Additive Manufacturing for Design in a Circular Economy

Marita Sauerwein

Additive Manufacturing for Design in a Circular Economy

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Marita SAUERWEIN
Master of Science in Industrial Design Engineering,
Delft university of Technology, the Netherlands
born in Vorden, the Netherlands

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	chairperson
Prof. dr. A.R. Balkenende	Delft University of Technology, promotor
Prof. dr. ir. C.A. Bakker	Delft University of Technology, promotor
Dr. ir. E.L. Doubrovski	Delft University of Technology, copromotor

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Voor mijn aanstaande kind,
aan wie ik een duurzame en vindingrijke wereld wens

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Summary

In this thesis, we present the results of our explorations into how the use of additive manufacturing (AM) or 3D printing as a production method can contribute to design in a circular economy. The aim of design in a circular economy is to preserve the value of products and materials by keeping them in the economic system, either by lengthening their lifetime or through high value reuse and recovery. Design in a circular economy needs to account for both product integrity and material integrity, which represent the quality of products and materials to remain whole and complete over time. AM is an emerging technology and is viewed as a promising production process for the circular economy because of its unique additive and digital character. The papers and chapters making up this thesis answer the following two research questions:

1. How can additive manufacturing support product integrity in a circular economy?
2. How can additive manufacturing support material integrity in a circular economy?

We addressed these questions by performing a literature and design review followed by experimental studies using "research through design"(RtD) as a research method. In RtD, design plays a formative role to generate knowledge by iteratively developing prototypes and framing, reflecting on, and communicating insights from these. We used the prototyping process to develop the emerging AM technology in the new context of a circular economy. The main contributions can be summarised as following:

- We helped establish of a new research direction by exploring design approaches for product integrity and material integrity in a circular economy.
- We developed a circular AM process flow for product integrity. This is demonstrated by showing that the digital and additive character of AM can be harnessed to develop reversible connections that enable products to be disassembled and reassembled without loss of quality. We developed reversible joints and demonstrated these with a proof-of-concept of a lamp and vase (figure I.A).
- We established a design approach for developing reprintable materials. This was demonstrated by producing reprintable materials from locally available bio-based resources, i.e. ground mussel shells with two different binders (sugar and alginate). We designed a lampshade and hairpin and 3D printed them using these materials (figure I.B and C).

- We contributed to the domain of 'research through design' by using the prototyping process for knowledge generation; a less common use. The design goal in the prototyping process was used to obtain relevant information (from other disciplines) for developing technology in a new context. This resulted in an iterative process between experimental prototyping processes and scientific knowledge generation.

The thesis includes a number of published and submitted articles: chapters 2, 3 and 5 have been published, chapter 4 is under review, and chapter 6 is accepted for publication at the time of writing.

In chapter 2, the use of annotated portfolios was extended to analyse qualitative interview data. With this development, interview data can now be visually analysed, which is valuable when designers are interviewed about their design projects. The visual overview of images with annotations led to fruitful discussions and contributed to a deeper understanding of the subject. We applied this novel approach in chapter 3.

In chapter 3, we explored to what extent the opportunities that AM offers for sustainable design are also useful when designing in a circular economy. we performed a literature review and held qualitative interviews with five designers about their sustainable 3D printing projects. The interviews were analysed using the extended annotated portfolios. Our results present opportunities (adapting digital design files for changing needs and using complex structures for recycling) and challenges (complex geometries can hamper disassembly and reassembly, and designers request for renewable materials) for how AM can support design in a circular economy. Based on these findings, we defined two areas for exploration in our experimental studies: 'pursuing high value reuse with reversible connections for product integrity' (Chapter 4) and 'the development of reprintable materials from bio-based resources for material integrity' (Chapter 5 and 6).

In chapter 4, a theoretical framework is presented for a circular AM process flow that considers high value reuse by including both materials and physical parts directly in the digital production process. The process flow is demonstrated with a prototyping process resulting in prototypes with reversible 3D printed joints and laser cut panels that can be both disassembled and reassembled.

In chapter 5 and 6, we established a design approach for the development of reprintable materials. Reprintable materials can be reconstituted to their original properties in terms of printability and functionality. A full material life cycle is described for the development of these materials. In chapter 5, we explore this approach by using locally sourced bio-based waste streams. This resulted in a material for extrusion paste printing from ground mussel shells and sugar that can be dissolved in water after use to retain a printable paste. In chapter 6, we further elaborate on the design approach and developed a reprintable bio-based composite material from ground mussel shells and alginate. This new material can be recovered based on reversable ion cross-linking resulting in water-resistant materials.

In Chapter 7, we describe the insights gained about product integrity and material integrity with AM for design in a circular economy. Furthermore, we evaluate our research process with 'research through design' and present practical insights for design as well as share directions for future research.

We would like to conclude by nothing that, in spite of all the optimism about the way the use of AM can accelerate the transition to a circular economy, there are currently few AM applications that actually support and enable the circular economy. Our exploration shows that to successfully print for product integrity and material integrity, both in-depth knowledge and understanding of the AM production technique is required.

Figure I. A: Lamp and vase with reversible 3D printed joints (design by the author). B: Lampshade from mussel shell-sugar material (design by Joost Vette). C: Hairpin from mussel shell-alginate material (design by the author).

Figuur II. A: Een lamp en vaas met omkeerbare 3D-geprinte verbindingen (ontwerp van de auteur). B: Lampenkap van mosselschelp-suikermateriaal (ontwerp van Joost Vette). C: Haarspeld van mosselschelp-alginaatmateriaal (ontwerp van de auteur).

Samenvatting

In dit proefschrift verkennen we hoe het gebruik van 3D-printen als een productiemethode kan bijdragen aan design in een circulaire economie. Design in een circulaire economie streeft naar het behoud van waarde van producten en materialen in het economisch systeem. Dit kan ofwel worden bereikt door levensduurverlenging, ofwel door het hoogwaardig hergebruik en herstel van producten of materialen. Productintegriteit en materiaalintegriteit zijn van belang voor design in een circulaire economie, omdat deze begrippen een ongeschonden product- en materiaalkwaliteit in verloop van tijd representeren. 3D-printen is een opkomende technologie die vaak wordt gezien als een veelbelovende productiemethode voor de circulaire economie. Om te onderzoeken hoe het gebruik van 3D-printen daadwerkelijk kan bijdragen aan design in een dergelijke economie, hebben we twee onderzoeksvragen opgesteld:

1. Hoe kan 3D-printen productintegriteit in een circulaire economie ondersteunen?
2. Hoe kan 3D-printen materiaalintegriteit in een circulaire economie ondersteunen?

We hebben de onderzoeksvragen benaderd door middel van een literatuuronderzoek en design review en vervolgens door het uitvoeren van experimentele studies met de methode “research through design” (RtD). Design speelt in RtD een bepalende rol bij kennisvergaring door iteratief prototypes te ontwikkelen en op inzichten hieruit te reflecteren en deze te framen en communiceren. Wij hebben het prototypeproces gebruikt om kennis te genereren, zodat we 3D-printen konden ontwikkelen in de nieuwe context van een circulaire economie. De belangrijkste bevindingen uit ons onderzoek zijn:

- We hebben bijgedragen aan de totstandkoming van een nieuwe onderzoeksrichting door ontwerpwerkwijzen voor productintegriteit en materiaalintegriteit in een circulaire economie te verkennen.
- We hebben een circulaire werkwijze voor 3D-printen en productintegriteit geïntroduceerd. We hebben deze werkwijze gedemonstreerd door te laten zien dat het digitale en additive karakter van 3D-printen kan bijdragen aan de ontwikkeling van omkeerbare verbindingen. Deze verbindingen zorgen ervoor dat producten zonder kwaliteitsverlies uit elkaar gehaald en in elkaar gezet kunnen worden. Om dit aan te tonen hebben we een lamp en een vaas ontworpen en gemaakt (figuur II.A).

- We hebben een ontwerpbenadering vastgesteld voor het ontwikkelen van herprintbare materialen. We demonstreren deze benadering met de ontwikkeling van herprintbare materialen van lokaal verkregen en biobased grondstoffen, namelijk van vermalen mosselschelpen met twee verschillende bindmiddelen (suiker en alginaat). Met deze materialen hebben we een lampenkap en haarclip ontworpen en geprint (figuur II.B en C).
- We hebben bijgedragen aan het domein van "research through design" door het prototypeproces te gebruiken voor kennisvergaring, wat minder gangbaar is binnen RtD. Het ontwerpdoel in het prototypeproces is gebruikt om relevante kennis te vergaren (van andere disciplines) voor technologieontwikkeling in een nieuwe context. Dit resulteerde in een iteratief proces tussen het experimentele prototypeproces en het ontwikkelen van wetenschappelijke kennis.

De inhoud van dit proefschrift is gebaseerd op publicaties. Hoofdstuk 2, 3 en 5 zijn gepubliceerd, hoofdstuk 4 ordt beoordeeld en hoofdstuk 6 is geaccepteerd voor publicatie op het moment van schrijven.

In hoofdstuk 2 hebben we het gebruik van 'annotated portfolios', een methode uit RtD, uitgebreid door het toe te passen op de analyse van kwalitatieve interviews. Op deze manier kan de interviewdata visueel worden geanalyseerd, wat interessant is wanneer ontwerpers worden geïnterviewd over hun ontwerpprojecten. Het visuele overzicht, bestaande uit foto's met annotaties, leidde tot vruchtbare discussies en een beter begrip van het onderwerp. Deze nieuwe methode is in het volgende hoofdstuk toegepast.

In hoofdstuk 3 hebben we verkend in hoeverre de kansen die 3D-printen biedt voor duurzaam design ook van toepassing zijn op design in een circulaire economie. Er is een literatuurstudie uitgevoerd, alsmede kwalitatieve interviews met vijf ontwerpers. Deze interviews zijn geanalyseerd met 'annotated portfolios'. De resultaten tonen kansen (digitale ontwerpbestanden kunnen worden aangepast voor hergebruik en complexe structuren kunnen worden gebruikt voor recycling) en uitdagingen (complexe structuren kunnen een belemmering vormen voor demontage en hermontage en ontwerpers vragen om hernieuwbare materialen). Op basis van deze resultaten zijn twee gebieden gedefinieerd om de verkennende studies in de volgende hoofdstukken uit te voeren. Deze gebieden zijn 'het nastreven van hoogwaardig hergebruik voor productintegriteit met omkeerbare verbindingen' (hoofdstuk 4) en 'de ontwikkeling van herprintbare materialen van biobased grondstoffen voor materiaalintegriteit (hoofdstuk 5 en 6).

In hoofdstuk 4 wordt een theoretisch model gepresenteerd voor een circulaire werkwijze voor 3D-printen. Deze werkwijze houdt rekening met hoogwaardig hergebruik door fysieke onderdelen en materialen bij het digitale productieproces te betrekken. In dit hoofdstuk wordt deze werkwijze gedemonstreerd door middel van een prototypeproces. Het resultaat van dit proces zijn prototypes waarin lasergesneden onderdelen zijn bevestigd met omkeerbare 3D-geprinte verbindingen. Deze verbindingen zijn bevestigd tijdens het 3D-printproces en ondersteunen hermontage.

In hoofdstuk 5 en 6 wordt een ontwerpbenadering vastgesteld om herprintbare materialen te ontwikkelen. Herprintbare materialen behouden na gebruik hun originele eigenschappen voor printbaarheid en functionaliteit. In de ontwerpbenadering wordt daarom een volledige levenscyclus doorlopen om dit soort materiaal te ontwikkelen. In hoofdstuk 5 is een eerste verkenning van deze werkwijze beschreven voor lokaal verkregen biobased afvalstoffen. Een materiaal voor extrusie pasta-printen is ontwikkeld uit vermalen mosselschelpen en suiker. Dit kan na gebruik worden opgelost in water waarna opnieuw een printbare pasta wordt verkregen. In hoofdstuk 6 is de werkwijze verder uitgewerkt en zijn herprintbare biobased composietmaterialen ontwikkeld uit vermalen mosselschelpen en alginaat. Na het printen wordt het materiaal gecrosslinkt, waardoor het eindproduct waterafstotend wordt. Voor hergebruik wordt het crosslinkingproces omgekeerd, waarna het materiaal weer printbaar is.

In hoofdstuk 7 worden de inzichten voor productintegriteit en materiaalintegriteit met 3D-printen voor design in een circulaire economie beschreven. Verder analyseren we het gebruik van "research through design" in ons onderzoeksproces en worden praktische inzichten voor ontwerpers en richtingen voor verder onderzoek gedeeld.

Hoewel er veel optimisme is over het gebruik van 3D-printen om de transitie naar een circulaire economie te stimuleren, ondervonden wij dat er momenteel weinig toepassingen van 3D-printen zijn die een circulaire economie ook daadwerkelijk ondersteunen en mogelijk maken. Daarom is een belangrijke bevinding van dit proefschrift dat diepgaande kennis en begrip van 3D-printtechnologieën nodig is om succesvolle printresultaten te behalen voor productintegriteit en materiaalintegriteit in een circulaire economie.

Chapter 1

Introduction

1.1 Introduction

3D printing, or additive manufacturing (AM), is a digital fabrication process that builds objects by adding material layer by layer from a digital 3D model. It is different from conventional techniques like injection moulding or milling and considered disruptive as it facilitates new opportunities (Kietzmann et al., 2015; Rayna and Striukova, 2016) such as on-demand production and the creation of complex structures (Lipson, 2012).

The first commercially available 3D printer was launched by 3D Systems in 1987 (Wohlers and Gornet, 2016). Since then, 3D printing processes have been largely improved and expanded, from the introduction of an open-source system by RepRap used to produce an accessible and affordable Fused Deposition Modelling (FDM) 3D printer, to the creation of dedicated material solutions with 'multi-material printing' (Doubrovski et al., 2015; Wohlers and Gornet, 2016). Significant progress has been made in recent years to speed up the process, reduce costs, improve quality control, and extend functionality (Bourell, 2016; Huang et al., 2015). These developments have allowed the integration of AM into our linear economic system.

The current linear economic system relies on a take-make-use-waste process which generates large waste streams and leads to resource depletion (Circle Economy, 2020; Den Hollander, 2018). This system incentivizes the manufacture of products at the lowest possible cost to be sold at the highest possible price. What happens to these products once they have become obsolete is of little interest to most manufacturers. In other words, the linear economy and the way it deals with products no longer functions within the planetary boundaries (Geissdoerfer et al., 2017), by this we refer to the space in which we can maintain a prosperous climate for humanity (Rockström et al., 2009).

The circular economy presents an alternative by emphasizing "the importance of high value and high quality material cycles" to preserve materials, energy, and nutrients for economic use (Korhonen et al., 2018). Products and materials are 'looped' back into the economic system at multiple levels, ranging from reuse, remanufacturing, refurbishment, to recycling, (Ellen MacArthur Foundation, 2013; Stahel, 2016). To achieve a truly circular economy, we have to change the way we design and produce products by prioritising end-of-life scenarios for increased product life time, reuse, and recovery (Bakker et al., 2014).

The opportunities of AM for a circular economy have not yet been studied in great depth (Despeisse et al., 2017). Design in a circular economy is a new approach in the wider field of sustainable design. It builds on sustainable design strategies and places these in the perspective of closing product and material cycles (Sauvé et al., 2016). The sustainable aspects offered by AM in product design are therefore also relevant for design in a circular economy. There are many, diverse examples of AM's sustainable advantage described in the literature. These range from the digital aspects of AM that facilitate on-demand production thereby reducing inventories and supporting repair through digital storage of spare parts (Ford and Despeisse, 2016; Huang et al., 2015; Loy and Tatham, 2016) to that of increased product personalization, which potentially extends product life through increased attachment (Diegel et al., 2016; Kondoh et al., 2017). Another example is the additive aspect of AM which allows the printing of complex geometries that can lead to reduced resource use and energy consumption through lightweight design (Mançanares et al., 2015; Nagarajan et al., 2016). However, these opportunities have not yet been explored in the context of design for a circular economy (Sauerwein et al., 2017). Moreover, these sustainable advantages are mostly exploratory and propositional in character and have hardly been tested in practice. Therefore, in this thesis we explore these opportunities and provide evidence for the sustainable use of AM for design in a circular economy.

1.2 Research aim and questions

In this thesis, we connect an emerging technology (AM) to a visionary worldview (circular economy) with the aim of providing insights into how to design with AM in a circular economy. AM's unique characteristics in comparison to conventional production, i.e. an additive and digital manufacturing technique, create opportunities that can support and enable product design in a circular economy.

Design in a circular economy implies preserving product and material value by keeping them in the economic system for as long as possible. Den Hollander et al. (2017) introduced the principle of 'product integrity', defining it as "the extent to which a product remains identical to its original state over time". Designing for product integrity in a circular economy includes any measure to extend a product's life, for instance through a durable and reliable design, but also by ensuring that a product can be easily maintained and repaired, upgraded and/or refurbished. Designing for material integrity can be similarly defined; by this we mean the extent to which a material remains identical to its original state over time. This implies that a material should retain its original properties, even after it has been recycled.

Product integrity and material integrity serve as guiding principles in a circular economy, therefore we investigated the use of AM for these principles in design. Two research questions were formulated:

1. How can additive manufacturing support product integrity in a circular economy?
2. How can additive manufacturing support material integrity in a circular economy?

To answer these research questions, we integrated insights from a range of disciplines, including the fields of sustainability, circular economy, additive manufacturing, product design, material science, computational fabrication, and human computer interaction. We performed a number of experimental studies to combine these disciplines using 'Research through Design' (RtD) as the primary methodology. We first narrowed the research questions down to two areas for exploration, based on initial findings from our literature and design review (chapter 3). These areas are:

1. In order to support product integrity, we aimed to adapt the AM process flow to develop reversible connections that allow product disassembly and reassembly.
2. In order to support material integrity, we aimed to develop reprintable, locally-sourced bio-based materials to be used to 3D print consumer products.

An additional aim of this research is to contribute to the domain of 'research through design' by sharing our insights on how we applied the prototyping process for knowledge generation and what the effect was of using RtD for technology development in a new context.

1.3 Scope

We scoped this research in the context of makerspaces. These are shared community workshops located around the world which are an important driver for AM innovation (Hennelly et al., 2019; Niaros et al., 2017). They give access to a wide variety of tools and machines to complete Do-It-Yourself-making and digital fabrication projects (Kohtala, 2017). In addition to their value for academic researchers, we expect our results to be of practical use for makers (i.e. the users of makerspaces) and independent designers. These groups are commonly working at and extending the boundaries of product design, and like to investigate new fields and opportunities. As a consequence, this research targets consumer products that allow room for exploration, instead of high end or high precision products.

FDM printing is relatively cheap and accessible and therefore the most commonly used 3D printing technique in makerspaces. It is classed as a 3D printing technique in the AM category Material Extrusion (ASTM, 2012), where a liquefied material is extruded from a nozzle in a line pattern to build layers. FDM printing works with a melted thermoplastic filament. Due to its accessibility, we focussed on Material Extrusion 3D printing in this thesis. We also explored paste printing, an interesting 3D print technology comparable to FDM printing in terms of usability and small scale production. It is classed in the same category as Material Extrusion, but in this case the nozzle does not have to be heated during printing, resulting in less energy use (Faludi et al., 2019).

1.4 Research through Design

In "Research through Design", design plays a formative role to generate knowledge by iteratively developing prototypes. RtD borrows methods from design practice with the goal of pursuing abstraction and generalisation (Koskinen and Krogh, 2015; Stappers and Giaccardi, 2017). Unlike classical research techniques that strive to understand the state of the art, RtD encourages researchers to study the future. To do this, prototypes are made with the goal of societal change, supporting the narrative of a new technology or approach (Zimmerman et al., 2010).

RtD was developed within the fields of interaction design and Human-Computer Interaction (Gaver, 2012; Koskinen et al., 2008; Zimmerman et al., 2010). In these fields, design is often used to create prototypes to study or provoke a certain interaction or reaction. The prototypes create situations that were not previously feasible, but that become observable through design (Stappers & Giaccardi, 2017). The prototypes are a research tool and a means to collect data for analysis.

The use of prototypes as research tool is most common in RtD and publications generally only communicate the prototype itself (Stappers and Giaccardi, 2017). However, Stappers and Giaccardi (2017) state that RtD can be applied more broadly by showing examples in which the prototyping process is prevalent. RtD is then applied to create insights through the development of prototypes and by communicating these insights to peers (Stappers, 2007). This changes the role of the prototype; where the prototype first served as a research tool, the prototyping process now becomes the research tool and the prototype itself is a proof-of-concept. This approach, often overlooked in academic research (Stappers and Giaccardi, 2017), is how we applied RtD in this study: we addressed the development of a digital production technology in a sustainable context through prototyping processes.

Prototyping processes are varied, multi-faceted, and heterogeneous. The description and explanation of the prototype and the process cannot always be adequately covered by plain text (Bowers, 2012). 'Annotated portfolios' is therefore a valuable method, because it meets the demands of generalizability in research, while showing the particularity and multidimensionality of design. Annotated portfolios represent a group of prototypes described together to highlight relevant dimensions and aspects that are not always directly visible. These annotations reveal the knowledge behind the object and make the prototypes suitable for discussion (Gaver and Bowers, 2012). We applied and further extended annotated portfolios in our research.

1.5 Thesis outline

This thesis is founded on a number of published and submitted articles. Chapters 2, 3 and 5 have been published, chapter 4 is under review, and chapter 6 is accepted for publication at the time of writing. In order to adapt the published and submitted articles into the thesis chapters, the layout, section and figure numbers, and some of the reference styles were adjusted and the authors are mentioned in a footnote reference. No changes were made to the content.

Chapter 2 presents a detailed description of a new approach for annotated portfolios; this is then used in chapter 3 to evaluate interviews with designers of exemplary design projects. Chapter 3 shows the results of our investigation of opportunities, challenges, and the current state of the field. Based on the challenges, two areas were defined to explore product integrity in chapter 4 and material integrity in chapters 5 and 6. These chapters describe the experiments and prototyping processes performed. The design experiments are the main body of this study and the resulting knowledge answers the research questions. Finally, in chapter 7 we discuss and reflect on the outcomes. The thesis outline is shown in figure 1.1.

Chapter 2. Annotated portfolios as a method to analyse interviews
In this chapter, we present a new way of using annotated portfolios, i.e. as an approach to analyse qualitative interview data. We developed this approach because designers were interviewed about their design projects and this provided the opportunity to visually analyse the data. This chapter supports the next chapter, in which the method is applied.

Chapter 3. Exploring the potential of additive manufacturing for product design in a circular economy
In this chapter, we explore to what extent the opportunities for sustainable design presented by AM are also useful when designing in a circular economy. We conducted a literature review and held qualitative interviews with five designers which were then analysed with annotated portfolios. The outcome shows to what extent AM can support design in a circular economy, as well as current challenges and limitations. The research topics for the following chapters were based on these findings, i.e. high value reuse for product integrity (Ch. 4) and reprintable materials for material integrity (Ch. 5 and 6).

