research area in the wider field of sustainable design. Product life extension and complete recovery of products and materials form essential elements of this approach, where a hierarchy between the recovery strategies guarantees product integrity i.e., the extent to which a product remains identical to its original (den Hollander et al., 2017). In other words, design for a circular economy “highlights the importance of high value and high-quality material cycles in a new manner” (Korhonen et al., 2018). The opportunities and difficulties of AM for (design for) a circular economy have hardly been addressed in the literature. Despeisse et al. (2017), who developed a circular economy research agenda for AM, published one of the few articles that directly address this topic. Therefore, the aim of this paper is to explore whether the opportunities that AM offers for sustainable design are also useful when designing for a circular economy, and to what extent AM can support design for a circular economy.

We first present a literature review on sustainability aspects of AM. Subsequently, we discuss the findings from interviews with five designers conducted to gain a greater understanding of the relation between design for sustainability and for a circular economy, based on practical design projects. We developed a new approach to analyse these interviews: it incorporates ‘annotated portfolios’ (Gaver & Bowers, 2012) and results in a visual representation of the outcomes, which supports the discussion on the role of AM in design for a circular economy. We conclude with insights on the opportunities and limitations of AM in relation to sustainable and circular product design.

2. Sustainability and additive manufacturing in relation to the circular design strategies

In previous research, we conducted a literature review (Sauerwein et al., 2017) which serves as the starting point for this paper. Sixty papers were screened on insights about AM and sustainability in product design; we found relevant information in 35 papers. We then analysed the papers and categorised the information. It should be noted that this is an emerging field and, although rapidly expanding, it is not yet mature. Many papers were exploratory in character, often relying on (grey) literature; there were only a few empirical studies.

Generally, the literature describes either the sustainability of the production process itself or the sustainability opportunities of 3D printed objects. The environmental impact of the production method is still unclear due to many influencing factors (Faludi et al., 2015; Rejeski et al., 2018). There is a strong focus on the energy use of the machine, and most results show that AM is often more energy intensive than conventional production methods (Kellens et al., 2017; Rejeski et al., 2018). The sustainability of AM should however also be analysed *beyond* the process parameters of the technology itself and include the whole life cycle (Jin et al., 2017). This makes quantification more challenging. The current literature on sustainable options for 3D printed objects is therefore mostly qualitative. We found several recurring aspects of AM that are expected to support sustainability. After categorisation, we consolidated these into four overarching strategies related to sustainability: product attachment through personalisation; resource efficiency through complex geometries; reparability; and, improved efficiency and local empowerment through distributed manufacturing. These are detailed below.

- *Product attachment through personalisation*
  Products are not only discarded because of technical failure, but often for psychological reasons. Design for sustainability uses design for product attachment to improve the bond between user and product in order to extend product lifetime (Ceschin & Gaziulusoy, 2016). Customisation and personalisation are seen as design strategies to create a stronger user-product relationship. AM enables these aspects because it makes unique and small series products accessible and affordable, e.g. AM does not require specialised tooling (Ford & Despeisse, 2016; Kondoh et al., 2017; Loy & Tatham, 2016). However, the literature presents little evidence as to whether customised and personalised design with AM actually results in stronger attachment and an associated longer lifetime (e.g. Diegel, 2010; Kondoh et al., 2017; Loy et al., 2016).

- *Resource efficiency through complex geometries*
  AM allows the creation of complex geometries, which can lead to a reduction of material usage, part consolidation, simplified assembly lines, increased product functionality, and reduced energy consumption (e.g., Huang et al., 2015; Nagarajan et al., 2016). AM can result in energy savings because it is well suited to lightweight design. Through topology optimisation, a part can be optimised considering the applied stress and required stiffness, resulting in lighter structures (Klippstein et al., 2017). Kellens et al. (2017) give an overview of several projects that show the energy reduction of transport vehicles as a result of lightweight design with AM.

- *Reparability*
  Digital production supports repair because broken parts can be imitated and reproduced. Some AM technologies can even directly print onto existing surfaces (Bertling et al., 2014; Matsumoto et al., 2016). AM is therefore recognised as a production technique that could favour repair. The digital production process makes it possible to store spare parts digitally and produce them on-demand (e.g., Mani et al., 2014). This reduces inventories and eliminates storage room, making repair more accessible (e.g., Esmaeilian et al., 2016; Ford & Despeisse, 2016).

- *Improved efficiency and local empowerment through distributed manufacturing*
  Distributed manufacturing (also referred to as local production) stands for a network of local production plants to meet the needs of a certain community or region by means of small scale and versatile production (Johansson et al., 2005). AM supports this system because the digital file of a product can be sent to be produced locally (Singh Srai et al., 2016). This concept is seen as a potentially sustainable alternative for centralised mass production, because of shorter supply chains, reduced transportation, decreased overproduction through on-demand supply, and localised repair and recycling (e.g., Ford & Despeisse, 2016; Kreiger et al., 2014; Van Wijk & Van Wijk, 2015). Several authors also state that local production can 'empower local communities' by creating 'community responsive solutions' and respecting 'cultural assets' (Chen et al., 2015; Ford & Despeisse, 2016; Loy et al., 2016; Prendeville et al., 2016). Although AM seems very suitable for distributed manufacturing, it is not clear whether this production system is actually more sustainable than centralised production. For instance, transportation reduction is often mentioned as a sustainable benefit (e.g. Chen et al., 2015; Ford & Despeisse, 2016), but this is often of minor impact in a complete life cycle assessment (Hanssen, 1998). Moreover, little information is given on the societal impact of distributed manufacturing.

The literature shows that AM as a production process is energy intensive. On a more systemic level, however, AM does seem promising for a number of sustainable design strategies, as illustrated above. The literature describes circular design strategies (Bakker et al., 2014; Bocken et al., 2016) which encapsulate some of the identified sustainable design strategies for AM. An additional strategy emphasises the focus on high value and high-quality cycling of materials (Korhonen et al., 2018). We now describe these circular design strategies in relation to product integrity, i.e., the first strategy is the most preferable in terms of product preservation:

1. *Design for attachment and trust*
   The intention is to create products that will be loved, liked, or trusted longer. The potential contribution of AM to this strategy is discussed above.
2. *Design for reliability and durability*
   The goal is to define optimum product reliability and durability. Products should operate throughout a specified period without experiencing failure when maintained properly.
3. *Design for ease of maintenance and repair*

Products stay in a good condition by facilitating repair and replacement of broken parts. The potential contribution of AM to this strategy is discussed above.