Thesis Outline

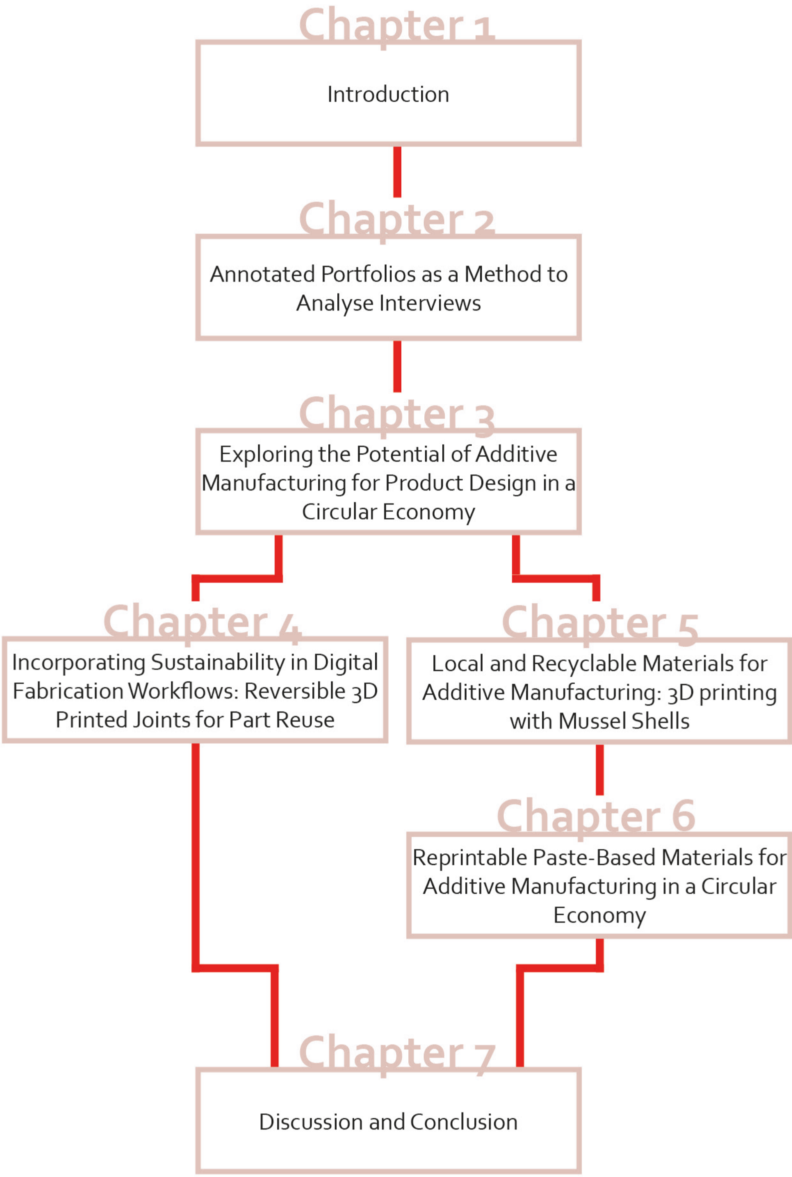

Figure 1.1. Thesis outline

Chapter 4. Incorporating Sustainability in Digital Fabrication Workflows: Reversible 3D Printed Joints for Part Reuse
In this chapter, we present a theoretical framework for a workflow for digital fabrication that considers high value reuse and recovery. It states that parts, products, and materials should be directly incorporated into the digital working process to facilitate product integrity. To address the empirical evidence of this theoretical framework, we explored the practical details of the framework with prototyping. This resulted in a concrete example of products with reversible 3D printed joints and laser cut panels that can be disassembled and reassembled, and a demonstration of the developed workflow.

Chapter 5. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells
In this chapter, we describe an initial study on processing locally sourced waste streams into 3D printable materials for a circular economy; these materials meet the criteria for high value recovery. We developed a material from ground mussel shells and sugar-water for extrusion paste printing that can be dissolved after use to regain a printable paste.

Chapter 6. Reprintable paste-based materials for additive manufacturing in a circular economy
This chapter builds on the previous chapter and describes the development of reprintable bio-based composite materials with alginate as a binder. These are water-resistant and can be recovered based on reversable ion cross-linking. We established a design approach and went through a full material life cycle during the development of these materials, and demonstrate a proof-of-concept.

Chapter 7. Discussion and conclusion
We describe the insights gained about product integrity and material integrity with AM for design in a circular economy. Furthermore, we evaluate the RtD research process and present practical insights for designers and makers, as well as share directions for future research.

1.6 Author's contribution

The main body of this thesis consists of the following research publications:

- *Chapter 2: Sauerwein, M., Bakker, C.A., & Balkenende, A.R. (2018) Annotated portfolios as a method to analyse interviews. In C. Storni, K. Leahy, M. McMahon, P. Lloyd, & E. Bohemia (Eds.), Design Research Society 2018 (pp. 1148–1158). https://doi.org/10.21606/dma.2017.510)*

- *Chapter 3: Sauerwein, M., Doubrovski, E.L., Balkenende, A.R., & Bakker, C.A. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production, 226, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108*
- *Chapter 4: Sauerwein, M. & Peek, N. (under review). Incorporating Sustainability in Digital Fabrication Workflows: Reversible 3D Printed Joints for Part Reuse. TEI'21*
- *Chapter 5: Sauerwein, M., & Doubrovski, E.L. (2018). Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications, 15, 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028*
- *Chapter 6: Sauerwein, M., Zlopasa, J., Doubrovski, E.L., Bakker, A.C., Balkenende, A.R. (accepted manuscript). Reprintable paste-based materials for additive manufacturing in a circular economy. Sustainability.*

As first author of these papers, I set up and performed the experiments, collected and analysed the data, and wrote the main body of the manuscripts. My promotors, prof. dr. ir. Conny Bakker and prof. dr. Ruud Balkenende, and copromotor, dr. ir. Zjenja Doubrovski, supervised this process and provided input and feedback on the experiments and manuscripts. The paper in chapter 4 was written together with dr. Nadya Peek. She supervised the study, wrote part of the introduction and related work, as well as revised the manuscript. In chapter 6, dr. Jure Zlopasa contributed to the paper by providing research materials and feedback on the experiments.

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Chapter 2

In the introduction, the research objectives were outlined and the 'Research through Design' methodology and the use of the 'annotated portfolios' method were introduced. In this chapter, we further explore the use of annotated portfolios and show how it is extended into a new context by applying it to the analysis of interview data. In this way, interview data can be analysed visually, a novel and interesting approach when designers are interviewed about their design projects. This approach is illustrated with a case study on design projects related to 3D printing and sustainability.

Annotated Portfolios as a Method to Analyse Interviews[1]

Abstract

This paper explores the use of annotated portfolios as a method to support the qualitative analysis of interview data about design projects. Annotated portfolios have so far been used to support artefacts with text in order to discuss them in the context of 'research through design' In this paper, we interpret the five-step method of McCracken and relate it to annotated portfolios to analyse interviews. We use a case study on design projects related to 3D printing and sustainability to illustrate the process. Five designers were interviewed to obtain a deeper understanding of the role of Additive Manufacturing in practice. These interviews were analysed in a visual process with annotated portfolios. The use of annotated portfolios is considered a meaningful approach to analyse interviews, because it leads to a more transparent analysis process: The visuals are rich in information, bring clarity to the data for interpretation and pattern finding and make this stage insightful for discussion with peers.

Annotated portfolios; Visual analysis of interviews; Research through design; Circular economy

[1] Sauerwein, M., Bakker, C. A., & Balkenende, A. R. (2018). Annotated Portfolios as a Method to Analyse Interviews. In C. Storni, K. Leahy, M. McMahon, P. Lloyd, & E. Bohemia (Eds.), Design Research Society 2018 (pp. 1148–1158). https://doi.org/10.21606/dma.2017.510)

2.1 Introduction

This paper explores the use of annotated portfolios as a method to support the qualitative analysis of interview data. We want to explore this in the context of design research, because it creates the opportunity to obtain insight about design objects and the process that led to these objects; data is approached differently, because visuals can be incorporated in the analysis phase. 'Annotated portfolios' is a research through design approach that shows a selection of annotated artefacts to analyse these artefacts. Annotations can be described as "the indexical connection with artefacts" (Gaver & Bowers, 2012), making them topical for discussions and comparison with other annotated objects. The annotations draw attention to aspects in the design that are not directly visible, but for example part of the ideas or system behind the object. The combined annotated artefacts generates the annotated portfolio, i.e. a group of artefacts that is described together to show a domain of design and its relevant dimensions (Bowers, 2012; Gaver, 2012; Gaver & Bowers, 2012). Annotated portfolios allow to translate particular aspects of artefacts into more generalizable theory. They can be seen as a form of intermediate-level knowledge, which indicates the space between the particular artefact and the general theories (Lowgren, 2013). We consider pattern finding in the interview analysis process as a form of intermediate-level knowledge. Therefore, including annotated portfolios in the interview analysis is expected to bring more transparency to the analysis process.

Although annotated portfolio is often mentioned in literature as a meaningful approach, only few examples exist of actual implemented 'annotated portfolios'. All studies have in common that the authors apply the method to describe their own design in order to make the design process, with all its considerations, more insightful. Some describe their design and insights in a paper, either directly linking annotations to pictures of their design project(s) (e.g. Srivastava & Culén, 2017) or summing up annotations in the body of the text (e.g. Hobye, Padfield, & Löwgren, 2013). Others use the approach as a means in their process, for example for collaborative use of annotations to communicate between team members (Kelliher & Byrne, 2015). We consider it appropriate and interesting to describe the work of others with this method as well, especially in the context of qualitative interview analysis. The insights from interviews about the (design) process can be captured in annotations.
Applying annotated portfolios for qualitative data analysis has to our knowledge not been performed before. In this paper, we explore the combination of these methods with a case study on design projects related to 3D printing and sustainability. We first describe the case study in some detail, including the use of annotated portfolios, and then reflect on the use of the annotated portfolios.

2.2 Case study: 3D printing for design in a circular economy

The circular economy aims to accomplish sustainable production and consumption. Additive manufacturing, also known as 3D printing, could be an enabling production technology, because its production characteristics differ from conventional production methods: It is a digital and additive production process (Despeisse et al., 2017). We are particularly interested in the way in which designers can use additive manufacturing to support sustainable design in a circular economy. Therefore 'research through design' is the applied methodology, because it creates knowledge through the act of designing and in this way allows for the creation of theoretical, as well as practical understanding (Stappers, 2007).

Literature describes many potential sustainability advantages of additive manufacturing. However, it is still unclear how these aspects can be applied in practice. In previous work, literature about the sustainability of additive manufacturing was compared to circular design strategies in the context of five selected design projects (Sauerwein et al., 2017). The circular design strategies support product longevity and are described by Bakker et al. (2014) and Bocken et al. (2016). An example of such a strategy is 'Design for standardisation and compatibility', which can be explained as "creating products with parts or interfaces that fit other products as well" (Sauerwein et al., 2017).

The five design projects were selected, because the designs were produced with additive manufacturing and related to sustainable product design. In figure 2.1 each project is described. The designers of these projects were interviewed to obtain a deeper understanding of the role of additive manufacturing in practice.

2.3 Methodology

2.3.1. Interview design

Semi-structured interviews were conducted with the purpose to gain insight in the design projects related to 3D printing, sustainability in general and the circular design strategies in specific. The interview was divided into three sections with questions on:

1. The designer's experience of working with 3D printing
2. Sustainability aspects of the designs
3. The applicability of the circular design strategies and the relation to 3D printing.

All designers of the selected design projects accepted the invitation for an interview, which lasted between 40 and 65 minutes. Interviews were preferably

‘Standard products’: Jesse Kirschner and Jesse Howard (2016)

Furniture is made from standard wood elements, with 3D printed joints. Therefore people can online adjust the furniture to their preferences. Further, they can choose to download the files, receive the printed joints or the complete product.

‘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.

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

Value Added Repair (VAR) extends the product lifespan of broken products not only through repair, but also through the addition of an extra functionality. In this way extra value is added to the product.

‘Project RE_’: Samuel Bernier (2012)

This project explores 3D printing as a do-it-yourself tool for reuse of products. The functionality of used cans and jars is expanded through the addition of customized lids.

‘Screw it’: David Graas (2013)

Graas designed connectors that transform old PET bottles and their lids into new user objects, e.g. a vase or bracelet.

Figure 2.1. Explanation of the five design cases.

conducted face to face, but due to time and distance constraints two of the five interviews were held through a video-conference over the internet. Three interviews were in Dutch and two in English.

2.3.2. Analysis

The interviews were recorded and transcribed for analysis. The use of annotated portfolios was considered a meaningful approach to analyse the interviews, because the design projects were the focus of the interviews. We interpreted the five step interview analysis method of McCracken (1988) and related it to annotated portfolios. The 5-step analysis provides a scheme to follow in the treatment of data. It describes the steps to take from data to knowledge contribution, each step representing a higher level of generality. The first two steps focus on the creation of observations. The third and fourth step translate these observations into themes. The final step seeks for patterns between the interviews (table 2.1). Our interpretation of the 5 steps for interview analysis with annotated portfolios integrates visuals from the start of the analysis process, other than just grouping text. Each step and our additions are described below. The work of Piercy (2004) helped us to better understand the 5-step analysis of McCracken. However, we did not always follow her interpretation.

	1	2	3	4	5
5-step analysis McCracken (1988)	Read transcript carefully to create observations	Develop observations	Examine interconnection of observations	Determine themes among observations	Determine patterns between interviews

Table 2.1. Five step method and analysis for annotated portfolio's based on the 5-step analysis (McCracken, 1988)

Step 1

As described by Piercy (2004), the interview transcript is read carefully to identify the important material. She explains 'important material' as the predetermined focus or subject of the analysis. In our case we focus on interview data directly related to the artefact, i.e. the design project. Therefore, we highlighted all sentences that where directly related to the design project. The highlighted sentences create an observation (McCracken, 1988, p. 42).

Step 2

The observations have to be developed beyond their original form to exploit their full potential. Subsequently, they are related back to the transcript and examined, "one in relation to the other"(McCracken, 1988, p. 45). To further develop the observations, we summarized and translated them to English (if needed). These summarized observations were annotated to a picture of the design project to make the design project topical for examination. Throughout this paper we will indicate 'the summarized observations' as 'annotations' and 'the annotated picture of a design project(s)' as 'visual(s)'.

Step 3

McCracken (1988, p.45) describes these stages as follows: "Observations are once again developed on their own accord, and, now, in relation to other observations." In other words, the observations are examined to identify connections and categories (Piercy, 2004). The focus shifts from the transcript to the observations. We assigned colour codes to the annotations to cluster them into different categories.

Step 4

After examining the observations, the investigator has to seek for more general themes on the level of each individual interview. The developed observations are linked to compose a theme. (McCracken, 1988, p.46; Piercy, 2004). In our case a first evaluation on the level of the visual was made. We indicated the relations between the categories with dotted lines.

Step 5

The final stage seeks for patterns among the themes by comparing all interviews. Patterns are the predominant themes of the data and serve as answers to the research questions (Piercy, 2004). We repeated step 1 to 4 for each transcript. In order to enable comparisons across the visualisations, the same visual language was used for each design project (i.e. colour coding and dotted lines). This enabled the identification of patterns between the interviews. We created separate visuals to make these patterns more insightful, to "subject them to a final process of analysis" (McCracken, 1988. p. 42) and to complete the procedure from the particular details to the general observations.

2.4 Results

To illustrate the analysis process, we focus on the results of the interview about 'standard products'. The interview data contains knowledge to answer several research questions about 3D printing and design for a circular economy. This section shows the visuals that support the analysis of the relation between 3D printing and the circular design strategies, in particular design for standardisation and compatibility. The result of the analysis is not yet complete (it is part of an ongoing research project), but is shown here to support the explanation of the analysis process.

Step 1

The transcripts were read carefully and relevant sentences were highlighted. For example, in the interview about 'standard products', the following sentence was highlighted: "well, this standardisation and

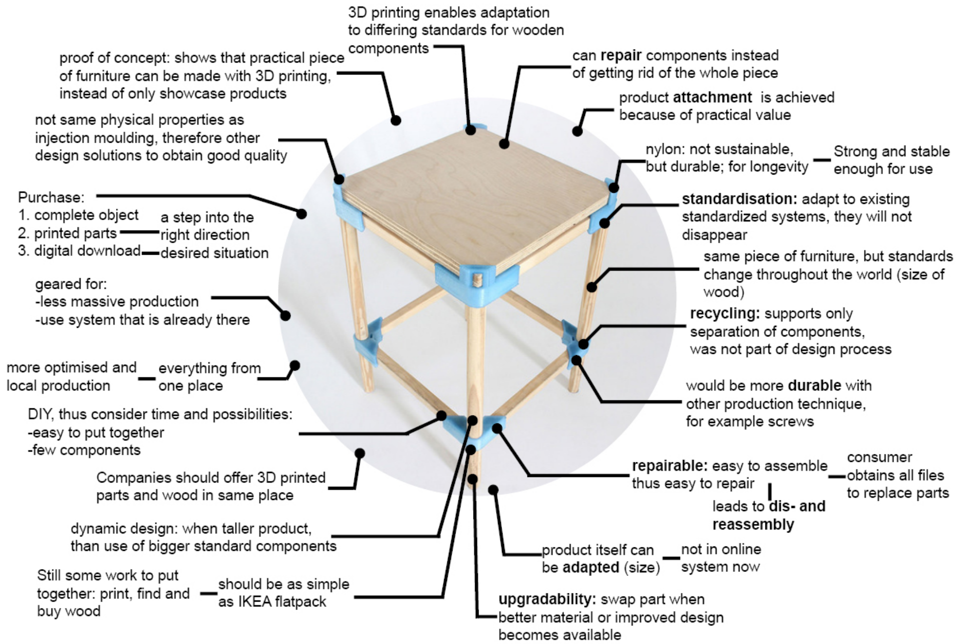

Figure 2.2. Annotations made by 'standard products'

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

The process of summarizing observations into annotations can be illustrated by the sentence from the interview about 'standard products' cited above. This sentence was summarized into the annotation "standardisation: adapt to existing standardised systems, they will not disappear". All annotations were connected to specific parts of the design project as shown in figure 2.2 for 'standard products' to illustrate the written text. The demonstrated annotation above, for example, is attached to the connection between the wooden beam of the leg and 3D printed joint to illustrate that this annotations applies to this part of the design project. When the text is not directly connected to the object (e.g. "product attachment is achieved because of practical value), it means that the annotation applies to the whole product, or the idea or system behind it.

Step 3

The interview had three focal points: '3D printing', 'sustainable aspects' and 'circular design strategies'. These were used to categorize the annotations. From the transcripts two more categories appeared, i.e. 'future opportunities' and 'other aspects'. Below a description of each category is given:

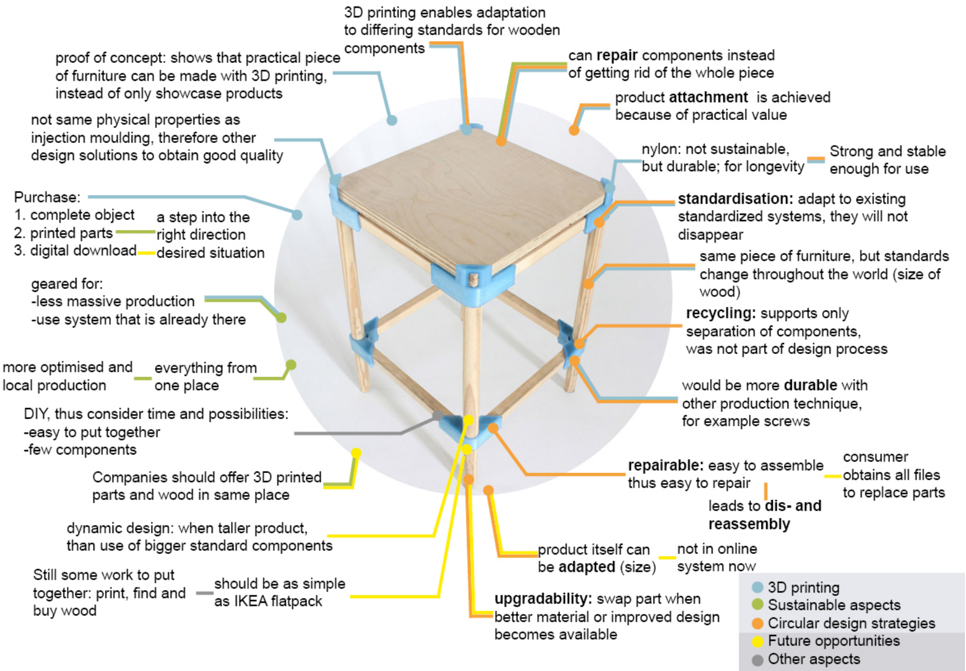

Figure 2.3. Coloured annotations

- 3D printing: annotations in this category refer to 3D printing as a production technique. They cover its abilities and shortcomings, but also when a certain aspect could be realized because of 3D printing.
- Sustainable aspects: this category depicts when the interviewee assigned a certain aspect to sustainable behaviour/use/ production or lack of it.
- Circular design strategies: this category is used when the circular design strategies are mentioned or when something is mentioned about the circular economy.
- 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 realized.
- Other aspects: annotations in this category give insight about the design project, but do not belong to one of the categories mentioned above.

A colour was assigned to each category and these colours were used to highlight the annotations as depicted in figure 2.3. Each annotation can belong to one or more categories. The colours put the annotations in context and show the connections within the categories.

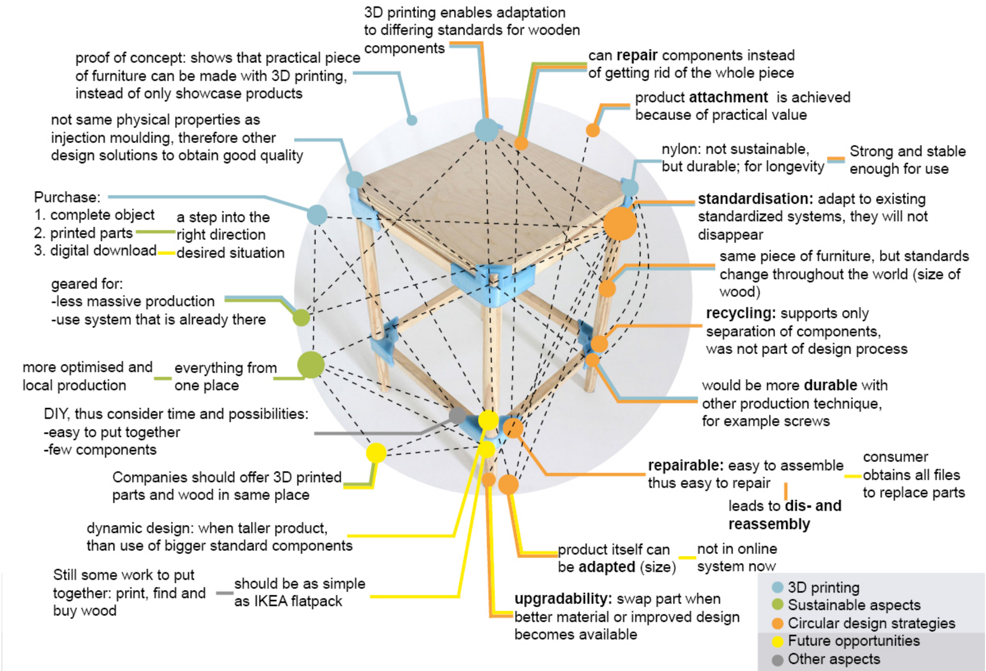

Figure 2.4. Coloured and connected annotations

Step 4
Dotted lines were used to find patterns on the level of the design project. The size of the dots was increased with an increasing number of connections between and within categories (figure 2.4). This helped to determine the most prominent themes, to bring hierarchy to the themes and potentially eliminate redundant themes. Sorting the themes is valuable for support of the final arguments (McCracken, 1988, p. 46). Figure 2.4 shows that for the presented case the annotation on 'standardisation' (in orange) has the largest circle, followed by the annotation on 'optimised and local production' (in green). These annotations exhibit most connections with other annotations and therefore it is likely that they will play an important role in the final evaluation.

The connections help to interpret the annotations, because they show the relations between them. We illustrate this with an example about the relation between standardisation and additive manufacturing. We found that in this project, the use of standard dimensions for wood in combination with 3D printed joints is considered as a means to realize sustainable production. The following connected annotations led to this conclusion. The use of local standards optimizes the production process, because of the accessibility of parts. All parts can be produced in the same place on a local scale. Besides this, adopting local standards increases the reparability and the upgradability of the product: parts can be replaced instead of the whole product, because standard components are widely

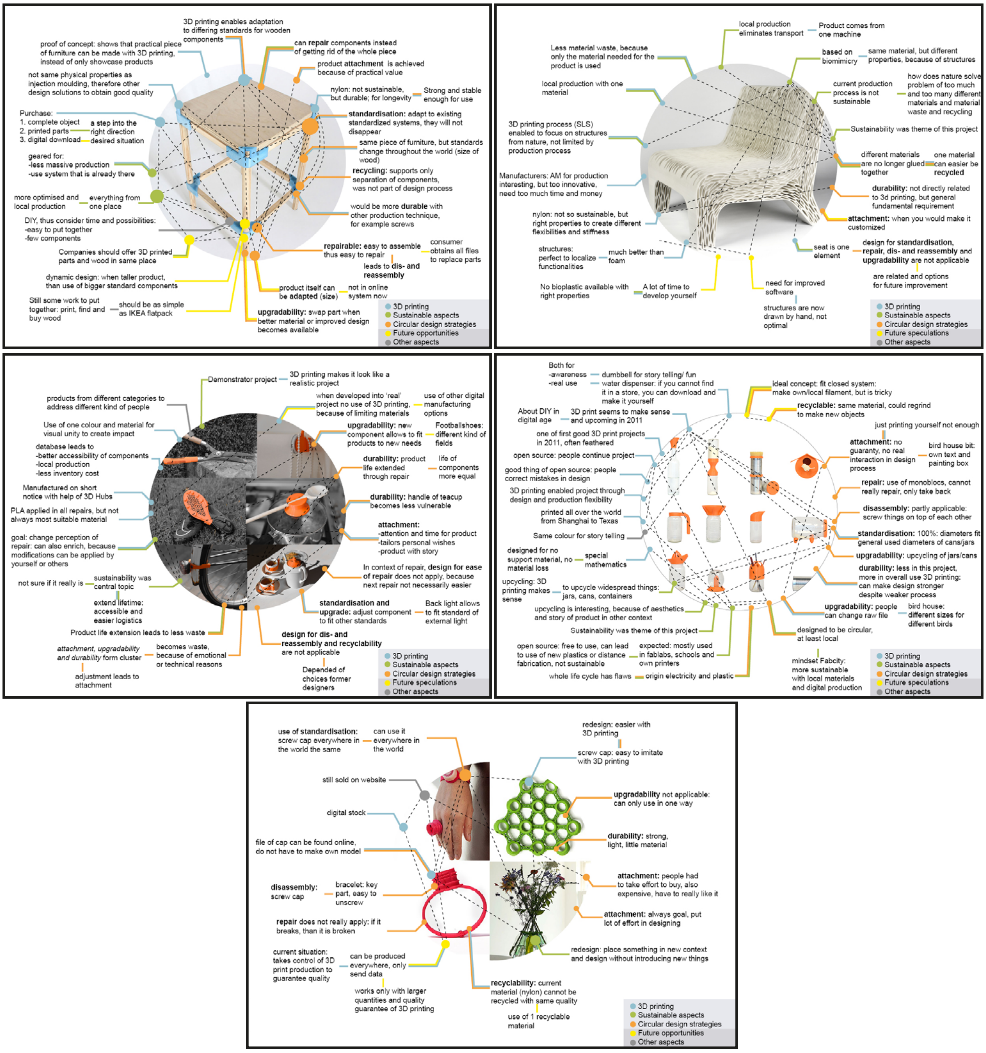

Figure 2.5. Annotated portfolio for 3D printing for design for a circular economy

available. The user will obtain the digital files of the joints, so that he or she can reproduce them him/herself. Our interpretation of these observations is that the design of the object is universal, but local standard dimensions can be used, because of additive manufacturing. Standard dimensions differ throughout the world, making digital storage and adjustability key for successful functioning of this project. Without the digital characteristics, the result would be a too wide range of components to be stored.

Step 5

All visuals together create the annotated portfolio. Figure 2.5 gives an impression of the result of the five design projects. The annotated

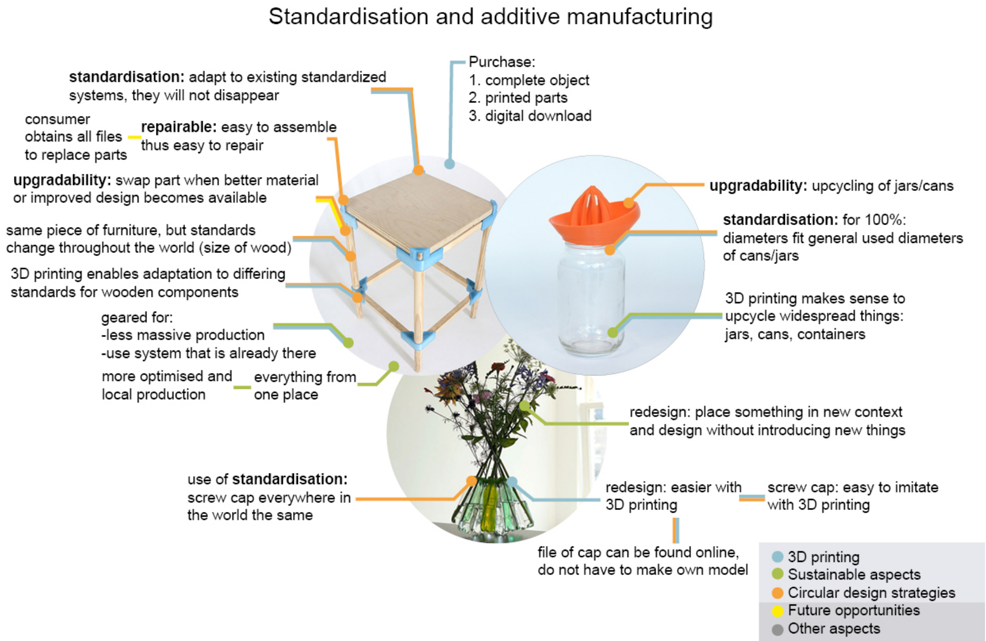

Figure 2.6. Visual representation of annotations about standardisation and additive manufacturing

portfolio allows for the particularity of individual objects, but also show the issues that join and differentiate them (Gaver, 2012).

When establishing relations between the design projects, patterns were found, which in turn can be visualised. When looking for example at the annotations about the circular design strategy 'design for standardisation and compatibility', the explicit use of standardisation in combination with 3D printing to support sustainable production returns throughout the portfolio. In Figure 2.6 this is illustrated with a combination of all artefacts and the supporting annotations related to this pattern. This figure is the final step of the interview analysis and should therefore reveal the findings.

In this case, the annotations about standardisation and additive manufacturing in figure 2.6 present a paradox. In general, it is expected that designers would neglect standardisation and embrace design flexibility with 3D printing. However, the interviewed designers embrace both and use standardisation in an interesting way. The design projects illustrate that additive manufacturing simultaneously enables both the adaptation to standards and the creation of unique solutions. For example, in 'project Re_' and 'screw it' (picture below) standard fittings are used to upgrade an existing product and extend its use. Thus, all three projects embrace the ability of 3D printing to digitally adapt the design to fit a specific context, while using standardisation to make it accessible all over the world. This could lead to product longevity and an efficient use of resources.

2.4.1. Visuals

The generation of the visuals can roughly be divided in three levels, that are respectively the result of step 1 and 2, step 3 and 4, and step 5. First, annotations are assigned to the product without further interpretations. Next, colours and relations are introduced to categorize the annotations and identify themes. Finally, new visuals are created based on the annotated portfolio, showing patterns that relate specific aspects of the design projects and annotations.

2.5 Discussion and Conclusion

In this section we reflect on our process and discuss the findings and limitations that we experienced. In general, we experienced that annotated portfolios support the data interpretation in interviews that focus on design projects and make the analysis process more transparent. Being a form of intermediate-level knowledge, annotated portfolios support verification during the analysis process, increasing the responsiveness of the investigator and therefore supporting rigor throughout the process (Morse et al., 2002). The visuals allow the communication of this intermediate-level knowledge to peers. Therefore, this stage becomes accessible for discussion, which increases the transparency of the process.

Besides communication to peers, it is also insightful during analysis process itself to visually show the steps needed to transform data into knowledge. Figure 2.2 to 2.6 clearly show the development from data interpretations to pattern finding; at first only annotations are assigned to the individual design projects, next meaning is given to these annotations and finally all design projects are connected through the annotations. The development of the visuals structured this process, which can be very fuzzy and therefore difficult to keep track of when analysing interviews. When coding an interview with analysis software for example, many layers of interconnectivity can be created. The amount of codes can be overwhelming. Although many software tools allow the creation of visuals (mind maps) to better understand the linkages between different observations, this is only possible after categories and themes have been assigned to the observations. The disadvantage is that it is not directly clear which observations have the most connections. Annotated portfolios, by contrast, allow the creation of visuals right from the start of the analysis process and connect the analysis to (specific parts of) the design artefact. The visuals directly show the amount of connections between annotations and therefore bring clarity to the data.

The visuals allowed us to apply as many layers of interpretation as desired. They could be adjusted according to the focus of the research question. The overall outcome was a visual rich in information, showing that many annotations belong to multiple categories. For example, the annotation 'companies should offer 3D printed parts and wood in the same place' belongs to the categories 'sustainable aspects' and 'future opportunities' (figure 2.3). Showing this in a visual representation can be seen as a unique advantage, when compared to other interview analysis tools. However, the final version of the visual is likely to have a very high density of information and might therefore be less understandable for outsiders. Therefore, we found it beneficial to create new visuals (figure 2.6) with a selection of annotations that belong to a certain pattern to make outcomes more insightful.

In comparison to qualitative data analysis software, the analysis with annotated portfolios needs an extra step of interpretation. Analysis software directly links the transcript to categories, but annotated portfolios require the creation of annotations; the observations are first summarized, before they are categorized. These summaries and short sentences are important to present an overview in the visuals. However, the investigator should be careful when summarizing, as this is the first interpretation of the transcript. The summary should be as literal as possible to avoid misinterpretations later on.

Further research is needed to develop this exploration into a more rigorous method. A possible approach could be to perform a comparative analysis between the classic qualitative data analysis and the analysis with annotated portfolios. The same data should then be analysed by two experienced researchers in two rounds, one first performing the classic method and then the method with annotated portfolios and the other vice versa. This approach would allow for analysis within and between the subjects.

To conclude, this study shows that annotated portfolios do not only have the ability to communicate the design process, but also to support the communication of interview analysis regarding design processes. Applying annotated portfolios to the field of interview analysis broadens the scope of this method. Our study shows that annotated portfolios are also suitable to give meaning to and evaluate the work of others, instead of only own design projects. We even expect that the use of annotated portfolios to analyse interviews does not have to be limited to interviews about design projects, but could be extended to all topics that can be visualized, for example systems or relations. The advantage of visuals is that they stimulate the detection of relations between annotations, as well as patterns within the bigger picture. Therefore, by introducing a visual analysis this approach has the potential to contribute to the toolbox of interview analysis, in addition to the current textual analyses.

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Chapter 3

In chapter 2, we introduced the use of annotated portfolios to visually analyse interview data and illustrated it with a case study on interviews about sustainable 3D printing projects. In this chapter, we present the outcomes of this interview analysis and link them to a literature review to explore to what extent the opportunities that AM offers for sustainable design are also applicable when designing in a circular economy.

Exploring the Potential of Additive Manufacturing for Product Design in a Circular Economy[2]

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.

Additive manufacturing, Circular economy, Product design, Product life extension, Design for sustainability, Annotated portfolios

[2] Sauerwein, M., Doubrovski, E., Balkenende, R., Bakker, C., 2019. Exploring the potential of additive manufacturing for product design in a circular economy. Journal of Cleaner Production. 226, 1138–1149. https://doi.org/10.1016/j.jclepro.2019.04.108

3.1. 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.

3.2. 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 et al., 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., 2018). 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 and 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 and Despeisse, 2016; Kreiger et al., 2014; Van Wijk and 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 and 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 and 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.

3.3. Method

3.3.1. Semi-structured interviews

We interviewed designers who created pioneering 3D printed and sustainable design projects (section 3.3). We conducted semistructured 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 3.1) 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.

The interviews lasted between 40 and 65 min 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.

3.3.2. Qualitative interview analysis with annotated portfolios

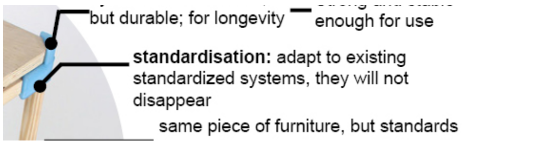
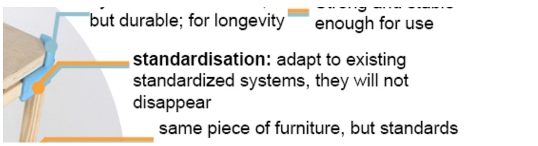
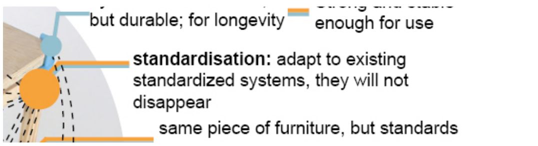
We developed a novel approach to analyse qualitative interviews by incorporating 'annotated portfolios' (see Sauerwein et al. (2018) for an extensive description). This allowed us to integrate visuals from the start of the analysis process, other than simply grouping text. Annotated portfolios are described by Gaver and 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 3.2.

Figure 3.1. Example of one of the cards with a description of the circular design strategies.

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 or patterns by analysing the visuals from the design projects. New visuals were created to communicate these patterns and explain the results.

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.

<table>
<tr><td>Step 1</td><td>Highlighted sentence from manuscript</td><td>“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.”</td></tr>
<tr><td>Step 2</td><td>Annotation

Annotated visual</td><td>“standardisation: adapt to existing standardised systems, they will not disappear”

</td></tr>
<tr><td>Step 3</td><td>Categorised annotation using coloured lines</td><td>
</td></tr>
<tr><td>Step 4</td><td>Relations between categorised annotations using dotted lines</td><td>
</td></tr>
<tr><td>Step 5</td><td>Annotated portfolio

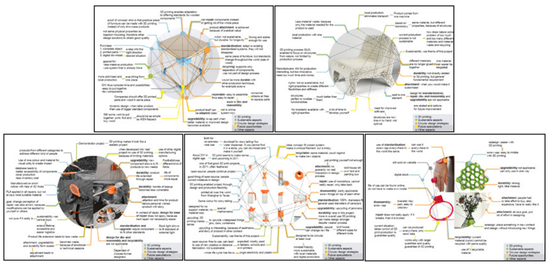
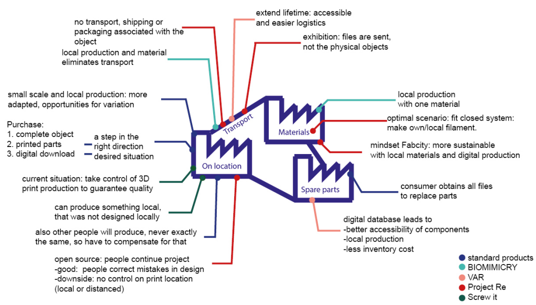
New visual to illustrate a specific final pattern</td><td>

</td></tr>
</table>

Figure 3.2. Visual representation of ‘annotated portfolios as a method to analyse interviews’.

3.3.3. 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.

'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 3.3 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).

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 3.4). 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 3.3. 'Standard products' by Jesse Kirschner and Jesse Howard.

Figure 3.4. 'BIOMIMICRY: soft seating' by Lilian van Daal.

'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 3.5). 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.

'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 3.6), through the addition of customised lids. The project is open source and people can download the

Figure 3.5. 'Value Added Repair' by Marcel den Hollander and Conny Bakker.

Figure 3.6. 'Project RE_' by Samuel Bernier

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)).

'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 3.7). This design project was featured in an overview exhibition on 3D printing (Materialise, 2016).

Figure 3.7. 'Screw it' by David Graas

3.4. Results

3.4.1. 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).

Figures 3.8-3.12 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.

3.4.2. 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

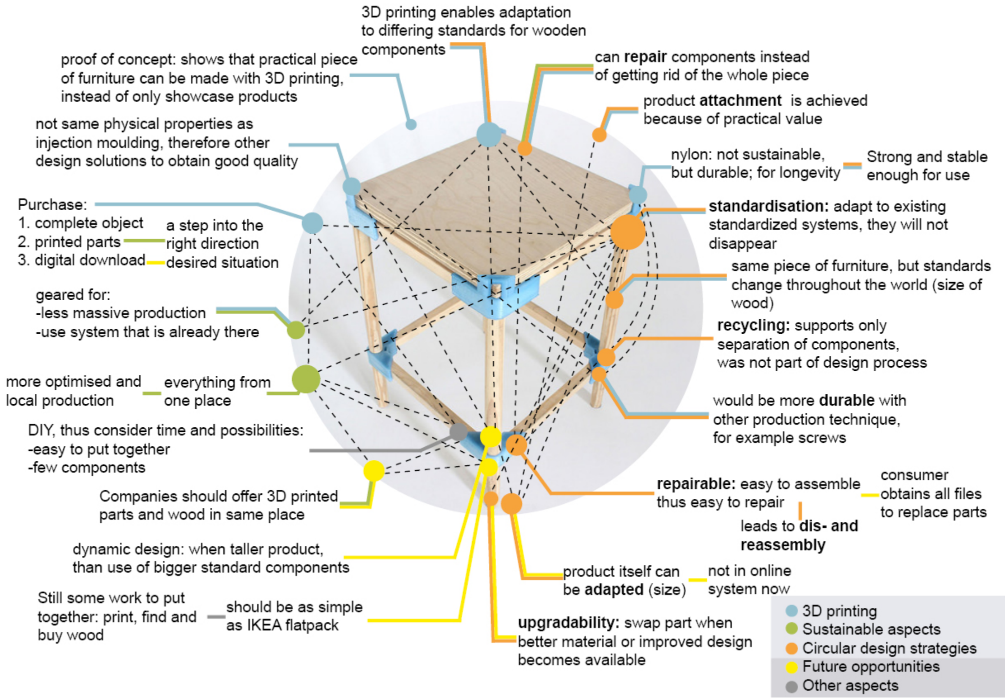


Figure 3.8. 'Standard products' with annotations. In this project, the categories '3D printing', 'circular design strategies' and 'future opportunities' are most present. The annotation about standardisation is most connected, followed by the annotation about local production.

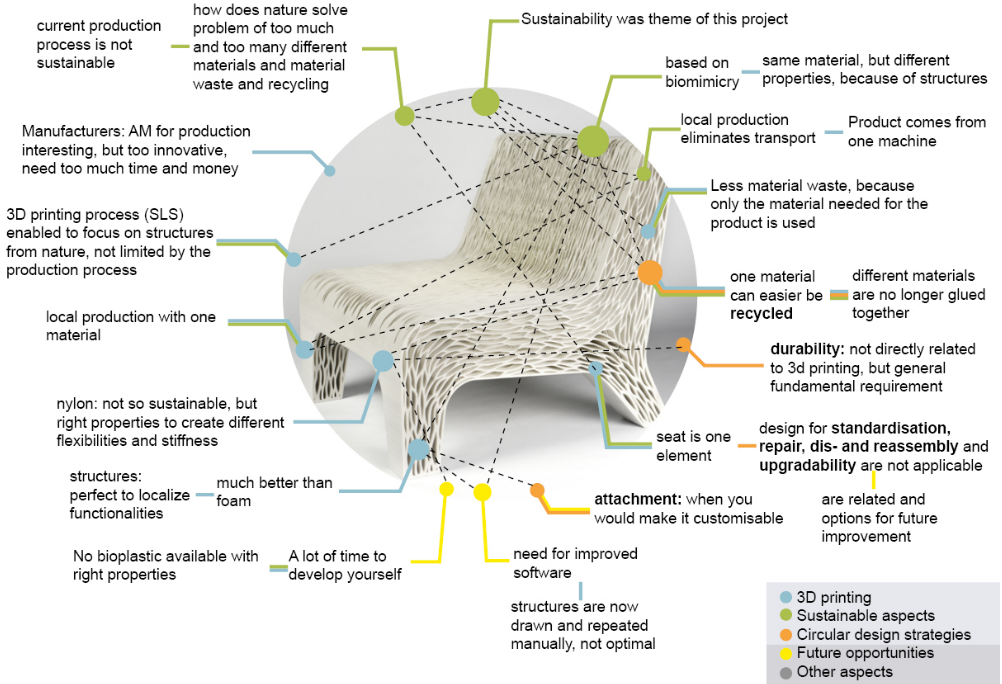


Figure 3.9. 'BIOMIMICRY: soft seating' with annotations. This project has mainly annotations belonging to the categories '3D printing' and 'sustainable relations'. The annotation about biomimicry received the most connections.