4. *Design for upgradability and adaptability*
   Products should incorporate options to be expanded and modified to continue being useful under changing conditions, and to improve quality, value, effectiveness, and performance.
5. *Design for standardisation and compatibility*
   This strategy aims to create products with parts that fit other products as well to facilitate intergenerational modularity.
6. *Design for disassembly and reassembly*
   The aim is to ensure that products and parts can be separated and reassembled easily. This strategy can be applied to increase future rates of material and component reuse. This strategy is also vital for separating materials that enter different product cycles through e.g., repair or remanufacturing.
7. *Design for recyclability*
   Products should support their material recovery to establish continuous flows of resources. Recycled materials with equivalent properties have to be obtained.

In this paper, we explore to which extent designers have used (consciously or unconsciously) the design for sustainability strategies in their AM projects, and subsequently, the potential contribution of AM to these circular strategies. Since this field is emergent, designers and manufacturers are still exploring the solution space of AM through conceptual designs that have little commercial value. We have therefore decided to focus on qualitative analysis based on experiences from design practice. By interviewing pioneering professional designers who are exploring the possibilities of AM through their work, we obtained greater insights in the sustainable and circular potential of this exciting new field.

3. Method

3.1. Semi-structured interviews

We interviewed designers who created pioneering 3D printed and sustainable design projects (section 3.3). We conducted semi-structured interviews divided into three sections, with questions on:

1. The designer’s experience of working with additive manufacturing
2. Sustainability aspects of the design
3. The applicability of the circular design strategies in relation to additive manufacturing.

In order to minimise bias in the answers concerning the sustainability of the design project, we initially only notified the interviewees about the goal to obtain knowledge about 3D printing in a design context. During the interview, we informed them about the research focus on sustainability. We asked them to name the sustainable aspects of their design and the role AM played in achieving these aspects. Subsequently, the circular design strategies were introduced by reading cards with the descriptions of the circular design strategies (see figure 1) out loud. The designers were asked to indicate which strategies were applicable to their design and the extent to which AM supported the use of these strategies.

Figure 1. Example of one of the cards with a description of the circular design strategies.

The interviews lasted between 40 and 65 minutes and were preferably conducted face to face. However, due to time and distance constraints, two of the five interviews were conducted through video-conference. Three interviews were held in Dutch and two in English. They were recorded and transcribed for analysis as described below.

3.2. Qualitative interview analysis with annotated portfolios

We developed a novel approach to analyse qualitative interviews by incorporating 'annotated portfolios' (see Sauerwein et al. (2018) for an extensive description). This allowed us to integrate visuals from the start of the analysis process, other than simply grouping text. Annotated portfolios are described by Gaver & Bowers (2012) as a method to annotate text to artefacts to facilitate a discussion among peers. We combined this method with McCracken's (1988) 5-step interview analysis method which describes the steps from data to knowledge contribution, each step representing a higher level of generality. The steps are illustrated in figure 2.

1. We transcribed the interviews and highlighted the sentences directly related to the design projects.
2. To further develop the highlighted sentences for interpretation, we transformed them into annotations. The sentences were summarised and translated into English (if needed). Subsequently, the annotations were connected to specific parts of a design project, resulting in annotated visuals.
3. Categories were identified from the interview setup and transcripts. These categories were assigned to the annotations with colour codes. Each annotation can belong to one or more categories. The colours put the annotations in context, and show the connections within the categories.
4. Relations between the categorised annotations were indicated with dotted lines to find patterns at the level of a particular interview. This helped to determine the most prominent annotations, to bring hierarchy, and to potentially eliminate redundant annotations.
5. The visuals of each design project were combined into the annotated portfolio. We sought for patterns by analysing the visuals from the design projects. New visuals were created to communicate these patterns and explain the results.

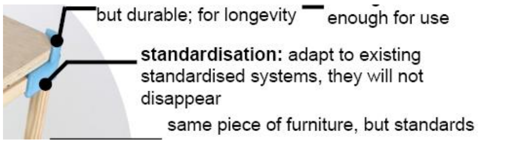
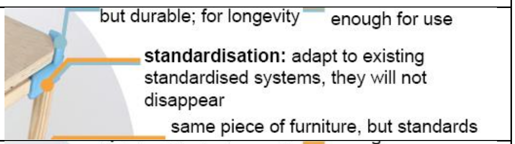
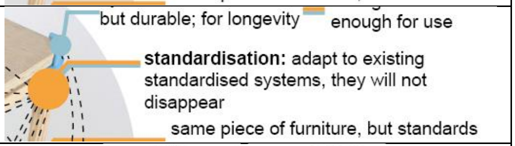
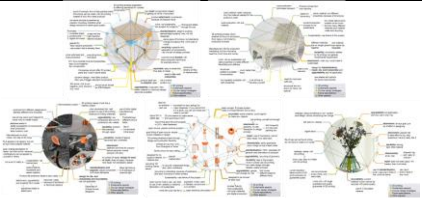
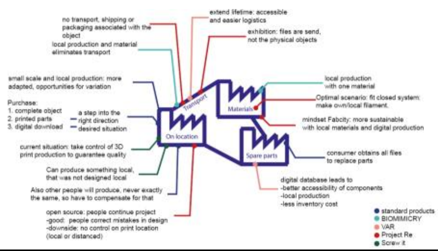
Step 1	Highlighted sentence from manuscript	“Well, this standardisation and compatibility is really about the fact that there are these standard components and huge infrastructures behind them, so they are not going anywhere, so let’s adapt to those.”
Step 2	Annotation Annotated visual	“standardisation: adapt to existing standardised systems, they will not disappear” 
Step 3	Categorised annotation using coloured lines	
Step 4	Relations between categorised annotations using dotted lines	
Step 5	Annotated portfolio New visual to illustrate a specific final pattern	 

Figure 2. Visual representation of ‘annotated portfolios as a method to analyse interviews’.

The stage between data and the general theories (i.e., intermediate-level knowledge (Lowgren, 2013) is often difficult to communicate. The annotated portfolio allowed us to clearly visualise this part of the interview analysis process. Statements and explanations from the interviewed designers are illustrated in a visual that directly links the information to the object. This leads to a comprehensive overview, as well as to a better understanding and communication of the analysis process.

3.3. Selected design projects

We searched for design projects on the internet based on several criteria: ‘produced with additive manufacturing’, ‘conveys sustainability’, ‘created by professional designers’ and ‘the project has been presented at a design-related exhibitions’. This last criterion served as an indicator of the projects’ pioneering and model roles.