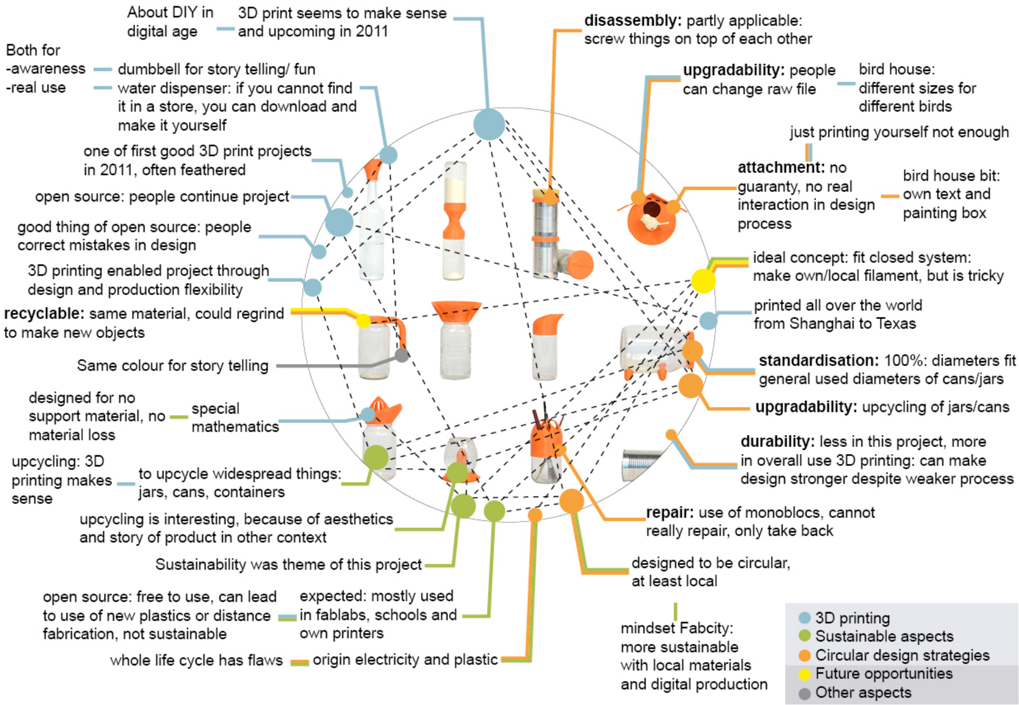


Figure 3.10. 'Project Re_' with annotations. The annotations in this project are evenly distributed between the categories '3D printing, 'sustainable aspects' and 'circular design strategies'. The annotation about DIY in the digital age received the most connections.

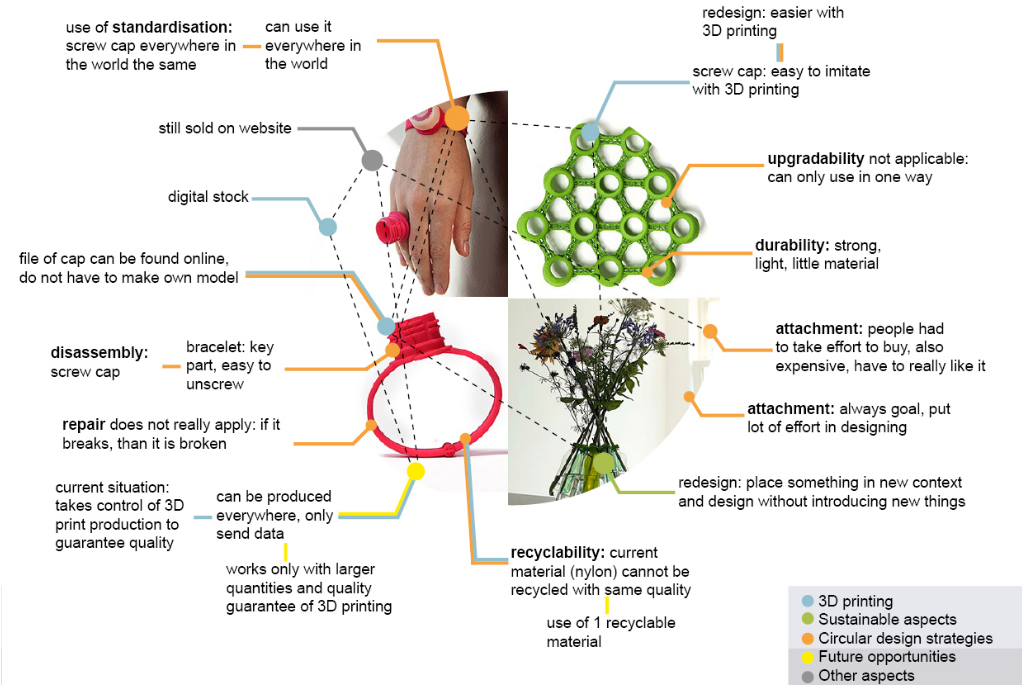


Figure 3.11. 'Screw it' with annotations. This project received the least annotations. Most belong to the category of 'circular design strategies'. The annotation about standardisation received the most connections.

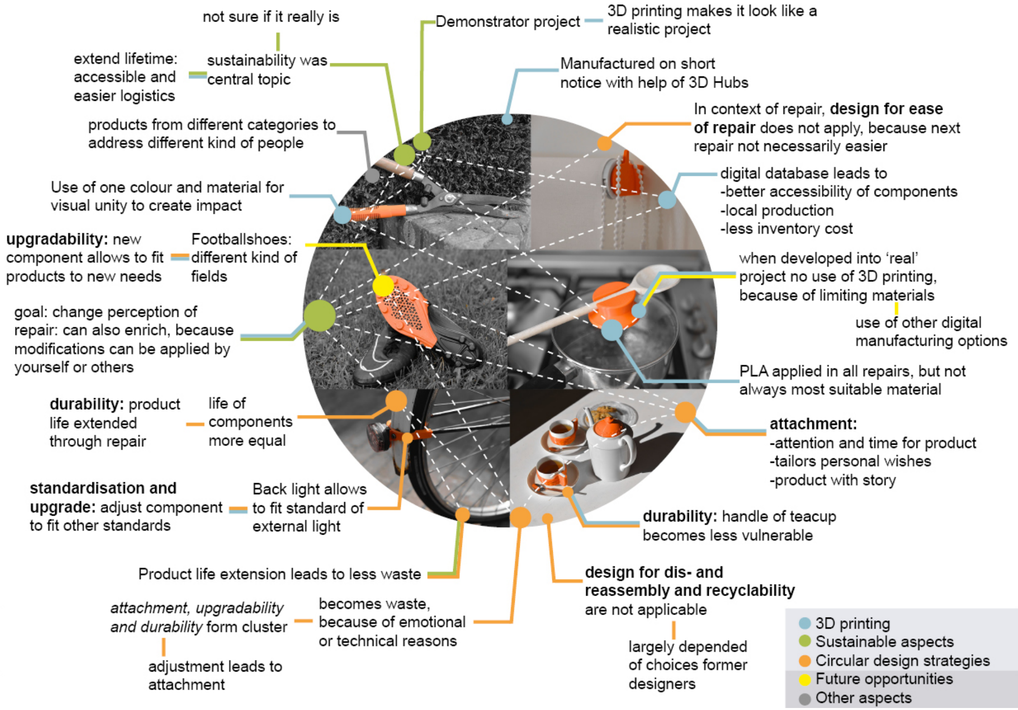


Figure 3.12. Value added repair (VAR)' with annotations. In this project, most annotations belong to the category of 'circular design strategies'. The annotations about the goal has the most connections and is well connected to the 'circular design strategies' category, but does not belong to this category.

'design for upgradability and adaptability', and we found sustainability of 3D printable materials to also be a recurring topic.

Distributed manufacturing in the design projects

In Figure 3.13, the annotations about distributed manufacturing as stated by the designers are presented in a graphical representation of distributed manufacturing, because this logistic model is not 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 location. 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

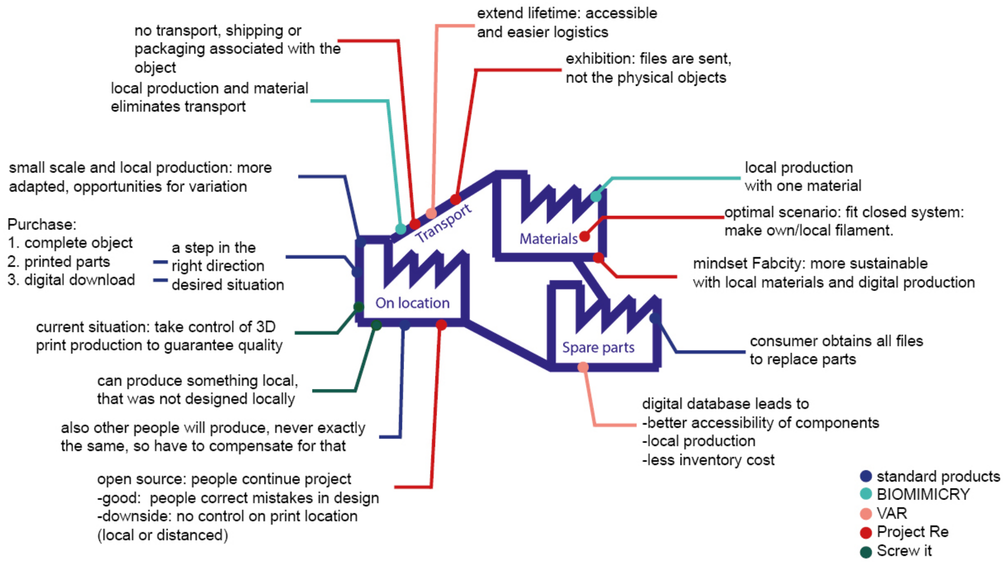


Figure 3.13. Annotations related to distributed manufacturing as stated by the designers

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.

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 3.14, 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.

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.

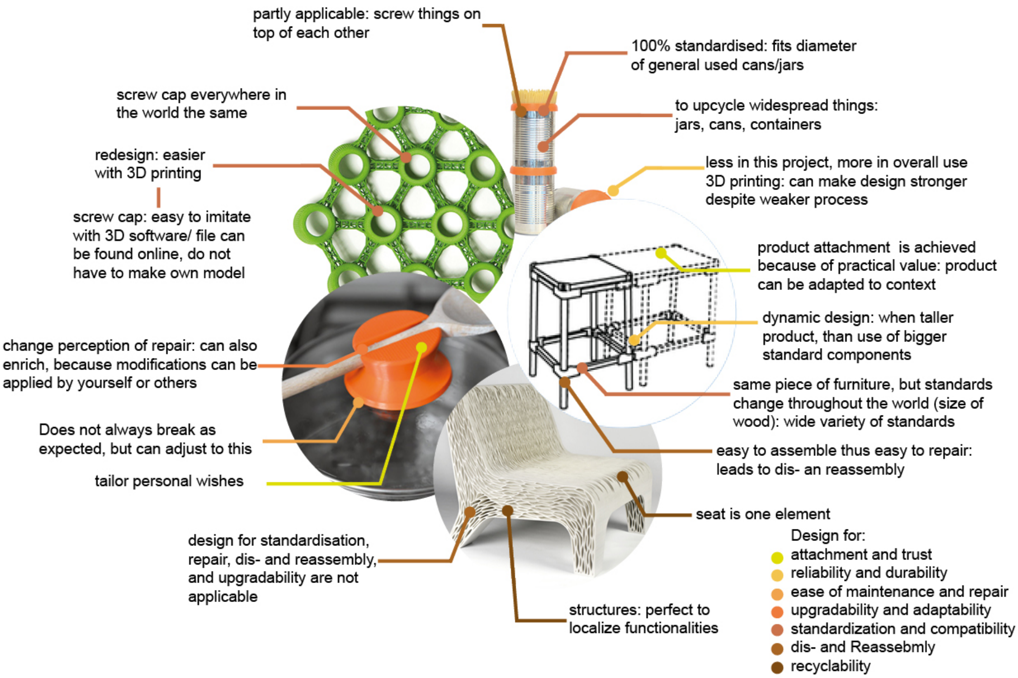


Figure 3.14. Annotations related to the circular design strategies

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

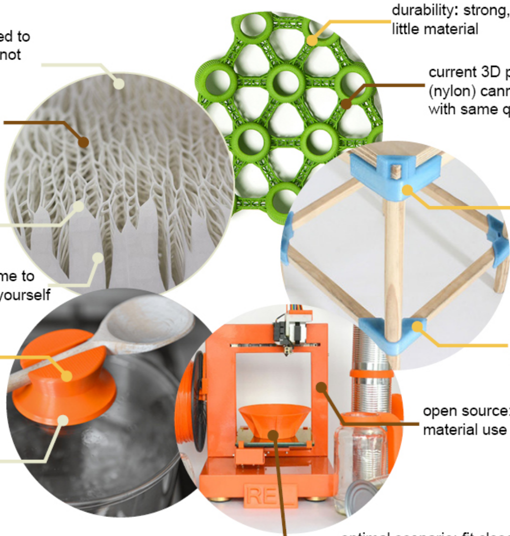


Figure 3.15. Annotations related to the material input of additive manufacturing.

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**.

3D printable materials in a circular economy

All designers expressed tensions regarding their material choices and sustainability/circularity, as is evident from the annotations in Figure 3.15. 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.

3.5. 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 biobased 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 cellulosebased materials on cellulosic fabrics, resulting in a material mixture from the same resource. Mogas Soldevila and 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 shellbased 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.

3.6. 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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Chapter 4

Additive manufacturing can print monolithic and structurally complex products to create optimized solutions for lightweight design and recycling. This can support sustainable design solutions, but does not, per definition, lead to high value reuse in a circular economy. Therefore, in this chapter we explore the integration of high value reuse in the digital fabrication process as a direction for research in the field of human computer interaction (HCI).

Incorporating Sustainability in Digital Fabrication Workflows: Reversible 3D Printed Joints for Part Reuse[3]

Abstract

Current digital fabrication workflows still lack close integration with sustainable practices. We argue that including sustainability guidelines in digital fabrication workflows is a critical direction for future fabrication research in HCI. The circular economy advocates for reuse and recovery to halt problematic material flows. As a first step in this direction, drawing on research in sustainable HCI,
the circular economy, and HCI fabrication, we present a theoretical model for digital fabrication workflows that facilitates reuse and recovery by directly incorporating parts, products, and materials. We demonstrate the practical implications of this model with a prototyping process that addresses design for dis- and reassembly with laser-cut panels connected by reversible 3D printed joints. As HCI researchers explore novel fabrication workflows for an influx of new makers, including explicit sustainability guidelines enables broader consideration of the impact of digital fabrication and the opportunities for sustainable practice.

Digital Fabrication; Sustainability; Design for a Circular Economy; Hybrid Workflows; Design for Dis- and Reassembly

[3] Sauerwein, M. & Peek, N. Incorporating Sustainability in Digital Fabrication Workflows: Reversible 3D Printed Joints for Part Reuse. Under review at TEI'21, the 15th ACM International Conference on Tangible, Embedded and Embodied Interaction at the time of writing

4.1 Introduction

Sustainability practices aim to eliminate negative impact on the planet's ecosystems. Sustainable design does this by carefully considering the environmental context of products and services. Resource depletion, the trade of conflict minerals, and mounting quantities of toxic waste are urgent issues that stem from material consumption. The Circular Economy intervenes in this problematic material flow, advocating for reuse and recovery. Its guidelines aim to keep products at their highest values for as long as possible (Ellen MacArthur Foundation, 2013; Korhonen et al., 2018). Products should be at least recyclable, but preferably be recovered at a higher level using less energy. Therefore, product prolongation and reuse are promoted over refurbishment and remanufacturing, which in turn are preferred to recycling (Stahel, 2016).

Within the HCI community, Blevis (2007) introduced Sustainable Interaction Design (SID), with goals that are aligned with a circular economy. Sustainable Interaction Design gives a perspective on sustainability that provides design goals for new technologies and systems including "linking invention and disposal" and "promoting renewal and reuse". Blevis argues that any new object or system should incorporate a corresponding disposal plan, and preferably, that these objects and systems are first considered for renewal and reuse. The circular economy goes a step further by envisioning a future without waste in which all resources are reused and recovered (Ellen MacArthur Foundation, 2013).

Sustainable making has been identified as a promising area for further HCI investigation (Roedl et al., 2015). Early identified research topics in HCI and fabrication included end-user design tools, personalization of artefacts, and hands-on learning (Mellis et al., 2013), many of which included implicit sustainability considerations. The 'maker' in particular is a rich subject in HCI research, identified as a constituency who will "return to physical materials" (Lindtner et al., 2014), building a sensitivity for material consumption. This broadening of participation in manufacturing by makers rather than specialists necessitates new interfaces, workflows, and experiences, e.g. (Jacobs and Buechley, 2013; Schmidt and Ratto, 2013; Torres and Paulos, 2015), which can incorporate sustainability goals. Furthermore, the 'maker' provides a counterpoint to HCI's 'user', where agency can be extended from selection, use, or consumption to hacking, modding, diverting, and repairing (Dew and Rosner, 2019; Houston et al., 2016; Poretski and Arazy, 2017; Toombs, 2017).

The benefits digital fabrication might have for sustainability practices are so far yet to be proven. Sustainable making practices are far from well-established. The environmental implications of 3D printing are rapidly changing (Rejeski et al., 2018). In studying awareness of sustainability in fablabs, Kohtala and Hyysalo (2015) found a problematic gap between people who could assess environmental impacts of making versus people who were skilled at digital fabrication. Here we identify a need to more deeply explore how sustainability practices and digital fabrication could connect. To do so, we first take a step back to consider what constitutes a workflow for digital fabrication.

We argue that the existing digital fabrication workflows are not well suited for incorporating circular principles. In those workflows, digital designs are produced through computer-controlled equipment using generic stock material. Existing parts or non-generic materials are difficult to incorporate. We therefore identify a need to develop workflows which are not linear, but integrate principles from the circular economy, directly incorporating solutions for product reuse and recovery. We argue that the disconnect between HCI fabrication and HCI sustainability research is due to the separation of the design process (in CAD/CAM) from material embodiment (in physical parts/products) in digital fabrication.

We contribute a theoretical model of circular digital fabrication workflows which incorporate existing parts or non-standard materials. In circular digital fabrication workflows, the initial design idea initiates an iterative process between physical parts/materials and the CAD/CAM process to inform each other for machine fabrication. In this way, a product is created that supports high value product reuse and recovery. To understand how such a model will work in practice, we need concrete examples of how the model can be applied in real-world digital fabrication workflows. We therefore also contribute a specific circular digital fabrication workflow using 3D printing and existing parts. To do so, we applied 'research through design' (RtD) with a prototyping process to better understand how such a digital fabrication workflow would work in detail. We iterated on the integration of design for dis- and reassembly into hybrid digital fabrication with FDM printing and laser cutting, ultimately developing reversible 3D printed joints for part reuse. The practical details that make up this workflow are crucial in evaluating its feasibility as a sustainable fabrication practice. The specific workflow design process we contribute in this paper can inform other HCI researchers about the possibilities and challenges they might encounter when developing other novel sustainable digital fabrication workflows. We believe that sustainable fabrication is an important direction for future HCI research.

4.2 Circular digital fabrication workflow

In "The Textility of Making", Tim Ingold argues against a paradigm where making involves imposing form on the material world (Ingold, 2009). In this paradigm, the idealized form as perfectly imagined in the mind is imposed on the passive and imperfect material world. We represent this paradigm as applied to digital fabrication as a linear digital fabrication workflow (Figure 4.1). In a linear digital fabrication workflow, form is dictated by the digital model in CAD. The toolpath calculations, or

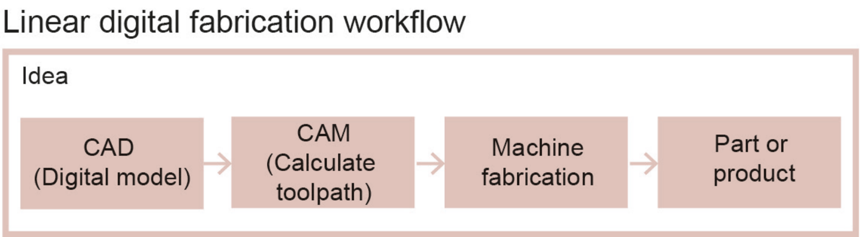

Figure. 4.1. A paradigm for making where digital fabrication is construed as a linear progression or pipeline from digital design to physical product. Computer-Aided Design dictates Computater-Aided Manufacturing dictates machine execution.

CAM, are determined by the CAD model. Perfect raw materials are assumed, and CAM settings only adjust for trade-offs in speed or precision. While fabricating, the machine just executes CAM instructions, and cannot react to other events in the material as it is executing. If any errors occur, it is easier to print the object again than it is to modify the process while it is running.

In opposition, Ingold (2009) argues that actually in making "*the forms of things arise within fields of force and flows of material. It is by intervening in these force-fields and following the lines of flow that practitioners make things. (...) Rather than reading creativity 'backwards', from a finished object to an initial intention in the mind of an agent, this entails reading it forwards, in an ongoing generative movement that is at once itinerant, improvisatory and rhythmic*." We must consider the role of materiality in a digital fabrication pipeline to apply Ingold's textillic paradigm of making to digital fabrication. Digital fabrication tools take in materials in standardized forms: if the filament is kinked, or the sheets warped, it is no longer possible to achieve an acceptable fabrication result on most equipment. The presumption of homogeneous materials was inherited from mass manufacturing practices, but we argue it no longer holds.

In Figure 4.2, we redraw the linear steps of a digital workflow to include a circular flow of materials and parts. Drawing from Ingold, we make explicit the pathways for physical parts to inform digital design and vice versa. By adopting a broader view of what constitutes a fabrication workflow, we can incorporate sustainability practices such as the strategies of a circular economy into making. This brings together the design process and its digital implementation in CAD/ CAM with the material embodiment in physical parts and products.

4.3 Related work

Our work draws from sustainable HCI, the circular economy, fabrication research, and maker culture. In this section we provide an outline of this work and how our contribution relates.

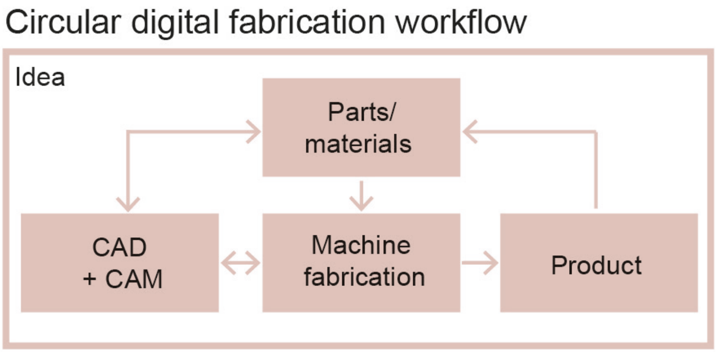

Figure 4.2. The circular digital fabrication workflow integrates physical parts and materials into the digital fabrication workflow to secure reuse and recovery. To achieve this, we need to construct pathways between existing parts and materials and each step of digital fabrication.