The selected design projects are briefly described below.

Figure 3. 'Standard products' by Jesse Kirschner and Jesse Howard.

3.3.1. 'Standard products': Jesse Kirschner and Jesse Howard (2016)
In this project, the dimensions of furniture pieces are adjusted to standard wood dimensions that differ throughout the world. The stool in figure 3 is made of standard wood elements connected by 3D printed joints. These joints can be adjusted online to the right dimension. Customers can also customise the furniture according to their preference, for example, from a stool into a bench. Afterwards, they can choose to either purchase the digital files of the joints, the printed joints, or the complete product. This project was exhibited at the Dutch Design Week in 2016 (Strikwerda, 2016).

Figure 4. 'BIOMIMICRY: soft seating' by Lilian van Daal.

3.3.2. BIOMIMICRY: soft seating': Lilian van Daal (2014)
Van Daal aimed to design soft seating that is better suited to recycling. Soft seating or sofas are usually made of a combination of different materials (e.g. frame, pillows, spring, etc.), that are often hard to separate. Van Daal designed a seat made from a single material and fabricated in one print with AM. By varying the local structures, different material properties are obtained to fit the requirements of the different elements, like the legs or the seating (figure 4). The recyclability of the seat is increased through the use of a mono-material. A prototype has been exhibited in several places; it is considered an innovative example for soft seating (e.g. the Dutch Design Week 2014 (Hobson, 2015)).

Figure 5. ‘Value Added Repair’ by Marcel den Hollander and Conny Bakker.

3.3.3. ‘Value Added Repair’: Marcel den Hollander and Conny Bakker (2015)

Value Added Repair (VAR) aims to change the perception of repair. The product lifespan of broken products is extended, not only through repair, but also through the addition of an extra functionality (figure 5). The handle of a hedge cutter, for example, was given a better grip, or the fixture for a broken wheel arch now also holds a rear light. The flexible design options and accessibility of AM make it possible to add value to the products. The digital files can be adjusted and stored online. This project was exhibited at the Dutch Design Week in 2015 (Mind the Step, 2015), where it served as a demonstrator project.

Figure 6. ‘Project RE_’ by Samuel Bernier

3.3.4. ‘Project RE_’: Samuel Bernier (2012)

This project explores AM as a do-it-yourself tool for the reuse of products. The functionality of used cans and jars is converted into, for example, a pencil holder or piggy bank (figure 6), through the addition of customised lids. The project is open source and people can download the files online to print the lids themselves. In 2012, this project was one of the first inspiring examples of AM and is, therefore, still frequently exhibited all over the world (e.g. ‘Immediate Future – 3D printing’ in Madrid (Fabian, 2016)).

Figure 7. ‘Screw it’ by David Graas

3.3.5. ‘Screw it’: David Graas (2013)
David Graas designs products based on existing objects. The goal of this design project was to give a new function to PET bottles. He designed connectors that transform used bottles and their lids into new products, like a vase or bracelet (figure 7). This design project was featured in an overview exhibition on 3D printing (Materialise, 2016).

4. **Results**

4.1. The annotated portfolio
Based on the interview transcripts, we created annotations and assigned them to pictures of the design projects. We identified five categories (represented with colour codes): Three of the categories followed from the interview setup (‘3D printing’, ‘sustainable aspects’ and ‘circular design strategies’), the other two emerged from the transcripts (‘future opportunities’ and ‘other aspects’):

- 3D printing: annotations in this category refer to 3D printing as a manufacturing technique. They cover its abilities and shortcomings as a production technique, but also in terms of output and results (blue).
- Sustainable aspects: this category shows when the interviewee assigned a certain aspect to sustainable behaviour/use/production, or lack of it (green).
- Circular design strategies: this category depicts when the circular design strategies are mentioned or when something is mentioned about the circular economy (orange).
- Future opportunities: annotations in this category refer to the instances where designers talked about future possibilities of their design. This was either because they were inspired by the questions or had a future vision which could not yet be achieved (yellow).
- Other aspects: annotations in this category say something about the design project, but do not belong to one of the categories mentioned above (grey).

Figure 8 to 12 together form the annotated portfolio of this interview series. All visuals follow the same layout to support the comparison of the annotations between the design projects. The annotations are linked to details of the design project, and can thus be read in random order. The dotted lines indicate relations between the annotations to support pattern finding in the data. The size of the dots was increased with every additional connection. Since the annotated portfolio represents the stage of intermediate-level knowledge, it contains a high density of information.

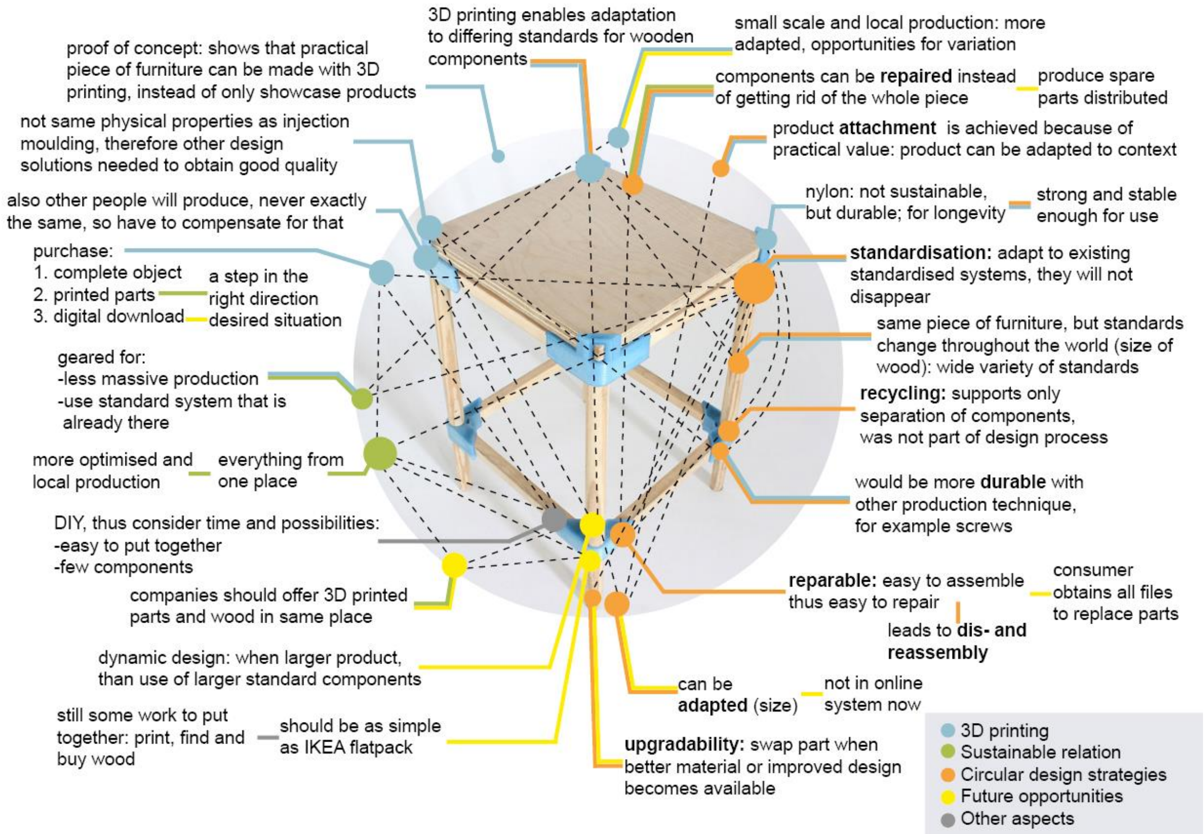


Figure 8. ‘Standard products’ with annotations. In this project, the categories ‘3D printing’, ‘circular design strategies’ and ‘future opportunities’ are most present. The annotation about standardisation is most connected, followed by the annotation about local production.

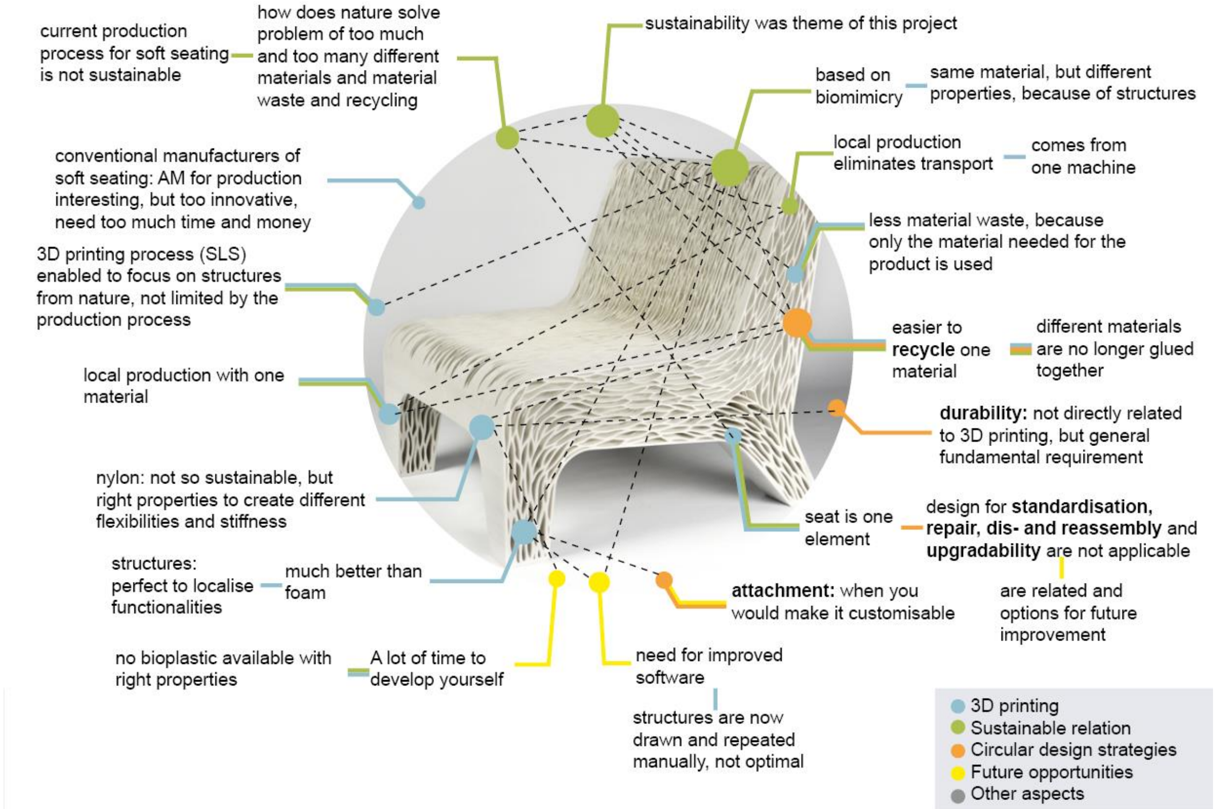


Figure 9. ‘BIOMIMICRY: soft seating’ with annotations. This project has mainly annotations belonging to the categories ‘3D printing’ and ‘sustainable relations’. The annotation about biomimicry received the most connections.