4.3.1 Sustainable HCI

Sustainability has been an ongoing topic within HCI research, often linked to how users might individually understand opportunities for living more sustainable lives. For example, understanding the environmental impact of how we travel, what we buy, or how we live (Froehlich et al., 2009; Kuo, 2018; Pierce and Paulos, 2011). DiSalvo et al. (2010) offered an early overview of this kind of work, where they distinguish between sustainability in design (e.g. minimizing energy expended in production) and sustainability through design (designs that encourage sustainable practices e.g. persuasive technology). In the face of widespread unsustainable practices, sustainable HCI can seem like a very small contribution. Dourish (2010) questions the political and cultural context that HCI research often places itself in, proposing that we must match the scale of our interventions to the scale of a problem the size of sustainability. In agreement, Knowles et al. (2014) proposes using HCI research to not only persuade individual behavior, but also to spur collective action.

In our work, we consider the material construction of products, categorizing our research as sustainability in design. However, we contribute fabrication workflows that foreground reuse and recovery. These workflows could be used to change how and when we produce products. We argue that such workflow development is a type of sustainability through design. By contributing an example workflow, we seek to demonstrate a novel type of contribution for HCI researchers, one which furthers the development of sustainable fabrication practices that can be taken up by a broader group than has been historically involved in manufacturing. We believe that concrete contributions to sustainable fabrication are necessary first steps for having large-scale impact on manufacturing and consumption.

4.3.2 Design for a Circular Economy

In a circular economy the economic and environmental value of products is preserved through product integrity or high value recovery. Several design strategies can be applied to support this aim, such as ease of maintenance and repair, upgrading and adaptation, standardization and compatibility, and dis- and reassembly (Bakker et al., 2014).

The aim to reuse and recover existing products and parts has consequences for digital fabrication. It requires a certain interaction between the digital and physical design. Teibrich et al. (2015) for example addressed sustainable production by integrating printing, milling and scanning into a hybrid fabrication machine to patch existing single part 3D prints for repair and upgrade. Weichel et al. (2015) introduced 'bidirectional fabrication' to allow interaction between the digital model and physical object to support an iterative process. Although sustainable production is not mentioned in the paper, the concept of 'bidirectional fabrication' has the potential to contribute to reuse and recovery. More generally, it has been found that additive manufacturing enables opportunities for repair and upgrading, but can hinder design for dis- and reassembly through the creation of integrated assemblies and complex parts (Sauerwein et al., 2019).

We want to explore what design for disassembly and reassembly implies for digital fabrication. Design for dis- and reassembly is a favourable design strategy, as it enhances product reuse through the release of parts and materials (Go et al., 2015), enabling high value product reuse and recovery, such as repair. Research into design for disassembly, and especially design for assembly, has been around for quite some time (Bogue, 2007). But while guidelines for design for assembly and disassembly are commonplace, they typically do not take reassembly into consideration and are meant for conventional production. For example, Bocken et al. (2016) provide initial strategies for incorporating design for dis- and reassembly in product design.

Disassembly as a practice has been explored in HCI. Jackson and Kang (2014) explored the practice of disassembling as part of their inquiry into repair. Landwehr Sydow et al. (2017) and Murer (2018) found that the practice of disassembly can lead to material understanding or material literacy. Recently, Wu and Devendorf (2020) explored designing specifically with disassembly in mind. They contribute a method and supporting software for producing smart textiles that allows for complete disassembly and reuse of constituent yarn. Their process forces the maker to slow down and consider and work with the existing material. By incorporating sensitizing and reflexive practices into the fabrication process, Wu and Devendorf (2020) establish not only how an object can be designed for disassembly and reuse, but also how such a design might shift the mindset towards sustainability.

Drawing from these design strategies from other disciplines and insights into material knowledge in HCI, we integrate design for dis- and reassembly as a requirement in our prototyping process. Here we make explicit the need for designing for product integrity, bolstered by evidence of growing material literacy in making.

4.3.3 Fabrication and HCI

The user experience of fabrication with digital fabrication equipment differs greatly from conventional manufacturing practices. Yet many assumptions remain, such as not being able to intervene during the manufacturing process. HCI researchers such as Devendorf and Ryokai (2015) in "Being the Machine" push back against these assumptions, exploring how fabrication instead could be situated and reflexive rather than efficient and abstracted.

Broadening participation in manufacturing will not only change the way fabrication takes place, but also where. Centralization has historically been beneficial for improving efficiency in manufacturing, especially when co-located with inexpensive labor. HCI researchers have already started exploring what digital fabrication in novel locations could look like, such as remote communities (Jacobs and Zoran, 2015) or in harsh environments (Quitmeyer and Perner-Wilson, 2015). Supporters of the Maker Movement envision a future where physical tooling is replaced with code and manual labor is replaced with automation at distributed sites such as makerspaces. How that vision is playing out is e.g. covered in "What to make of Makerspaces" (Fourie and Meyer, 2015), or specifically how distributed production is being explored in makerspaces in (Hennelly et al., 2019). Without necessarily claiming the maker movement a success, HCI researchers have been designing for this future of widespread fabrication in makerspaces. For example, the Cardboard Machine Kit imagines a future where makers will create application specific machines out of modular and reconfigurable parts (Peek et al., 2017). Kim (2017) formalizes how different makers and makerspaces might collaborate on fabrication. Our research is similarly optimistic about the role of distributed digital fabrication in future manufacturing.

By combining different digital fabrication processes into hybrid digital fabrication workflows, makers can take advantage of the benefits of each constituent process to efficiently produce a high-performance objects. The Hybrid Carpentry approach of Magrisso et al. (2018) takes advantage of the geometrical flexibility of 3D printing for its joinery, while CoFiFab (Song et al., 2016) and faBRICKator (Mueller et al., 2014) use the speed of laser cutting to quickly fabricate coarse internal volumes to more efficiently complete higher resolution and larger 3D printing tasks. RevoMaker (Gao et al., 2015) prints around laser cut cuboidal facets that enclose electronic components to create out-of-the-printer functional prototypes. This approach reduces the amount of build and support material, but also complicates the recovery of the enclosed electronics.

In our workflow, we also combine fabrication methods. Similar to the workflows in this section, this allows us to selectively take advantage of benefits of particular fabrication methods. We are in particular interested in tight integration of processes, where we can take advantage of the precision of the machine when combining components rather than relying on manual assembly.

4.3.4 Material Interventions

We see value in zooming out from "maker" specific material engagement to broader material practices, such as done by Houston et al. (2016) in "Values in Repair". Change can only happen if the possibilities uncovered by proposed workflows are adopted. Ethnographies such as the above help identify the productive and unproductive intersections of sustainability and fabrication research. In our research, we are indebted to the insights that these qualitative studies provide.

We would like to highlight a research tradition of combining qualitative work with design inquiry and intervention. In "Making within Limits", Dew et al. (2018) combine ethnographic and design methods to identify how waste diversion is practiced in makerspaces and harness it for salvage-based fabrication workflows. In "Designing with Waste", Dew and Rosner (2019) practice material recycling, and in so doing uncover embodied attributes of materials that create opportunities and frustrations for waste-diverting workflows. The knowledge that these situated inquiries uncover, especially with respect to working with scarcity, is deeper than either theoretical or applied contributions would be on their own.

4.4 Methods

We are using Research through Design (RtD) to explore the new circular digital fabrication workflow. In RtD, we generate knowledge by prototyping (Gaver, 2012; Koskinen and Krogh, 2015; Zimmerman et al., 2010). Making prototypes and artefacts reveals insights and requirements that are only obtainable through experimentation (Stappers and Giaccardi, 2017). Although RtD is often used in a social context to study or provoke certain interactions or reactions with a prototype (Koskinen et al., 2011), we are using RtD as a method for exploring sustainability and design practices. We iterated with artefacts, balancing the guidelines of designing for a circular economy with the existing practice of digital fabrication with each iteration in order to make products for high value reuse. Both how we documented our prototyping process and what tools we used to prototype are detailed in this section.

We used a design diary to support the generation and development of ideas and to keep track of progress. Design diaries and workbooks are established methods in RtD practice (Gaver, 2011; Sadokierski, 2019).

Ideas were first explored on paper with (annotated) sketches to meet the set requirements. Some designs, for example, were interesting solutions for disassembly, but the sketches made clear that they were impossible to reprint with FDM printing. The more promising ideas were further developed to fabricate prototypes. Each prototyping attempt, such as 3D printing with new settings or laser cutting new material, was logged into the design diary with date and action points. Each (attempt to create the) artefacts was evaluated based on what went right and wrong. Subsequently, further iteration took place through sketching to explore new solutions to prototype, resulting in a process of constant trial and reflection. The diary supported an ongoing conversation between the imagined solution and the actual feasibility.

We selected a triangular prism as the target artefact for our prototyping process to confirm we were able to make joints at non-right angles. The prism was used to test several requirements: manufacturability, joint reliability, capacity for dis- and reassembly, and part reuse. To evaluate the outcome of our prototyping process, we tested the final prism design's assembly, disassembly, and reassembly. Finally, two separate prototype objects, a vase and lampshade, were made from the same panels to evaluate the reuse opportunities and shape diversity of the parts.

We use FDM 3D printing and laser cutting in our fabrication process. Both techniques complement each other. Additive manufacturing (AM) is energy intensive and slow, but it can produce intricate geometries that are impossible to make through other fabrication methods (Kellens et al., 2017; Rejeski et al., 2018). Laser cutting can quickly produce planar shapes from sheet stock, but making 3D objects requires joinery steps. Connecting the planar sheets with AM would enable a wide variety of shapes.

4.5 Workflow iterations

Figure 4.3 summarizes our prototyping process and shows four iterations with the prism artefact. We iterated on an initial idea: placing laser cut panels in the 3D printer and connecting them with 3D printed joints. The 3D printed joints consist of two parts, the corner part and the closure part. For each artefact, we evaluated a list of requirements for ease of positioning and assembly, dis- and re-assembly, joint reliability, reuse of laser cut parts, corner prints and closure prints. Whether they were achieved is shown below each iteration with checkmarks (Figure 4.3).

As shown in the first attempt in Figure 4.3-1, the prism could not be made due to issues with fixturing. In subsequent attempts (Figure 4.3-2,3,4) the prism was produced, but positioning and fixturing remained difficult. To address this, we designed a clamp to hold the panels of the prisms in place. The prism could be dis- and reassembled after the second prototyping iteration, but the recovery rate of the parts was low, as shown

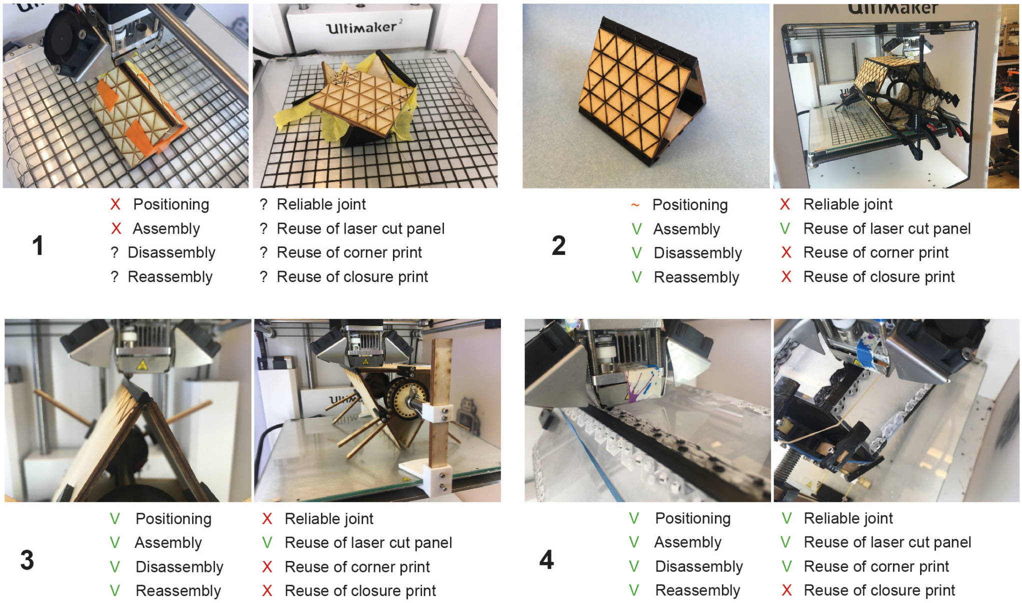

Figure 4.3. Four iterations in the prototyping process are shown. For each iteration, we evaluated the prototypes on manufacturability (ease of positioning and assembly), dis- and reassembly, robustness, and reuse of parts. We conducted several artefact iterations to explore the new circular digital fabrication workflow in practice.

in the list of requirements in Figure 4.3-2. Furthermore, the joints were not reliable. The list of requirements of the final prototyping iteration (Figure 4.3-4) demonstrates that this approach was manufacturable, could be dis- and reassembled, and could have almost all parts reused. As we were 3D printing on top of existing parts and this is not covered by existing slicing software, we had to modify the G-Code 3D printer instructions we produced with Cura with our own custom software in Python. Below we describe the modifications for positioning and fixturing as well as the joint design in more detail.

4.5.1 Positioning and Fixturing

We found that positioning and fixturing existing parts was essential for successful assembly. The laser cut panels were placed in the 3D printer and 3D prints were made on top of these panels instead of on the print bed. Therefore, the digital input to the 3D printer had to correspond to the physical laser cut panels. We designed a clamp to securely hold the panels at different angles during the print process, shown in Figure 4.4. This clamp accommodates multiple shapes, e.g. triangular or hexagonal prisms of different widths, lengths, and heights. These prisms can be made up of panels of varying thickness. The clamp is connected to the 3D print bed, holding the panels to be printed on in position such that the print head cannot collide with the assembly. To fine-tune the assembly's

Figure 4.4. A clamp holds face panels of different widths and lengths at specific angles with corner parts on the 3D print bed. The height of the prism can be raised or lowered.

position, we developed additional software similar to 3D printer bed-leveling routines to move the print head to a known point on the assembly. In this way, we could manually align the assembly to the print head position to print on top of the panels.

4.5.2 Joint Design for Reuse

The final approach includes joints that are dis- and reassemblable and support part reuse. Reassembly implies that the same starting point has to be created as was used for assembly (Go et al., 2015). However, reusing parts for a subsequent product life cycle in digital fabrication does not automatically result in the same initial assembly conditions. Reassembly will reuse already manufactured parts. In the first prototyping attempts, we disassembled through uncontrolled breaking of the 3D printed joints, rendering the reuse of these parts impossible. We wanted to have more part reuse, and thus needed to create reversible joints. We designed a new joint based on z-pinning that would allow for controlled breaking (Figure 4.5A).

Duty et al. (2017) describe z-pinning as an approach to improve the mechanical strength of FDM prints in the z-direction. They found that samples with z-pins to have higher mechanical performance than unpinned samples (Kim et al., 2018). The weakest point in the resulting material is between z-pins, because it requires bonding a cold and warm layer instead of successive warm layers. (Duty et al., 2017). We adapted z-pinning to hybrid digital fabrication by using pins in voids that were introduced in laser cut panels. The 3D print head fills a void in the panel,

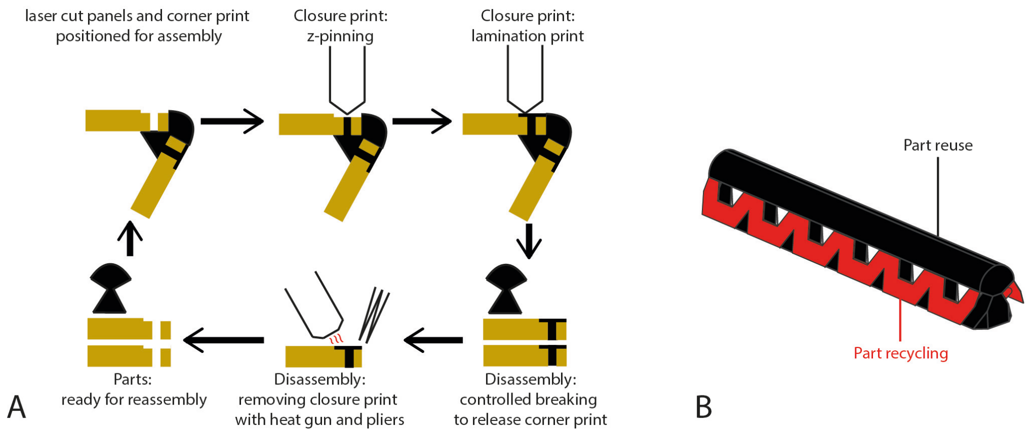

Fig. 4.5. A: Z-pinning as applied in the joint design. Voids in the laser cut panels are filled, connecting the corner part to the panel. The z-pin is covered with a lamination 3D print. To disassemble the object, the z-pin is broken from the corner part, releasing the joint. Finally, the panels are prepared for reuse by heating the PLA and cleaning them with pliers. B: The corner part can be reused, only the closure part is removed and has to be recycled after breaking.

connecting the corner part below to the lamination about using a z-pin. The cold/warm connection between the z-pin and the corner part is designed to be the failure point for disassembly (Figure 4.5A). In this way, the laser cut panels and corner part can be reused, only the closure part is removed and has to be recycled after breaking (Figure 4.5B). We accepted the lack of reuse of the closure part because it is a small print, both in time and material.

4.6 A circular digital fabrication workflow to create products with reversible joints

We developed a workflow to create reversible joints as a practical example of the circular digital fabrication workflow. In these joints the corner part determines the angle the panels will be joined at, while the closure part connects the corner part to the laser cut panels with a thin lamination print that fills the laser engraved pattern in the panels. A step-by-step overview of the workflow is shown in Figure 4.6, which we explain: The laser cut panels contain laser engraved ridges, as well as laser cut holes for z-pinning (1). The corner parts are separately 3D printed (2) and brought into position in the clamp together with the laser cut panels (3). The closure print consists of G-code for the lamination part created with Cura (4) and G-code written with Python in Grasshopper for z-pinning and pausing (5). These files are combined with python into the G-code for the closure 3D print (6). When starting the closure print, the printer head first pauses at the coordinates of the z-pins, without extruding, to manual position the clamp by placing the laser cut holes below the nozzle. After positioning, the print continues to create the z-pins and pattern for

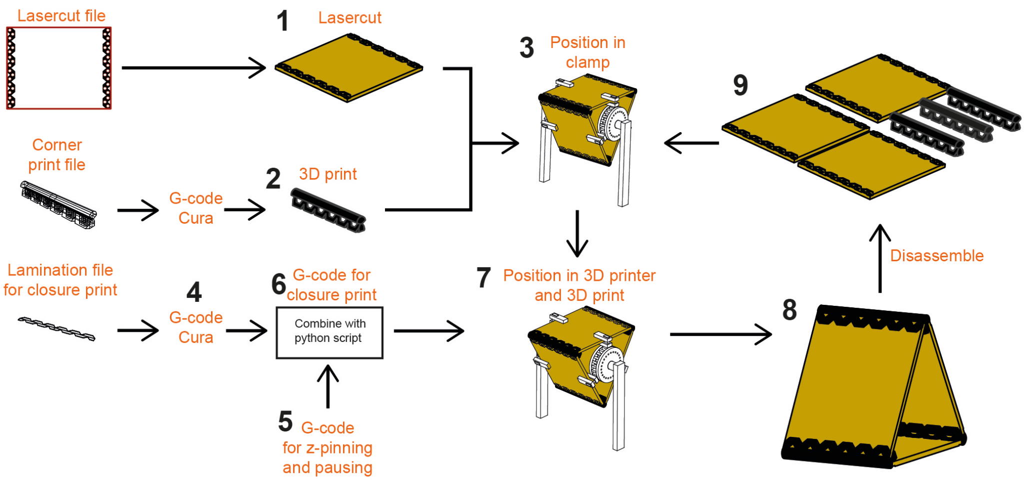

Figure. 4.6. The workflow to create reversible joints. Corresponding to the circular digital fabrication workflow described in Figure 4.2, CAD/CAM is employed in conversation with existing parts and materials.

lamination (7). The closure print is repeated for all corners to create the end product (8). This product can be disassembled later on into parts for reassembly (9).

4.7 Evaluation

The workflow to create reversible joints in Figure 4.6 incorporates guidelines of a circular economy, supporting dis- and reassembly and maximizing the number of parts that can be reused. It introduces a novel design element in its joints, extending the design vocabulary that can be employed for digitally fabricated objects. To evaluate the reversible joints, we conducted assembly, disassembly, and reassembly with our test shape (a triangular prism). The prism was successfully fabricated, disassembled, then reassembled into the prism. This process is shown in detail in Figure 4.7. To disassemble the prism, the connection between the corner prints and z-pins were broken manually. The plates were cleaned, completely removing the closure part using a heat gun and pliers. Heat softens the 3D printed PLA, facilitating manual removal. This process was repeated twice with no observable differences between the first and second recovery round.

The same shape was reassembled in Figure 4.7, but this does not always have to be the case as demonstrated by the lampshade and vase in Figure 4.8. The lampshade is an odd-sided hexagonal and the vase is a hexagonal with tapered sides, but both objects are made from the same laser cut components, which can be reused in different configurations. A variety of shapes can thus be obtained when reusing the same panels. This is accomplished by using parametric design to combine generalized panels

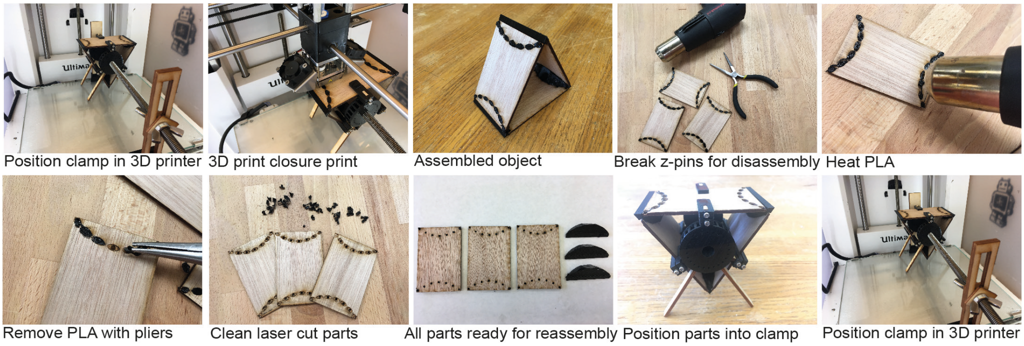

Figure 4.7. Assembly, disassembly and reassembly of the prism

and product specific joints. The 3D printed corner shapes are product specific and contribute to a seamless look. In the lamp, for example, the form of the joints is extended to serve as legs. This way, a family of products is created which is less restricted in shape freedom than products from fully standardized components. This influences the aesthetic appearance and broadens the design language.

The prototyping process led to reversible joints that allows for part reuse for different purposes and on different levels:

- As stated above, the laser cut panels are versatile and can be reassembled into different configurations. They can be reused in the same or different products.
- The corner part of the joint is product specific and can be reused to retain the same object, for example to repair or improve. The first time we assembled the lamp, the closure print was messy and did not meet our expectations. Therefore we broke the connections and removed to closure prints to reuse the laser cut panels and corner parts to obtain a satisfying result.
- The relatively small closure part is broken and can only be recycled.

4.8 Discussion and future work

Digital fabrication workflows are rapidly changing as new research is conducted and equipment becomes more accessible. There is an urgency to have novel fabrication workflows and technology depart from problematic wasteful practices. In digital fabrication, we believe this requires a departure from a linear pipeline model. We propose a new theoretical model for circular digital fabrication workflows (shown in Figure 4.2) that integrates reuse and recovery by connecting physical parts and materials to the design process in CAD/CAM and machine fabrication.

We explored practical implications for making with digital fabrication tools and circular economy guidelines to encounter possibilities and

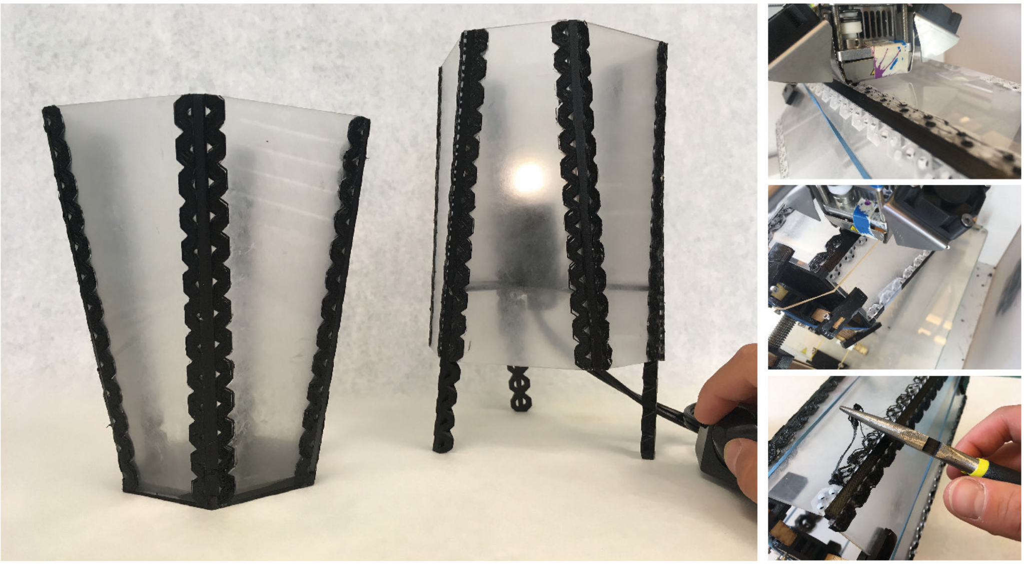

Figure. 4.8. This vase and lampshade (right) are made of the same laser cut panels, which can be dis- and reassembled for reuse and recovery. They demonstrate the application of reversible joints, where panels are joined through direct 3D printing (right top and center) and can be disassembled (right bottom).

challenges in enacting a circular digital fabrication workflow. Our prototyping process led to a concrete example of how to make products for high value reuse with reversible joints. The reversible joint should not be seen as the only, or even best solution, but as a tangible example of the workflow. Figure 4.9 shows how details of each step fit in a (re)fabrication cycle of the schematic workflow. In this section, we discuss our findings and relate them to prior work in sustainable HCI and HCI fabrication to encourage the HCI community to further explore workflows that adhere to our theoretical model of circular digital fabrication.

While the design opportunities that AM enable often lead to the production of complex mono-part solutions that are difficult to disassemble (Gao et al., 2015; Sauerwein et al., 2019), we show that such opportunities can also contribute to integrated solutions that support high value reuse. Our reversible joints are an integrated part of the product; we take advantage of the weakness of cold-weld connections during 3D printing for 'controlled breaking' with z-pinning. Besides the joint's functional role, it also plays a role in the the aesthetic appearance. This gives designers the opportunity to develop new design languages. Previous guidelines for high-value reuse often result in bulky designs with large connectors. By integrating the connector into the design and offering a parametric system for modifying it, the designer is given greater freedom without sacrificing circular principles. Integrated part solutions previously could not meet

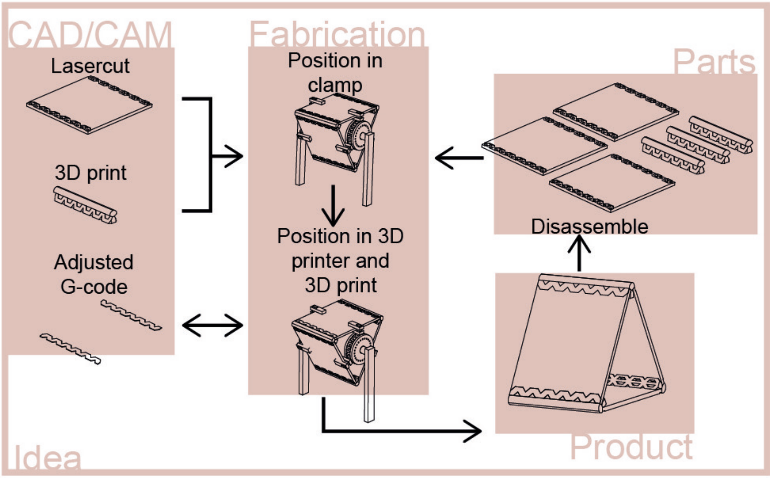

Figure. 4.9. An illustrated example of how the workflow for reversible joints fits into a circular digital fabrication workflow.

the requirements for reuse and recovery; our approach demonstrates that further exploration of these sleek designs are possible without increased waste streams.

Recently, Wu and Devendorf (2020) called for the inclusion of design for disassembly in smart textile design. While designing for unravelling is a promising approach for textile design, other product design processes are more difficult to revert. Then part reuse becomes more important, for example by incorporating predefined shapes into subsequent product life cycles. Our aim was to explore what design for disassembly and reassembly implies for part reuse in digital fabrication; we found a combination of reassembly and part reuse particularly challenging. We were only able to arrive at an approach that supported both conditions after an iterative process. Special attention for high value reuse is therefore required in design for dis- and reassembly within digital fabrication workflows.

In addition, design for dis- and reassembly is not the only strategy that supports reuse and recovery. Depending on material, product, and digital fabrication method, other strategies can be applied such as the previously mentioned approach to patch physical objects of Teibrich et al. (2015) or to design with waste (Dew and Rosner, 2019). As long as reuse and recovery are considered, a wide range of solutions can be explored that fit the desired outcome. It is, however, important to keep in mind, that integrating design for reuse and recovery in the digital fabrication workflow requires a mind shift because it no longer only considers making, but also includes remaking. This requires the development of tools that support such approaches.

Tools are needed to enact the circular digital fabrication workflow in practice. We found interesting tools presented by Vogel et al. (2020) that fit within this model. Their tools aim to facilitate design decisions on sustainable material choices to foster the design of closed material loops. On a production level, we call for tools that enable positioning and fixturing. There are not enough features in digital fabrication equipment to accommodate the measuring and fixing to position physical parts in the machine for fabrication. Therefore accessible toolkits for making novel CAM toolpaths and tools that allow for the inclusion of physical input—existing parts—in FDM printing are interesting paths for future work to realise the application of circular digital fabrication workflows in practise.

We see here a role for the HCI community to embrace this mind-set and close the current gap between HCI fabrication and HCI sustainability as indicated by Kohtala and Hyysalo (2015). To give an example, standard CAM software for toolpath calculation did not support our explorations beyond normal use of the machine and we had to create our own software to generate custom G-code toolpaths. While this step is perhaps not considered complex for HCI researchers, it does raise the threshold for contributing novel (sustainable) workflows for designers and makers without programming skills. We thus identify a need for accessible toolkits that include makers with a wider perspective and skill set.

When enacting circular digital fabrication workflows with a variety of experimental studies and accessible toolkits, not only substance is given to Blevis' call to "promote renewal and reuse" (Blevis ,2007) and Ingold's argument for "an ongoing generative movement" (Ingold, 2009), but, moreover, the boundaries between sustainable HCI and HCI fabrication research will fade, much needed to realize digital fabrication in a circular economy.

4.9 Conclusion

Digital fabrication lacks close integration with sustainable practices. Circular economy guidelines advocate for reuse and recovery to halt problematic material flows. By expanding the typical, linear digital fabrication pipeline to a circular process that considers actual physical parts, products, and materials, we developed a novel fabrication workflow for a circular economy. We demonstrate the practical implications of this circular digital fabrication workflow with a prototyping process that uses hybrid digital fabrication and integrates design for dis- and reassembly. In this approach, laser cut panels are connected with reversible 3D printed joints. The reversible joints are part of the design aesthetic and allow for recovery and reassembly through controlled breaking for disassembly. This approach is only one example of the interpretation of the circular digital fabrication workflow to advance research into sustainable fabrication, an area where we believe HCI could make many productive contributions.

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Chapter 5

In chapter 3, we show that designers express a desire for a wider palette of materials based on renewable sources that meet the needs of their design projects. In this chapter, we explore a way to address this need by developing a 3D printable paste material from locally sourced, bio-based (waste) streams. We investigate the recyclability of this new 3D printable material to meet material integrity for a circular economy.

Local and Recyclable Materials for Additive Manufacturing: 3D Printing with Mussel Shells[4]

Abstract

The potential of additive manufacturing (AM) for distributed production is often mentioned as an enabler for sustainable manufacturing within a circular economy. Currently, even if manufacturing with AM is distributed, the used materials can rarely be acquired locally and are usually obtained from a centralized location. Addressing this issue, we are developing an approach that supports the search for local materials that are suitable as material input for AM and are recyclable to serve multiple product lifecycles. The approach is an iterative process consisting of four phases; “material in AM context”, “recycling opportunities”, “material property testing”, and “application possibilities”. As an initial example, we present a process to adapt mussel shell waste into AM material. Mussel shells are a voluminous waste stream in the Netherlands. The shells, which mainly exist of calcium carbonate, are ground into a powder and combined with sugar water. Using a modified material extrusion process, 3D objects are created. In this paper, we discuss the iterations through our approach and illustrate the initial 3D printed results. With this project, we intend to demonstrate the potential of using local waste streams for AM processes for a circular economy. This is a first step towards the development of a methodology for linking local material streams to novel AM processes and meaningful applications.

Additive manufacturing, Recycling, Local materials, Circular Economy

[4] Sauerwein, M., & Doubrovski, E. L. (2018). Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Materials Today Communications, 15, 214–217. https://doi.org/10.1016/j.mtcomm.2018.02.028

5.1. Introduction

Additive manufacturing (AM), also known as 3D printing, can support distributed production, which is often mentioned as an enabler for sustainable manufacturing within a circular economy. AM's ability to print on-demand and on a small scale supports local production (Esmaeilian et al., 2016; Kohtala, 2015). Local production is seen as a sustainable alternative for centralized production, because of reduced transportation (Ford & Despeisse, 2016) and an enhanced connection between user and product (Kohtala & Hyysalo, 2015; Prendeville et al., 2016). Besides this, local production supports recycling of materials, avoiding information loss stemming from the aggregation of waste by large-scale recycling facilities (Despeisse et al., 2017). For example, distributed recycling for HDPE filament could save up to 80% embodied energy (Kreiger et al., 2014).

While it has been suggested that local material sourcing would be beneficial (Chen et al., 2015), materials needed for production with AM can rarely be acquired locally and are usually obtained from a centralized location. Some companies (e.g. Refil (2019), Fila-cycle (2017)) have started to pay attention to recycling and to exploit recycled plastic filaments. However, local sourcing of raw materials remains a challenge.

A circular economy represents a system in which resource loops are closed. Closing the material loop is at the heart of the circular economy (Bocken et al., 2016; den Hollander et al., 2017). With the goal to apply AM in a circular economy, we intend to develop a methodology for linking local material streams to novel AM processes and meaningful applications. The methodology needs to support the search and processing of local material streams into material input for AM. These materials should also be able to serve multiple product life cycles.

Demonstrating the principles of our approach, in this paper we present our initial study on processing a locally sourced waste stream into a 3D printable material.

5.2. Design approach

The proposed approach, as developed during this study, is intended to support the development of 3D printable materials for a circular economy. The approach consists of four stages, as depicted in Figure 5.1. Through an iterative process that follows the stages, the material and AM process are refined in each loop, i.e. starting with exploration and ending with determination. In the "Material in AM context" phase (Figure 5.1), the material opportunities of the raw material are analysed in relation to additive manufacturing. The 3D printer and material are modified to achieve a reliable process. When a workable material is obtained, the "recycling opportunities" are investigated, as we do not only want to create a material for production, but also guarantee the

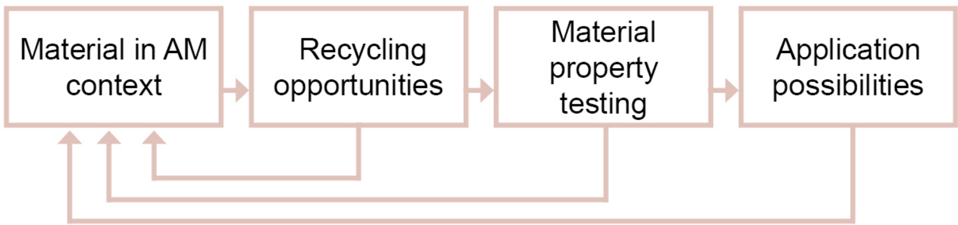

Figure 5.1. Schematic overview of proposed approach.

recyclability and reusability of the material. During "material property testing" characteristics of the developed material are tested; initially rudimentary and more precisely in a later stage. During "application possibilities", product applications are explored to establish a meaningful purpose of the developed material. It should be noted that every AM material development can start from a different phase. It is, for example, possible to start with the "Application possibilities" and continue to formulate requirements for the exploration in "Material in AM context".

5.3. Experimental

5.3.1. Material

To illustrate the development of a locally sourced material, we searched for local and voluminous waste streams in the Netherlands. We identified mussel shells as a candidate source for AM material, as approximately 50 million kg of mussels are produced in the Netherlands annually (Het Nederlands Mosselbureau, 2014). The shell consist almost entirely out of calcium carbonate and comprises approximately 40% of the weight of a mussel (Hamester et al., 2012). Mussel shells can be considered waste that is not suitable for composting (milieu centraal, 2016). As the starting point is a locally sourced raw material, we started at the stage "Material in AM context" for the process discussed in this paper.

5.3.2. Printing methods

Materials from mussels shells were initially created to be used for a binder jetting additive manufacturing process. In a later stage, a paste suitable for extrusion was prepared. We used an Ultimaker 2+, a desktop material extrusion 3D printer, as well as Ultimaker's slicing software Cura. Both the 3D printer and the slicing software were modified to process the mussel material.

5.4. Results of material exploration for Binder Jetting

5.4.1. Material in AM context

To make the shells suitable for 3D printing, they were ground into a powder. Before griding the shells in a food processor, the shells were cooked for 20 min and heated at 200 °C for 1 h. Heating the shells makes them more brittle and easier to process (Hamester et al., 2012). A sieve fraction of particles smaller than 2mm was used.

The binder jetting process was imitated by dripping binders on the mussel powder with a syringe. For the binder, we tested water, sugar water, and starch. We obtained the best results from the powder mixed with sugar water and therefore decided to continue with this binder. Different binder concentrations were explored and it was found that a mass ratio of 2:3 of sugar and water worked well. After drying the part at room temperature, a solid part was obtained (Figure 5.2A). We further explored the material by firing it in a furnace at 250 °C. Through intermittent weighting of the part, we found that most of the water was evaporated after 50 min, resulting in a black part (Figure 5.2B).

5.4.2. Recycling opportunities

To explore the recyclability of the material, a fired part (Figure 5.2B) was ground into a powder and combined with the same binder as the initial part (Figure 5.2A). Figure 5.2C depicts the result before firing, the part obtained after firing is shown in Figure 5.2D.

5.4.3. Material property testing

Basic testing showed that part A (Figure 5.2) did dissolve in water, while part B (after firing) did not dissolve in water. This part was also more difficult to break by hand. The recycled parts behave similar to their virgin counter parts, i.e. part C behaves similar to part A and part D to part B.

The powder contained particles up to 2 mm, which is too coarse to make 3D prints with fine details. This implied that the material needed to be improved, leading back to the phase “material in AM context”. Introducing a sieve fraction of maximal 75 μm, the powder turned out to be too hydrophobic for binder jetting. The pores between the particles were not effectively filled with binder liquid. Instead of further adapting the binder properties, we decided to explore a different AM technique, i.e. material extrusion printing.

5.5. Results of material exploration for material extrusion

5.5.1. Material in AM context

Following the process as discussed in the previous section, the shells were ground into particles. The particles were sieved to obtain a powder with a sieve fraction of maximal 75 μm. Powder that was not fine enough was grounded and sieved again to minimize waste. Subsequently, the obtained powder was mixed with sugar water into a paste to explore the mussel material in combination with the AM process material extrusion. To print the paste, a syringe that is actuated by compressed air was attached to the

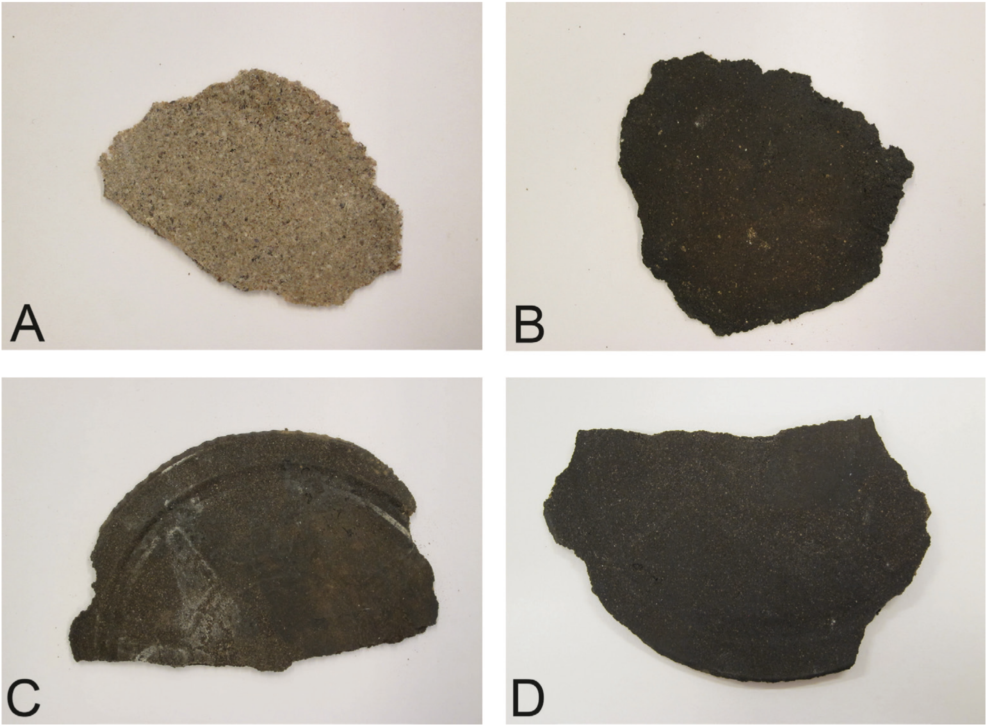

Figure 5.2. Results of material exploration. Part A. Initial 'print', Part B. Fired 'print', Part C. Initial 'print' with recycled powder, Part D. Fired 'print' with recycled powder

positioning system of the Ultimaker 2+ (Figure 5.3). A digitally controlled pressure regulator was connected to the controller board of the Ultimaker, which allowed us to control the extrusion pressure using the Cura slicer software.

Through an iterative process of adjusting the material ratios, printing speeds, printing pressure, and nozzle size, a working combination of material and printing process was found. A mass ratio of sugar and water of 1:1 results in a binder suitable for a stable and firm paste for extrusion, The mass of the binder in relation to the powder is critical, because too little binder results in jamming of the paste in the syringe. Adding too much binder, results in an unstable print, i.e. the printed structure sags or collapses. Table 5.1 outlines the settings that were found to achieve a successful extrusion print with the mussel paste.

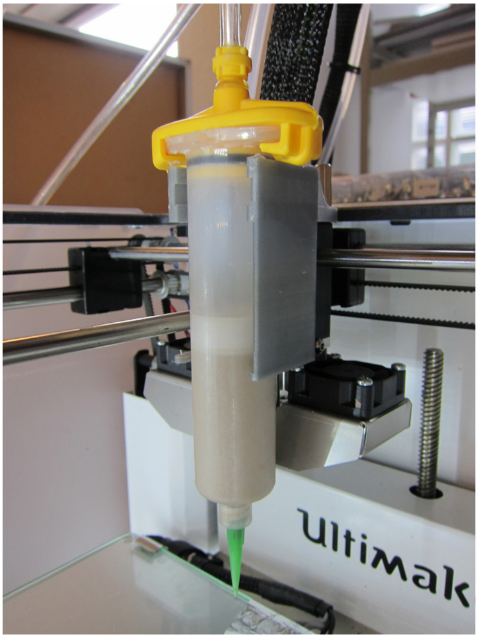

Figure 5.3. Extrusion printing setup

Settings	Value
Sugar weight percentage of paste	15 wt%
Water weight percentage of paste	15 wt%
Shell powder weight percentage of paste	70 wt%
Diameter syringe	22.5 mm
Nozzle size	0.84 mm
Pressure	0.22-0.34 bar
Print speed	5 mm/s
Layer height	1 mm
Layer width	1.5 mm
Build plate temperature	30°C

Table 5.1. Printer settings

5.5.2. Recycling opportunities

Parts obtained through the extrusion printing process were fired in a furnace at 250 °C, which resulted in samples comparable to the part of Figure 5.2B. However, to recycle the fired samples into a new paste, it was found that a different procedure is required. Therefore, it was decided to continue with the unfired material and further develop it. In order to recycle the unfired parts, the samples can be dissolved in water. Printed parts already contain sugar, therefore only water needs to be added to regain a paste suitable for 3D printing. It was found that parts should be

Figure 5.4. Result of material extrusion with recycled material.

dissolved in 15% water mass of its mass to obtain a printable paste. Figure 5.4 shows the result of a print with recycled mussel shell material.