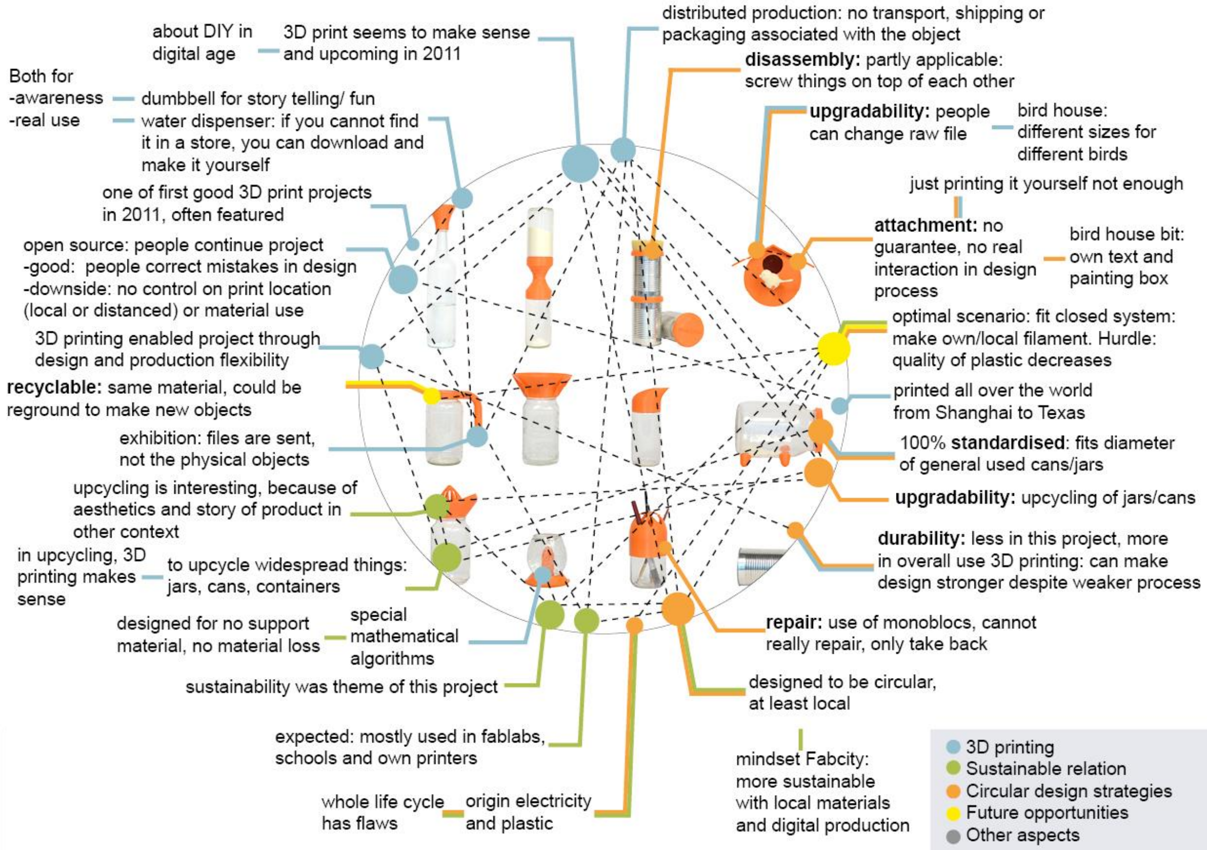


Figure 10. ‘Project Re_’ with annotations. The annotations in this project are evenly distributed between the categories ‘3D printing, ‘sustainable aspects’ and ‘circular design strategies’. The annotation about DIY in the digital age received the most connections.

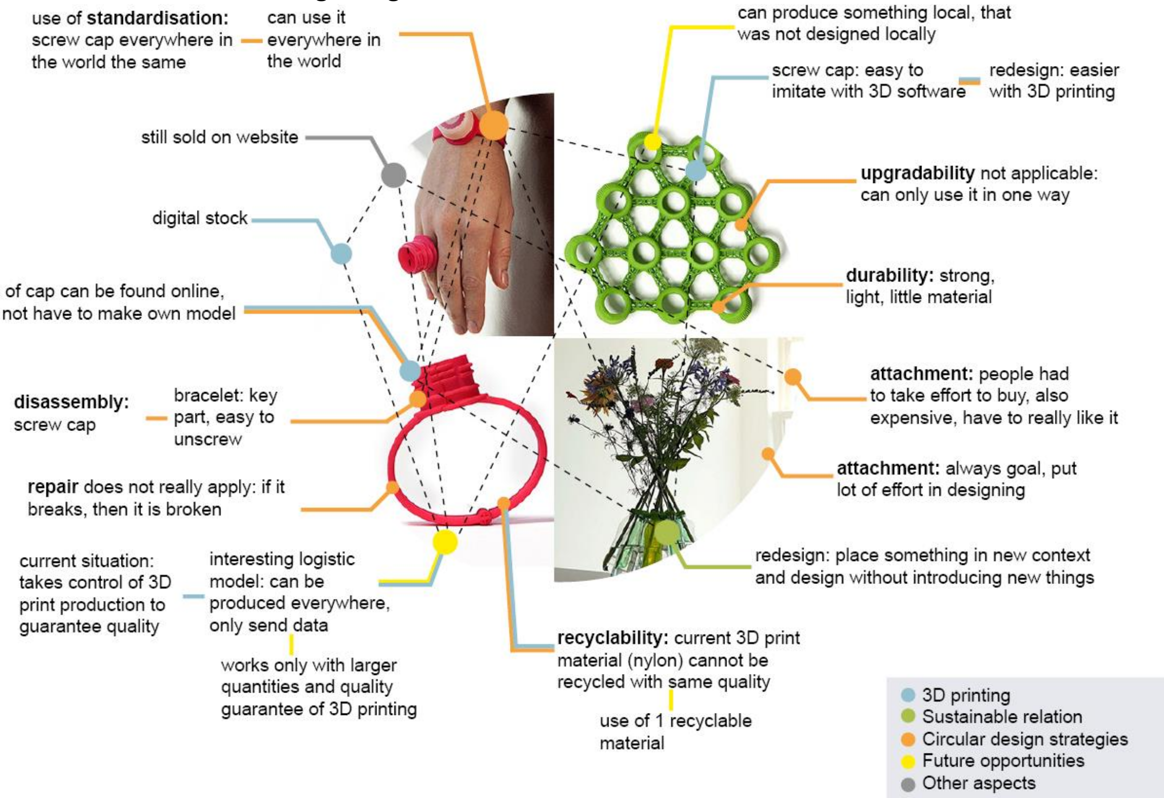


Figure 11. ‘Screw it’ with annotations. This project received the least annotations. Most belong to the category of ‘circular design strategies’. The annotation about standardisation received the most connections.