5.5.3. Material property testing

After achieving successful prints, several tests were performed on the unfired material prints to obtain the material properties as outlined in Table 5.2. A three point flexural test was performed to obtain E-modulus and flexural strength (ASTM, 2013). 3D printing the samples resulted in a homogenous cross section. The samples had a rectangular shape of 3 by 4 by 45 mm, but did show irregularities in shape. Both samples of the 'virgin' and the recycled material were tested after drying at room temperature. Besides this, printed parts were weighted and placed in water to determine the density. The found values should be considered indicative, as four samples for each material were tested in the experiments and dimension variations were present in the test samples.

Property	Value 'virgin' material	Value recycled material
Colour light brown	Light brown	Light brown
Odor	Slightly salty	Slightly salty
Water resistant	No	No
Density	1.7e3 kg/m3	1.7e3 kg/m3
E-modulus	11.3 GPa	12.6 GPa
Flexural strength	12.9 MPa	12.4 MPa

Table 5.2. Material properties.

5.5.4. Product

An initial application demonstrator for the material was explored. Mussel shell print material consists mainly of calcium carbonate, which is a suitable soil fertilizer (Tegethoff et al., 2001). Printing this material results in a ceramic-like material. Therefore, a flowerpot was considered a suitable initial product application to demonstrate the current applicability. The result is depicted in Figure 5.5.

5.6. Discussion and conclusion

This paper discusses a first step towards the development of a method for linking locally available materials to AM processes and meaningful applications to serve the circular economy. The results demonstrate that an accessible approach can be applied to convert a local waste stream into a material suitable for AM. The opportunities of 3D printing with ground mussel shells mixed with sugar water were explored. The obtained paste was found to be suitable for material extrusion 3D printing, as demonstrated with a printed product prototype. It is of importance to consider the recyclability of the material during the material development. Using the developed material, outdated designs or failed prints can easily be dissolved in water and reused as material input. This results in an equivalent material as outlined in Table 5.2. However, the values in this table should be considered indicative, as only four samples for each material were tested in the experiments and dimension variations were present in the test samples. More tests are needed to further explore, refine and optimize the material properties and printing behavior. In general, the 3D printable mussel shell material shows the unexplored potential of local materials as an input for AM. The approach, as depicted in Figure 5.1 gives guidance to the process and will be explored in further testing.

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Figure 5.5. Flowerpot printed with mussel shell material.

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Chapter 6

In this chapter, we further elaborate on our research on material integrity and we introduce the term 'reprintable materials'. In the previous chapter, we used the term 'recyclable materials', but 'reprintable materials' is more appropriate as our aim was to not only maintain material properties, but also to retain printing properties. We focus on alginate as a binder for extrusion paste printing that can be reversibly switched between water-soluble and water-resistant, i.e. durable products that can be reprinted at end of life.

Reprintable Paste-Based Materials for Additive Manufacturing in a Circular Economy[5]

Abstract

The circular economy requires high value material recovery to enable multiple product lifecycles. This implies for the need for additive manufacturing to focus on the development and use of low-impact materials that, after product use, can be reconstituted to their original properties in terms of printability and functionality. We therefore investigated reprintable materials, made from bio-based resources. In order to equally consider material properties and recovery during development, we took a design approach to material development. In this way the full material and product life cycle were studied, including multiple recovery steps. We applied this method to the development of a reprintable bio-based composite material for extrusion paste printing. This material is derived from natural and abundant resources, i.e. ground mussel shells and alginate. The alginate in the printing paste is ionically cross-linked after printing to create a water-resistant material. This reaction can be reversed to retain a printable paste. We studied paste composition, printability and material properties and 3D-printed a design prototype. Alginate as a binder shows good printing and reprinting behaviour, as well as promising material properties. It thus demonstrates the concept of reprintable materials.

Additive manufacturing, Circular economy, Bio-based resources, Material integrity, Product design, Recycling

[5] Sauerwein, M., Zlopasa, J., Doubrovski, E., Bakker, A.C., Balkenende, A.R. (Accepted manuscript). Reprintable Paste-Based Materials for Additive Manufacturing in a Circular Economy. Sustainability

6.1. Introduction

The circular economy is currently gaining momentum as it is viewed as a promising approach towards sustainable development. In a circular economy, products and materials are kept at their highest value for as long as possible by looping them back into the economy through reuse and recycling (den Hollander et al., 2017; Ellen MacArthur Foundation, 2013; Korhonen et al., 2018). To achieve high-value and high-quality recovery, a shift of focus is required when it comes to product and material development. Instead of allowing products and materials to degrade and be wasted, they should be recoverable, reusable, and recyclable to enable a next life cycle (Geissdoerfer et al., 2017; Stahel, 2016). The material choice should therefore be based on the material properties as well as recovery options (Bakker and Balkenende, n.d.; Sanchez-Rexach et al., 2020).

New design solutions with additive manufacturing (AM) or 3D printing, provide opportunities for product life extension, reuse, and recovery in the circular economy. AM is a digital production process that, for example, allows adjusting products to changing needs and contexts, thereby facilitating product life extension (Sauerwein et al., 2019). One of the issues with AM, however, is the limited availability of materials that can be recovered and reused at the end of a product's lifecycle, and thus complying with the aim of the circular economy. A typical example is PLA, one of the most commonly used materials for extrusion printing. Quality conservation after recycling is problematic as reheating reduces the material's rheological properties (Zhao et al., 2018). Other polymers, like PET, are better-suited to recycling, but these are based on non-renewable and oil-based resources (Zander et al., 2018). Ideally, after a 3D printed product becomes obsolete, the material can be reprocessed into ready-to-print material which matches the original specifications with respect to print properties as well as functional properties.

Material sourcing is another important aspect. To comply with circular economy principles, we need to develop materials derived from bio-based and abundant resources as an alternative for oil-based materials (Bakker and Balkenende, n.d.; Ellen MacArthur Foundation, 2013). Bio-based sources for AM are mainly studied in the field of bioprinting for tissue engineering. In this field, natural hydrogels like alginate, collagen, gelatin and chitosan are commonly used (Li et al., 2018). The interest in bio-based sources for AM is currently expanding beyond this field, and is also being explored in product design. Faludi et al. (2019), for example, printed products using bio-based paste materials to quantify the print energy and explore market viability. Sanandiya et al. (2018) have 3D printed a small wind turbine blade with a paste material from cellulose fibres bonded by chitin. Mogas-Soldevila et al. (2014) created 3D print paste materials from chitosan for printing functionally graded materials. Tenhunen et al. (2018) made a paste material based on cellulose for printing on textiles, and Rael & San Fratello (2018) 3D printed a pavilion from salt and a natural glue using the AM method of binder jetting.

Makerspaces are an important driver for developments in AM; these are shared community workshops found all over the world (Niaros et al., 2017). These spaces enhance local innovation through, for example, the use of local material resources (Hennelly et al., 2019). They give access to a wide variety of tools and machines to complete Do-It-Yourself-making and digital fabrication projects (Kohtala, 2017). The maker community is environmentally aware, but often lacks concrete guidance (Kohtala and Hyysalo, 2015). There is interest for guidance about sustainable materials within this community, as shown by amongst others, Materiom, an online platform which provides open source recipes for materials from natural ingredients (Garmulewicz and Corbin, 2018). The increased interest in materials from natural and local (waste) sources is also evident in the design community. Designers are experimenting with materials such as coffee grounds, citrus peel, and agricultural residues (Bahrudin et al., 2017; Rognoli et al., 2015) and developing their own custom-made design materials such as flip-flops from palm leather (Veenhoven, 2011), tableware from Zandglas (Atelier NL, 2018), and 3D-printed bowls and vases from seaweed filament (Studio Klarenbeek & Drost, 2018).

Makerspaces and design communities are an attractive starting point for developing circular economy materials. In contrast to common material development processes that tend to focus on optimisation of functional properties and manufacturability, a design approach permits quick and iterative testing of multiple lifecycle stages from material sourcing to the end product. Moreover, it enables recovery options for a material in the early development stage. In this study, we therefore explore the complete lifecycle during material development, in order to create a proof of concept for reprintable materials. These can be fully reconstituted to their original specifications with respect to print and functional properties during use. This in turn enables high-value and high-quality material recovery.

In a previous study, we used this approach to developed a calcium carbonate-based material to explore reprintable materials for extrusion paste printing from bio-based and abundant resources (Sauerwein and Doubrovski, 2018). We described the initial development of a composite material for paste printing with filler particles made from ground mussel shells and sugar-water as binder material. The reprintability of this material was achieved through dissolving; after the print was air dried to obtain the final object, the object could be turned into a printable paste again through immersion in water. A lampshade was 3D printed to demonstrate the use of this material in a design object (figure 6.1). However, an important disadvantage of this material is that it is inherently not water-resistant which limits its application in product design.

Figure 6.1. Lampshade 3D printed with a composite material from mussel shells and sugar water (design from Joost Vette)

In this study, we build on our preliminary study and specifically explore alginate as a binder for regenerative 3D paste printing. Alginate is a polysaccharide often used as a hydrogel in bioprinting because it increases the viscosity of water. The viscosity of alginate hydrogels is influenced by the molecular weight, the ratio of M to G blocks, and the concentration (Fu et al.,2011; Li et al., 2018). We are using sodium alginate as it can be reversibly cross-linked through ion-exchange, which provides an opportunity to achieve reprintability. We describe the process of developing a reprintable paste material with this binder and a filler from ground mussel shells Mussels shells are an abundant bio-based waste stream in the Netherlands. We present data about the paste composition, printability, material properties, and reprintability. Data for the material properties are obtained through tinkering (exploratory evaluation) to obtain a basic understanding of the material, mechanical testing to determine the technical characteristics, and from testing with participants to explore the material experience. In addition, a variety of fillers with sodium-alginate were tested on material composition and printability and reprintability to explore the influence of different fillers on sodium alginate as a binder for 3D printing. Finally, we designed and 3D printed a prototype using mussel shell-alginate material, also form regenerated paste, to express the material characteristics and demonstrate the material properties in an actual application.

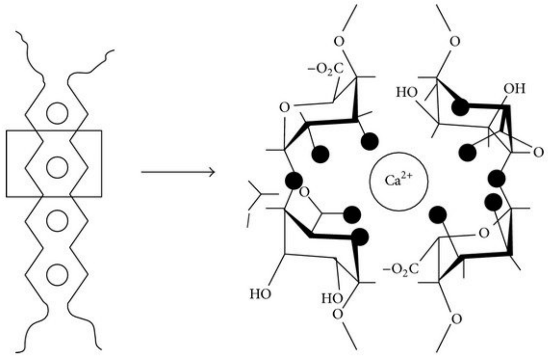

Figure 6.2. Schematic cross-linking of alginate with calcium-ions according the egg box model (Grant et al., 1973).

6.2. Materials and method

6.2.1. Paste materials

Water-based paste was developed with alginate as binder and filler particles derived from ground and sieved natural materials, primarily mussel shells. The reversibility of the printed material depends on its ability to re-dissolve the binder material. For binder material, we used sodium alginate as starting point (Sigma Aldrich; used as received). This is a linear polysaccharide block copolymer of 1,4-linked β-D-mannuronate (M) and α-L-guluronate (G) monomers with an average molecular weight of 150 kg/mol and the M/G ratio of 1.56. The sodium alginate was dissolved in tap water at room temperature to create the binder solution.

The opportunity to achieve reprintability is based on the formation of reversible ionic cross-linking of the polymer binder. The initial printing paste was made using a water soluble (non-cross-linked) sodium alginate that, after printing, was ion exchanged with a divalent cation, calcium. The calcium ion binds to two carboxylate groups of the polymer chains and forms a physical cross-link; this is commonly used to obtain rapid gelation (Lee and Mooney, 2012; Li et al., 2018; Liu et al., 2016). We used this exchange reaction to make the dried alginate water insoluble in a reversible way. The egg-box model, as shown in figure 6.2, is a schematic representation of the bonding between the polymer chains (box) by the calcium ions (egg) (Grant et al., 1973).

To retrieve a printable paste after use, the print is brought into contact with a sodium ion source. The calcium ions are then exchanged for sodium ions, thus reversing the cross-link between alginate chains to regain a soluble substance. Figure 6.3 gives an overview of the material (re)printability process based on ion cross-linking.

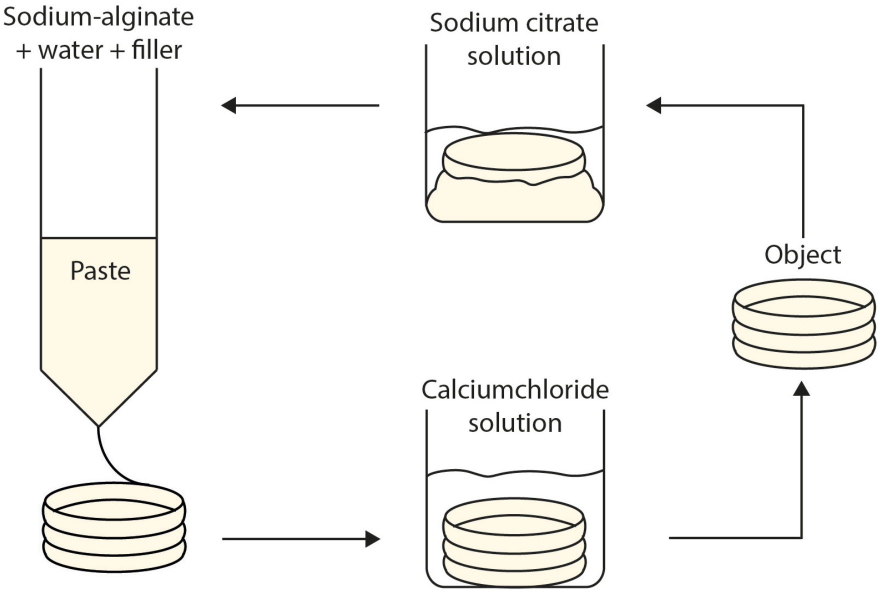

Figure 6.3. (Re)printability process based on ion cross-linking

For the majority of experiments, locally obtained ground mussel shells were used as filler material. The shells were collected at a Dutch processing plant in the province Zeeland. Mussel shells are a large waste stream in the Netherlands; approximately 50 million kg of mussels are annually harvested of which 40 w-% consists of the shell (Hamester et al., 2012; Het Nederlands Mosselbureau, 2014). Mussel shells consist for 95-99 wt-% of layers of calcium carbonate connected by an organic matrix of chitin and silk-like proteins accounting for 1-5 wt-% (Barros et al., 2009; Jackson et al., 1990). The shells were boiled in water for 20 minutes and subsequently heated in an oven for one hour at 200°C to make them brittle for grinding and to dry out organic residues (Hamester et al., 2012). The shells were ground in an industrial food processer. The ground powder was sieved to obtain a maximum particle size of 75 μm, suitable for the size of our printing syringe.

A larger variety of natural filler materials was used to test the generalizability of alginate as binder material, i.e. eggshell, walnut shell, olive pomace, cacao shell, and pine and maple sawdust. These are all bio-based waste products and therefore potential interesting resources. Variation of fillers is interesting as it allows to use different local rest streams as well as vary the mechanical properties. Explorations in this study focused on the printability and demonstrating the reversibility from print to paste for the variety of fillers. We treated the eggshells (like mussel shells calcium carbonate based) similarly to the mussel shells before grinding; other materials were ground as received and subsequently sieved with a maximum particle size of 125 μm for eggshell and walnut shell, and 75 µm for olive pomace, cacao shell, and pine and maple sawdust. The concentrations and amounts of solution that were needed to retain the paste for the different fillers were determined empirically.

6.2.2. Paste composition

To create the paste for 3D printing, the sodium alginate was first mixed with water by hand stirring to obtain the binder solution. Subsequently, the filler material was added to this solution and mixed by hand, stirring until a homogeneous paste was obtained for printing. To obtain a printable paste, the viscosity needs to be sufficiently low to uniformly flow from the nozzle, and the paste needs to be stable enough to maintain its shape after printing. We used a syringe with the same nozzle as for 3D printing to deposit a paste track by applying pressure by hand to imitate extrusion printing. In this way, different ratios of binder, filler, and water could be rapidly tested. If this led to a satisfactory result, the paste was tested in the 3D printer. The table below outlines the weight ratios for the mussel shell-alginate material found to be suitable.

	Sodium alginate	Water	Mussel shell powder
Weight percentage	3%	36%	61%

Table 6.1. Paste component weight percentages for mussel shell-alginate material

The composition for the paste from the other fillers was based on that of the mussel shell-alginate material (table 6.1). It was varied until a printable paste was obtained for the specific filler; these combinations are shown in table 6.2.

Fillers	Sodium alginate	Water	Filler
Eggshell ≤125 µm	6%	40%	54%
Walnut shell ≤125 µm	4%	75%	21%
Olive pomace ≤75 µm	4%	66%	30%
Pine sawdust ≤75 µm	8%	74%	18%
Maple sawdust ≤75 µm	7%	78%	15%
Cacao shell ≤75 µm	5%	66%	29%

Table 6.2. Paste component weight percentages for variety of fillers

After printing, the alginate samples were dried overnight at room temperature. The shrinkage during drying was determined by measuring the object's change in height and wall thickness.

6.2.3. 3D printing process

Test samples were made using a Ultimaker 2+ modified for paste printing with the Stoneflower Ceramic 3D Printing KIT Basic and micro printing set. In this system, the plunger of a syringe containing the paste is mechanically actuated with a stepper motor. A 60cc syringe was used with a 14 gauge nozzle (1.6 mm inner diameter). The paste extrusion 3D printer was used in combination with the slicer software programme Cura to prepare the digital file for 3D printing. The layer height was set to 1.1mm and the width to 1.5mm, the print speed was set to 6mm/s and the extrusion speed to 0.19 ml/s.

6.2.4. Post-treatment for water-resistance

The alginate binder was made water insoluble by exchanging sodium ions with calcium ions. Although mussel shells mainly consist of calcium carbonate, the calcium ions in this filler do not cause any apparent cross-linking because of calcium carbonate's limited water solubility. Therefore, an external calcium source is needed to achieve gelation, for which we used calcium chloride (CaCl2). For ionic cross-linking, the dried 3D printed object was submerged in a 2 wt-% calcium chloride dihydrate solution for 30 minutes (source: ≥99% purity, Sigma Aldrich, used as received). After removing the object from the solution, it was left to dry for several hours at room temperature until the object was no longer visibly damp.

6.2.5. Paste regeneration

Sodium citrate attracts calcium ions and is commonly used as a buffer for ionic cross-linking of alginate (Smidsrød and Draget, 1997). We used a solution of water and trisodium citrate dihydrate (source: ≥99% purity, Sigma Aldrich, used as received) to regenerate the mussel shell-alginate printable paste from printed objects that are considered obsolete.

We first weighed the obsolete object(s) to determine the amount of sodium citrate and water. The solution was made from 2wt-% trisodium citrate dihydrate and 50wt-% water of the weight of the objects. The obsolete objects were then ground using a mortar and pestle to facilitate the dissolution process before adding the citrate solution. The mixture was stirred with a laboratory mixer until a homogenous and printable paste was achieved.

6.2.6. Technical properties

The density, E-modulus, and flexural strength were determined to obtain an initial understanding of the technical properties of the ground mussel shell material. The density of the bio-based composite material was determined by measuring the weight and volume of printed rectangular bars. To measure the E-modulus and flexural strength, we performed a three point flexural test according to ASTM (2013). The test samples were 3D printed with a fully dense infill in the Cura slicing settings, and sanded afterwards to obtain precise dimensions of 3.0 by 4.0 by 40.0 mm with an accuracy of 0.05mm. We then tested samples made from the virgin material, as well as those from the first and second reprinted material.

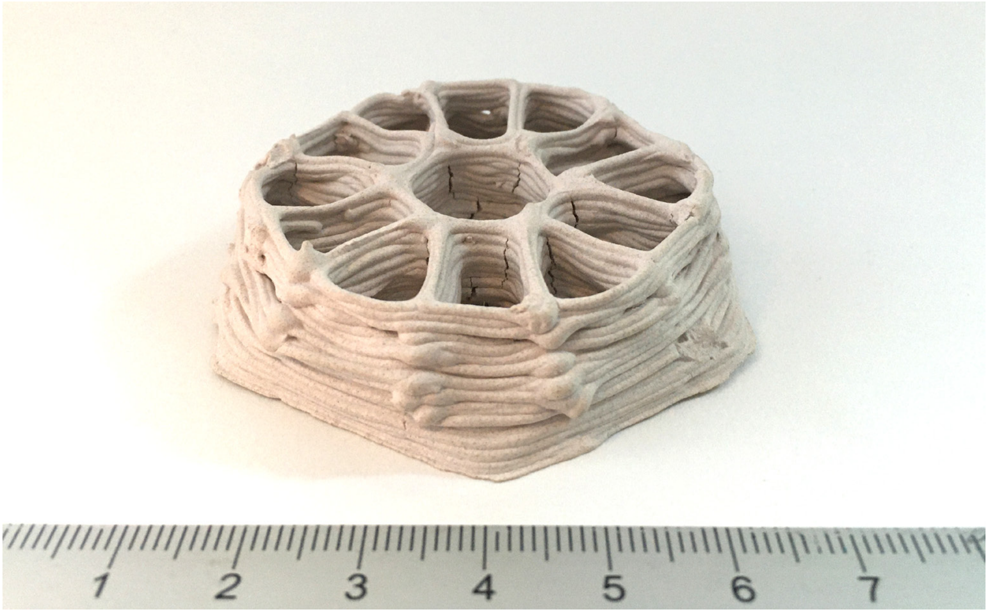

Figure 6.4. Sample to test the material experience using the Ma2E4 toolkit (design by Joost Vette)

Virgin samples were also tested in wet condition after 30 minutes in water. The samples were tested in a Zwick Roell Z010 machine with a load cell of 500N, tool radius of 10mm and test speed of 2mm/min.

6.2.7. Experiential properties

To obtain a basic understanding of the non-technical material properties, we tinkered with the material following Karana et al. (2015). The material's colour and smell were examined through direct observation. We tested brittleness by dropping a sample onto a hard surface from approximately 1 meter height and flammability by holding it in a small flame for 10 seconds.

The Ma2E4 toolkit was used to test the experiential characteristics (Camere and Karana, 2018). This toolkit provides guidance to test a material sample on its performative, sensorial, interpretive and affective qualities. The performative level explores different types of actions that the material causes, like touching, moving, and holding. The sensorial level describes several tactile and visual qualities, the interpretive level describes the meaning of the material and the affective level the association with the material (Camere and Karana, 2018). The shape of the test sample should be functionless (i.e. not implicating a direct function) as this might influence the perceived experience. Figure 6.4 shows the test sample. Twenty participants tested the experiential characteristics of the mussel shell-alginate material (male: 10, female:10, age:20-60, age average:28, Students from Industrial Design Engineering:13).