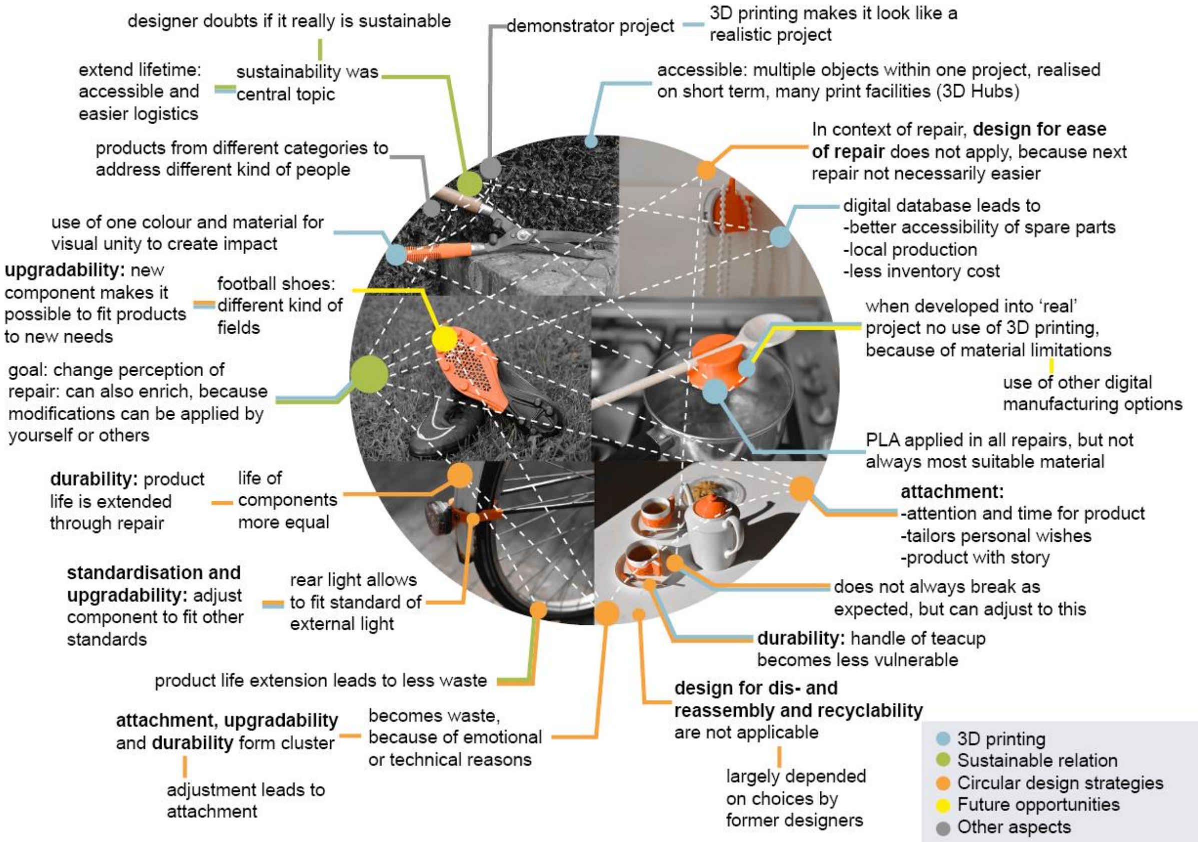


Figure 12. Value added repair (VAR)' with annotations. In this project, most annotations belong to the category of 'circular design strategies'. The annotations about the goal has the most connections and is well connected to the 'circular design strategies' category, but does not belong to this category.

4.2. Patterns in the annotated portfolio

When analysing the annotated portfolio, we looked for related annotations between the design projects that said something about sustainability and the link to design in a circular economy. We collected the annotations that could be clustered in a particular pattern and created new visuals with these annotations to communicate the findings. Distributed manufacturing using AM was a recurring topic in the design projects, adaptability with AM also appears in other circular design strategies than 'design for upgradability and adaptability', and we found sustainability of 3D printable materials to also be a recurring topic.

4.2.1. Distributed manufacturing in the design projects

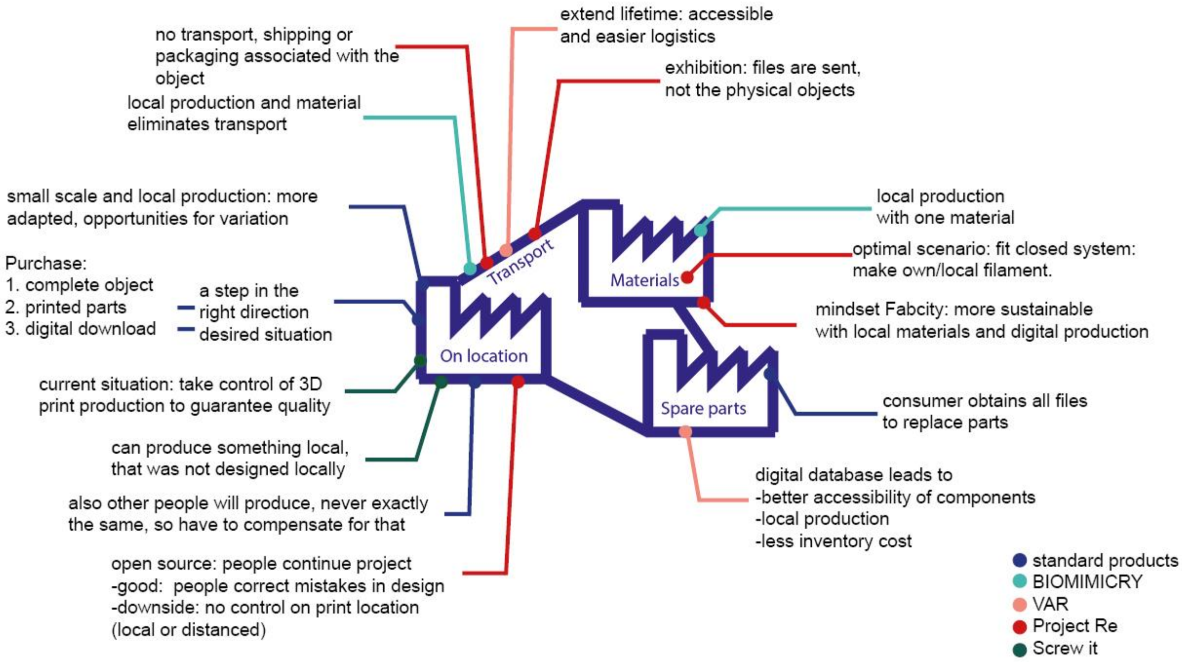


Figure 13. Annotations related to distributed manufacturing as stated by the designers

In figure 13, the annotations about distributed manufacturing as stated by the designers are presented in a graphical representation of distributed manufacturing, because this logistic model is 17not directly related to tangible aspects of the design projects. In line with the literature findings, the designers liked the possibilities AM creates for distributed manufacturing. The designer of 'Standard products', for example, uses local and small-scale production to create products that are adapted to the local context. Consumers have access to the digital files to replace parts when they break. In 'project Re_', the designer likes the idea that no transport and packaging of the product is needed when producing on loc
ation. The designer would prefer the filament to be locally produced as well to create a closed system. However, these filaments are scarce as AM materials are often specialised, originating from protected recipes only known to the producing company (Kellens et al., 2017).

Another difficulty is the precision of 3D printers as output can differ between printers, even with the same settings. For the designer of 'Screw it', this was a reason not to have the product produced locally, despite the fact that this was the initial intention. 'Project Re_' indicates a difficulty when distributed manufacturing is open source; even though open source enables people to continue the project and correct mistakes, the designer loses control over the printing process and cannot guarantee that the product is actually printed at the place of utilisation.

4.2.2. Additive manufacturing and the circular design strategies
To explore the role of additive manufacturing in design for the circular economy, we examined the annotations in more detail about the circular design strategies as indicated in orange in the annotated portfolio in section 4.1. In figure 14, a colour scheme has been used to identify the various circular design strategies. When reading the annotations, 'adaptability' (or variants) appear not only in 'design for upgradability and adaptability', but also in the other strategies.

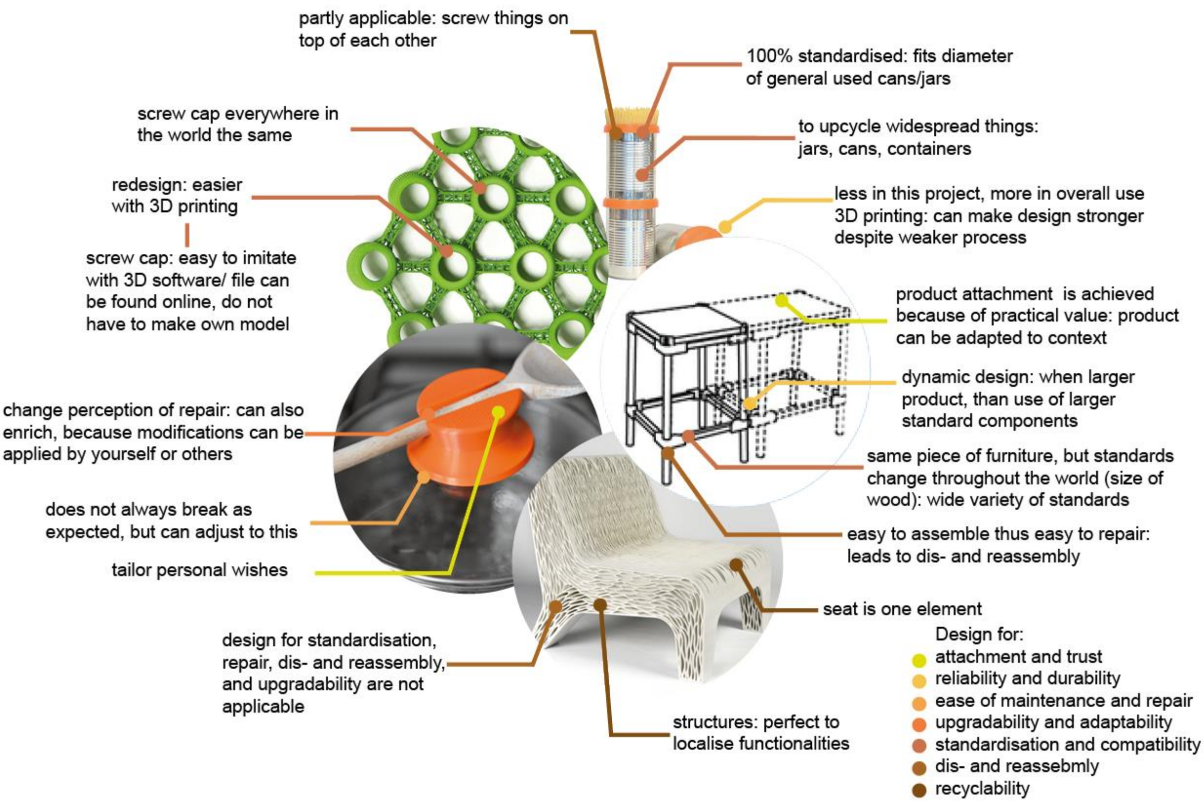


Figure 14. Annotations related to the circular design strategies

The project ‘standard products’ embraces adaptability, although its name suggests otherwise. Several furniture pieces can be made on an online platform. Consumers are given the opportunity to adjust the dimensions of furniture to their needs. They can, for example, create four stools that are perfectly sized to the width of their table. This creates the opportunity to achieve **product attachment** by adjusting the product to its surroundings. According to the designer of ‘standard products’, adaptability can also support **durability and reliability**; if the consumer decides to create a bench instead of a stool, the dimensions of the joints can be increased to match the forces applied to a bench.

Project ‘VAR’ illustrates how AM-enabled adaptability facilitates **repair** and **upgrades** of products that were initially not designed for these strategies. The replacement parts of the broken components were digitally modelled and upgraded after which they were 3D printed. In other words, through applying AM, the products became suitable for repair and upgradability. These modifications also enriched the act of repair as well as permitting customisation to personal wishes.

The designers of ‘project Re_’ and ‘screw it’ used AM to give a new life to existing products. Cans, jars and bottles obtained a new purpose with different kinds of 3D printed lids. They made use of existing standards to create non-standard design adaptations. The designers built on the standardised connector of these objects to guarantee wide applicability, and therefore a higher chance of actual reuse of discarded products.

‘Standard products’ are designed for **dis- and reassembly**, because the parts can easily be taken apart. However, this is mainly due to the shape and not specifically a result of AM production. The designer of ‘BIOMIMICRY: soft seating’, on the other hand, considers AM the only suitable production technique to achieve the complex and varying mono-material structures of this design project. Choosing a mono-material was possible because local properties can be tuned to local variations in structure that fit the product requirements. This resulted in a seat made out of one component. This completely eliminated the ability of dis- and reassembly, however, the choice for a mono-material optimally facilitates **design for recyclability**.

4.2.3. 3D printable materials in a circular economy

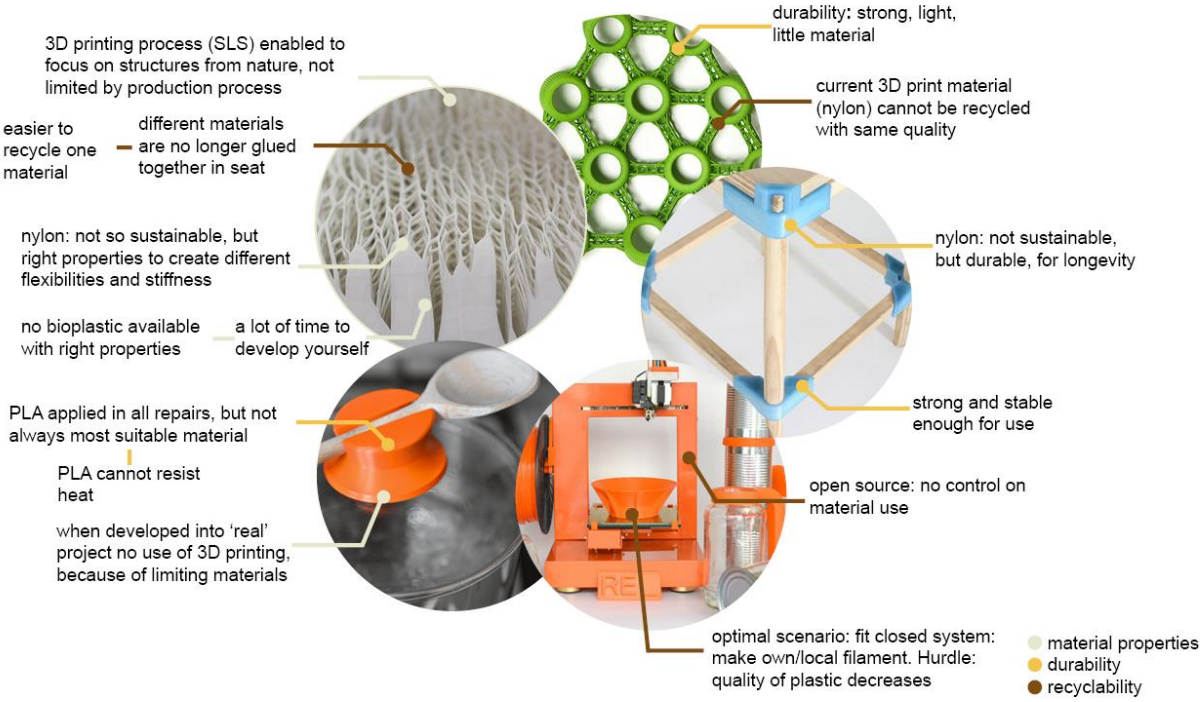


Figure 15. annotations related to the material input of additive manufacturing

All designers expressed tensions regarding their material choices and sustainability/circularity, as is evident from the annotations in figure 15. Most designers struggled to find a material they considered 'sustainable' and that also met their product requirements. In 'standard products', for example, the designers chose to use nylon although they did not acknowledge this a sustainable material; instead, it was chosen for durability considerations (i.e., the joints should be able to withstand certain applied forces). 'BIOMIMICRY: soft seating' is another example of this tension. This project aims to increase the recyclability of soft seating through the use of a mono-material. However, the material in the design project is nylon which is, according to the designer, currently not recycled after printing with the selected laser sintering (SLS) process. Therefore, the designer did not consider nylon as a sustainable material option; a bio-based plastic would have been preferable however this was unavailable for SLS printing and too time consuming to develop. The products in the design project 'value added repair' are actually made of a bioplastic: PLA. This material was well suited to the purpose of a demonstrator project. However, if the design objects were to be used in practice, PLA would not suffice because its mechanical and thermal properties do not fit the demands of these products. Although other printing materials exist that could fulfil these demands, the designer would prefer other digital manufacturing processes for functional production, because of the limited material availability for AM.

5. Discussion

In this paper, we set out to explore to what extent the opportunities offered by AM for sustainable design are also applicable when designing for a circular economy. In general, we found these opportunities also to be beneficial in a circular economy. However, there is a notable difference, as illustrated by the design project 'BIOMIMICRY: soft seating'. This project is designed for sustainability and can only be produced with AM, but most circular design strategies (such as ease of repair) are inapplicable. Due to the implementation of a mono-material, the design of the sofa is optimised for recyclability (despite the use of nylon which is currently not recycled in SLS printing), but this is “the least preferred option [in design for a circular economy] given that it involves the destruction of a product’s integrity” (den Hollander et al., 2017). In a circular economy, strategies that enable repair, refurbishment, and remanufacturing are preferred to recycling, as these help retain a product’s economic and environmental value over time. In this example, the ability to create complex shapes encouraged the designer to create a single part product which is easy to recycle and thus contributes to sustainability goals, but not necessarily to circular economy goals. This illustrates that design for sustainability with AM does not automatically lead to products that work well in a circular economy.

Our second aim was to explore to what extent AM can support design for a circular economy. AM gives a high degree of freedom to the design and production process. This is in conflict with standardisation as this aims to maximise compatibility and interoperability of products and parts. AM does, however, lead to a frequent use of ‘adaptability’ in the design projects. In addition, design for adaptability can even be applied beyond the first product life cycle. AM enables product repair or upgrade, thus extending product lifetime, even if the product was originally not designed for ease of repair or upgrading.

Durability and recyclability are extremely material dependent. Currently, little is known about the recyclability of 3D printed parts and products, due to the small scale at which AM is being applied. Moreover, the availability of recycled AM materials is limited; there are some recycled filaments for FDM printing like PET and ABS (Refil, 2019), but in SLS printing, for example, recyclability is only referred to in relation to the reuse of leftover powder after printing (Bourell et al., 2017). Another sustainable option is to choose bio-based materials: PLA filament is popular for FDM printing, but is limited in terms of durability and functionality. Alternative plastics with suitable properties would be oil-based plastics. Although these materials might be recyclable, the interviewed designers express a desire for a wider palette of materials based on renewable sources that meet the needs of their design projects. Recently, a number of studies were published on sustainable alternatives for 3D printable materials. Tenhunen et al. (2018) printed cellulose-based materials on cellulosic fabrics, resulting in a material mixture from the same resource. Mogas Soldevila & Oxman (2015) developed 3D printable materials based on Chitosan and water which are fully recyclable upon contact with water, and Faludi et al.(2019) calculated the sustainable gain of a pecan shell-based 3D printing material in comparison with ABS. These materials are based on abundant and local resources and therefore also satisfy the need to close the system on a local scale.

6. Conclusion

We explored a number of opportunities that AM offers for design for a circular economy. We conducted a literature review about AM and sustainability in product design. Subsequently, we interviewed five designers about the use of AM and the sustainability of their projects, and about the links of their projects to the circular design strategies. We developed a new method to present the analysed interview data with annotated portfolios. The strong visual representation of the data provides rich insights into our qualitative research findings.

The analysis of the design projects showed that AM creates opportunities to enable circular design strategies like upgrades and repair which extend a product’s lifespan, even if these were not considered in the original product design. This is attributed to AM characteristics like digital production and adaptability; digital product files can be adjusted to changing needs and contexts or to enable repair, essential for product life extension.

However, to fully support design for a circular economy with AM, a number of challenges need to be overcome. There is a need to develop materials that enable durable use, as well as high-value reuse.

Furthermore, monolithic structurally complex parts that support design for recyclability may hinder high value product recovery. It is therefore essential that sustainable opportunities offered by AM support multiple product life cycles when designing for a circular economy. Accounting for AM in the design process can lead to a new generation of products that successfully operate in a circular economy.

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