6.2.8. Prototype

In addition to test samples, also a prototype product was designed and 3D printed to demonstrate the material properties in actual applications for the material based on the experiential and technical properties. A hair pin was developed as prototype. The design takes advantages of special properties of the mussel shell material that simplifies the 3D printing process and was used to explore experiential properties.

6.3. Results

6.3.1 Technical properties

Table 6.3 presents the results of the flexural test and the density for the mussel-alginate samples. After breaking, internal cavities were visible in some test beams, demonstrating that the 3D printing process did not produce fully solid parts. However, the test results did not show a significant deviation for these samples in comparison to the homogenous test beams, indicating that the force at which fracture initiates was not determined by these flaws. The samples for the test with the wet virgin material were printed in two separate batches with significantly different treatments, which also affected the test results. The samples of batch 1 were printed with a less viscous paste (38% water) and dried for 44 days. The samples of batch 2 were dried for 3 days. Compared to the original material, the wet material in both cases exhibited a decrease of about three orders of magnitude in the flexural modulus and more than one order of magnitude in the E-modules. This clearly shows the transition from a rigid material when dry to a ductile material when wet.

Technical properties	Virgin material	Reprinted material (1x)	Reprinted material (2x)	Wet virgin batch 1	Wet virgin batch 2
Number of samples	10	10	7	5	5
Duration of paste drying (days)	7	7	7	44	3
Density [kg/m3]	1380 (σ=20)	1410 (σ =30)	1410 (σ =20)	not determined	not determined
E-modulus [GPa]	2.1 (σ =0.4)	2.0 (σ =0.4)	2.6 (σ =0.6)	0.0042 (σ =0.0005)	0.0014 (σ =0.0007)
Flexural strength [MPa]	9.8 (σ =0.8)	6.4 (σ =1.4)	6.9 (σ =1.9)	0.25 (σ =0.04)	0.08 (σ =0.01)

Table 6.3. technical characteristics of the mussel-alginate composite material

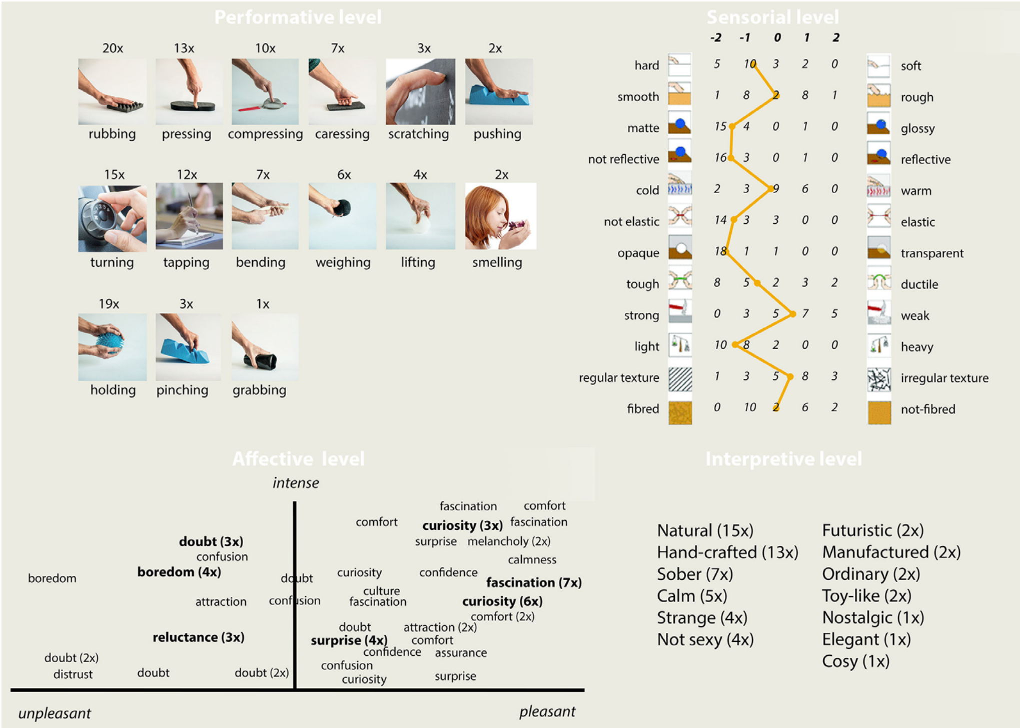

Figure 6.5. Test results of Ma2E4 toolkit

6.3.2 Experiential properties

The mussel shell alginate material was off-white after printing and became whiter after drying. The smell was negligible. When dropped onto a hard surface from 1m, the material samples broke. The cracks were clean cut, perpendicular to the printing lines. When held in a small flame, the material did not ignite but burn-marks were visible. The results of the Ma2E4 toolkit are shown in figure 6.5 and give an indication of the appearance of the material on the experiential levels, i.e. the performative, sensorial, affective and interpretive level. It should be noted that the material appreciation may have been influenced by the differences in printing quality as well it showing cracks after drying.

On a performative level, the participants handled the material with care. They held it in their hands and rubbed it to feel the texture. The participants judged the material on a sensorial level to be lightweight and relatively weak and hard, as well as matt, non-reflective, non-elastic, and opaque. On the affective level most words used were in the pleasant spectrum of the scale, of which fascination, curiosity and surprise were mentioned most often. The participants also doubted about the material, noting characteristics like reluctance and boredom. Finally, the material was interpreted as being natural and hand-crafted, as well as sober and calm. Natural, hand-crafted and calm had a positive connotation due to

Figure 6.6. 3D prints with a variety of fillers, from left to right: mussel shell, eggshell, walnut shell, olive pomace, cacao shell, maple sawdust, and pine sawdust

the material's uniqueness, light weight, and smooth surface. Sober had a negative connotation, because of the dull colour and matt finish.

6.3.3. Filler variation

We tested the (re)printability of pastes with different fillers to explore the potential for filler exchange The pastes were adapted with respect to the mussel shell recipe to achieve printability. Subsequently, all pastes were 3D printed using the same digital file so that the printed samples all exhibited the same geometry. Only the pine sawdust sample did not reach full height due to a too high viscosity of the paste causing the material to slip behind the plunger. The drying of the 3D printed samples caused significant shrinkage in case of the organic filler materials, as visible in figure 6 and table 4. Whereas shrinkage was only a few percent for the CaCO3 based particles (mussel and eggshell), it varied from 10-40% for walnut, olive, pine, maple and cacao.

Filler	Shrinkage in %		Breaks after drop test
	Height	Line width	
Mussel shell	4	6	Yes
Eggshell 125 µm	0	0	Yes
Walnut shell	26	12	No
Olive pomace	23	24	No
Pine sawdust	31	41	No
Maple sawdust	43	18	No
Cacao shell	35	41	No

Table 6.4. Shrinkage percentage and results of drop test for all fillers.

Most samples felt rougher than the composite material prepared with ground mussel shells, only the composite material with cacao felt smoother. All materials could be broken by hand, but some did not break after dropping from approximately 1m, as shown in table 4. All materials were rigid when dry, became ductile when submerged in water, and could be returned into a paste after submersion in empirically determined aqueous trisodium citrate dihydrate solutions.

6.3.4 Prototypes

A hairpin was designed based on the technical and experiential characteristics of the mussel shell-alginate material. The material was experienced as light and had a soft touch, which made it pleasant to wear on the head. The brittleness in combination with the natural and ceramic look indicated a delicate material which was considered a good fit for hair decoration purposes. The 3D printing process could be simplified due to the unique property of the mussel shell-alginate material of being rigid when dry and ductile after submerging in water. The hairpin was printed flat (figure 7) from virgin material and ion cross-linked with calcium chloride after drying. Subsequently, the hairpin was submerged in water to make the material ductile and slightly bent. It was left to dry in this position to obtain an end product that follows the contour of the head due to the curved shape (figure 8). A second hairpin was printed using paste that was obtained for the third time after subsequent earlier prints.

6.4. Discussion

We aimed to demonstrate a design approach to the development of materials for AM based on abundant natural resources that retain functional properties for reprinting after initial use. This support the increased interest in developing AM materials from bio-based resources, and provides an explicit focus on end-of-life behaviour. From a circular economy perspective, the ability to recover the material at the end of product life is essential, so we explored the complete lifecycle of material development of reprintable paste-based materials using an iterative design approach. The goal of this broad and explorative approach was to develop a proof-of-concept; the material is thus not fully optimised from an engineering perspective.

Reprintable materials require a system perspective, as aspects ranging from 3D printability and characteristics for use and recovery have to be accounted for. By adopting a design approach we were able to perform multiple iterations and consider the complete material lifecycle. We demonstrated this approach for the mussel shell-alginate material, making use of reversible ion cross-linking. This resulted in a proof-of-concept that demonstrates the desired capacities as well as allowing improvements and further optimisation. This approach provides insights into and guidelines for the first steps in material development that considers efficient reuse in addition to fabrication and use.

Although our aim was to fully reconstitute to the original material specification, but the starting point for reprinting material is different

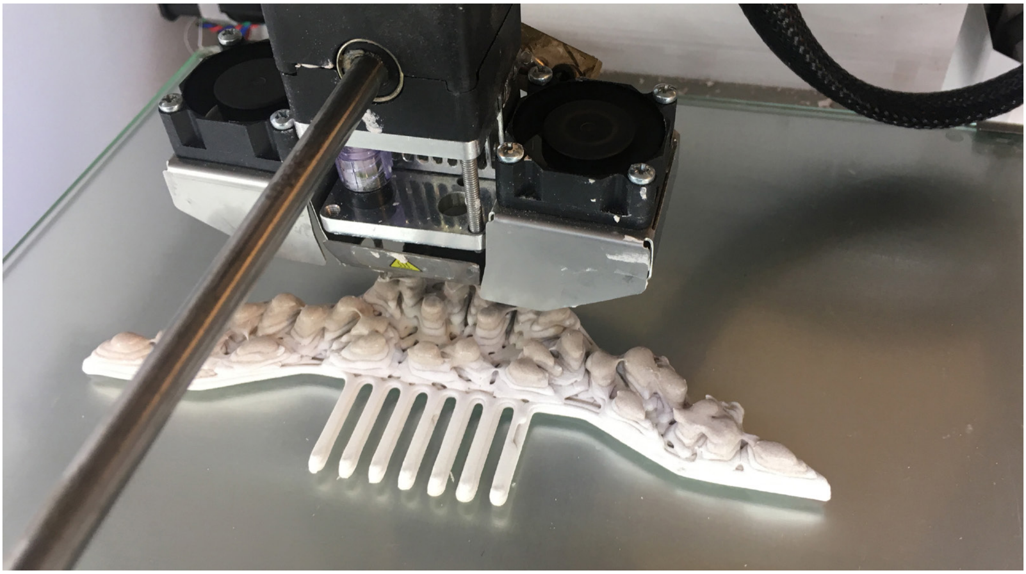

Figure 6.7. Flat 3D print of hairpin

Figure 6.8. Final result of bended hair pin

from that of the virgin material. Instead of mixing the pure starting materials to obtain a 'virgin' paste, the printed object needs to be reprocessed again before reprinting. This reprocessing should have a minimal effect on the constitution and properties of the resulting paste. Dissolving the binder in water, as explored for a sugar binder (Sauerwein and Doubrovski, 2018), cannot be used after ion cross-linking because it results in water resistance. Therefore, in addition to water, a compound is needed to reverse the ion cross-linking. In this case trisodium citrate dihydrate was added to exchange calcium ions with sodium ions, making the alginate soluble in a low environmental impact solution. The amount of trisodium citrate is negligible in theory, as a ratio of 1:0.0036 is needed to retain a printable paste with sodium alginate based on the molar masses of calcium alginate and trisodium citrate dihydrate. We added trisodium citrate dihydrate in a weight ratio to calcium alginate of 0.4:1 to obtain an acceptable speed of the dissolution process. This is a 100-fold excess compared to the stoichiometrically required amount, implying that in subsequent reprinting runs, some accumulation of citrate can be expected. Although this did not significantly affect the mechanical properties after two reprinting runs, the dissolution process may be subject to further optimisation.

The mechanical tests show that the properties of the dried material are largely maintained after a number of subsequent reprints with the original material. A slight decrease of the flexural strength was observed, but further experiments are needed to determine if this decrease is significant. Far more interesting is the 1000-fold decrease of flexural strength when, after cross-linking and drying, the printed object is returned to a wet state. As the material integrity is maintained, the achieved ductility allows for additional shaping operations, like the bending shown for the hairpin. The current investigations demonstrate the potential of the developed materials, however, more work is needed to establish the durability of the material.

Variations in filler material lead to pastes with properties comparable to the mussel shell paste regarding printer settings and water solubility after reversed ion cross-linking. It should be noted that the pastes were not fully optimised with respect to printability and subsequent material properties, as demonstrating versatility of the process was our main purpose. The original mussel shell paste recipe was therefore only modified to obtain a printable paste. However, most of the fillers have a different composition, resulting in different filler properties. From the water to filler ratios in table 2 it is evident that pastes with organic filler material need a much higher water content to achieve printability. This is attributed to the swelling of the organic particles in water; this also explains the different drying behaviour. Whereas the inorganic shell-based pastes hardly showed shrinkage, the organic particles exhibited 10-40% shrinkage, sometimes anisotropically. This large shrinkage can also be explained by the swelling of the organic particles in the paste. The observed anisotropy in shrinking directions is likely to be due differences in the shape of the particles. Further research in such modified pastes is needed to optimise composition and resulting properties.

Reprintable materials are needed to make AM suitable for a circular economy. For paste extrusion printing as done in this study, the binder acts as the adhesive between the filler particles and thus influences the reprintability, in addition to the printing and material properties. Its dissolution properties determine the approach to retaining a printable paste. Ion exchange to establish reversible cross-linking has shown to be a promising dissolution process for retrieving reprintable materials. Other suitable binders for ion cross-linking could be explored to extend this group of materials and obtain a larger range of binder properties. Interesting options are, for example, pectin, carboxymethyl cellulose, and guar gum (Ito et al., 2007; Voragen et al., 2009; Xie et al., 2016). Further, alternative mechanisms that could enable reprintability might be tested. Potentially interesting opportunities are thermosensitive bio-based binders, such as kappa carrageenan, agarose, or schizophyllan (Fuchs et al., 1998; Hur et al., 2020; Millane et al., 1988) or binders sensitive to changing pH values such as chitosan (Li et al., 2018).

The integration of design tools into the material development process is a promising approach for the development of a new, reusable, material for 3D printing. Testing the experimental properties provided insights into how the material is perceived and provided guidelines for further development towards use cases and user acceptance. The material research was further enhanced by developing 3D printed prototypes to create tangible objects that gave a better indication of the material's abilities. Moreover, the prototypes enabled us to demonstrate the properties of and experience with the material and thus contribute to acceptance by highlighting interesting characteristics.

6.5. Conclusion

Only a limited number of AM materials are currently available that meet the requirements of a circular economy, i.e. maintaining a high-level material integrity after use and enabling multiple use cycles. Resources, material properties and material reusability should be equally considered during material development. We followed a method inspired by the design and maker community approaches, in which we went through the full material and product life cycle of material development in order to meet the requirements of all stages and create a proof-of-concept.

We demonstrate the explorative development of reprintable materials. These are 3D printable materials that can be reconstituted to their original properties in terms of printability and functionality. Reprintability is obtained by retaining control over binder dissolution properties. We specifically describe the development of a reprintable bio-based composite material for extrusion paste printing from natural and abundant resources: ground mussel shells as filler and alginate as binder. Using calcium ions, the alginate binder is ionically cross-linked to obtain an insoluble material which can be reversed to retain a printable paste. Further to reprintability as a unique property, an interesting characteristic of this material is its rigidity in dry conditions, while being ductile and shapable after submersion in water.

Alginate as a binder shows good printing and reprinting behaviour, hence contributing to this new group of materials for AM. More material research is needed to further explore the properties of alginate-bonded composites and the durability, as well as other solutions for reprintability. It is essential to create a pallet of reprintable materials that maintain high level integrity in a circular economy by equally considering material properties and recovery during development.

Acknowledgement

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Chapter 7

Discussion and Conclusion

7.1 Introduction

The goal of this thesis was to explore how using AM as a production method can contribute to design in a circular economy. AM is often regarded as an enabling technology for the transition to a circular economy, due to its flexible design and manufacturing process, greater customization opportunities, local production, and simplified supply chains (Sauerwein et al., 2017). Building on these AM characteristics, this research has focused on ways AM can be used to enhance product integrity and material integrity in a circular economy.

One of the core principles of the circular economy is that the value of products and the materials they are made of can be preserved by keeping them in the economic system, either by lengthening the lifetime, or by looping them back into the system to be reused (Kane et al., 2018). Den Hollander et al. (2017) developed the idea of product integrity, which can serve as a guiding principle when designing for a circular economy. They defined product integrity as "the extent to which a product remains identical to its original state over time". Design for product integrity in a circular economy includes any measure to extend a product's life, for instance through a durable and reliable design, but also by ensuring that a product can be easily maintained and repaired, upgraded and/or refurbished. Material integrity can be defined along similar lines, as the extent to which a material remains identical to its original state over time. This implies that a material retains its original properties, even after it has been recycled.

The focus on product integrity and material integrity has resulted in our two main research questions:

1. How can additive manufacturing support product integrity in a circular economy?
2. How can additive manufacturing support material integrity in a circular economy?

We explored these questions by pursuing the following aims:

1. In order to support product integrity, we aimed to adapt the AM process flow to develop reversible connections that allow product disassembly and reassembly.
2. In order to support material integrity, we aimed to develop reprintable bio-based materials that can be sourced locally and that can be used to 3D print consumer products.

These aims are discussed in more detail in section 7.2. In sections 7.3 and 7.4, the research questions are answered. Section 7.5 consist of a reflection on 'research through design', the main methodology used in this research project. In section 7.6, we note our contributions to science and in section 7.7, our contributions to design practice. We conclude with directions for future research in section 7.8.

7.2 Defining areas for exploration

In the project's initial study, we contextualised the results of the literature review by relating them to interviews with designers of five sustainable and 3D printed design projects. These interviews were analysed by creating an annotated portfolio, the outcomes of which revealed opportunities and challenges for AM in the context of a circular economy for both product integrity and material integrity.

The ability of AM to print complex geometries and to adjust digital design files creates an opportunity to print bespoke products, which can support both product integrity and material integrity. The digital design files used in AM can be adjusted to changing needs and contexts. This flexibility enables reuse strategies for products that were initially not designed to be reused. Spare parts or upgrades, for example, can be printed to be compatible with products that were initially not designed for ease of repair or upgradability. On a material level, complex geometries can be used to create monolithic and structurally complex products. These can consist of a single material, which may result in high quality recycling and increased material integrity. However, monolithic and structurally complex products are usually difficult to dismantle and reassemble which hampers repair, upgrade, and reuse for product integrity. Another challenge of AM is the limited availability of renewable materials that are fully recyclable. There is an ambition in the design community to widen the palette of bio-based materials. We argue that these materials should be fully (re)printable and functional after recovery to fit a circular economy.

Based on these challenges, we identified two areas to explore the research questions and study AM's contribution to product integrity and material integrity:

1. To research product integrity, we explored how high value reuse can be integrated in the AM process. For this, we investigated how the complex geometries and adaptable digital design files enabled by AM can contribute to reversible connections that allow a product to be disassembled and reassembled. Integrated product solutions and monolithic structures result in products that are usually difficult to disassemble. We consider this a shortcoming of AM in a circular economy because this makes it very hard to repair, upgrade or reuse a product. We therefore developed a process flow that integrates high value reuse in the AM process. We focussed on design for dis- and reassembly to create a prototype in which we developed reversible 3D printed joints that form an integrated part of the product architecture.

2. For material integrity, we explored how the initial material quality can be preserved in the printing process using bio-based materials. For this, we introduced reprintable materials that preserve their material and printing properties after use. We employed life cycle thinking during the development of the reprintable materials to cover all material stages from sourcing, production (3D printing) and use to recovery. 3D printable paste-based materials were developed from ground mussel shells with two different binders, sugar and alginate. Their reprintable nature was demonstrated through 3D printing design objects.

We used 'research through design' as our core research methodology and used the making process to create prototypes. The findings and answers to the research questions are described below.

7.3 Additive manufacturing and product integrity

Our experiment shows that high value reuse can be incorporated in the AM process by using the complex geometries and adaptable digital design files enabled by AM to create reversible connections. We used AM in a new way to support product integrity for a circular economy. On a conceptual level, we demonstrate that the unique properties of AM can be harnessed to develop integrated design solutions that enable products to be dismantled and reassembled without loss of quality. On a practical level, we created reversible joints that connect multiple components and are part of the product architecture. This approach allows a high level of reuse for both joints and components. In this way, the complex geometry and adaptable digital design files of AM contributes to the integration of parts without creating single component solutions unsuitable for disassembly.

To support the integration of high value reuse in AM, we developed a circular AM process flow (figure 7.1). Process flows for traditional 3D printing do usually not support incorporating existing physical parts or products in the CAD/CAM process. In the circular AM process flow, the initial design idea initiates an iterative process between physical parts/materials and the CAD/CAM process to inform each other for 3D printing. In this way, a product is created that supports high value reuse. We demonstrated the use of this process flow by developing reversible joints for dis- and reassembly.

The reversible joint is shown in figure 7.2.A. Laser cut panels and 3D printed joint parts were fixed in a clamp to complete the joint assembly with the AM process (figure 7.2.B). After use, the joints can be disassembled by controlled breaking of predesigned fracture points in the joint. The joint comprises two parts of which a small part is removed and has to be recycled after breaking (figure 7.2.C). The major part of the joint can be

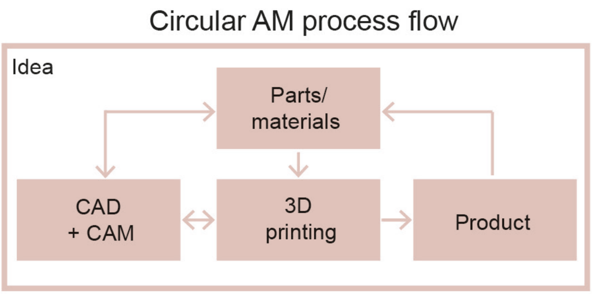

Figure 7.1. Circular AM process flow.

reused by placing it in a clamp with the laser cut panels for reassembly.

To demonstrate this process, a vase and lamp were assembled from the same laser cut panels with product specific joints that form part of the product architecture (figure 7.3). The pattern of the joints in these prototypes is just one example; the design can be adjusted within set boundaries.

This experiment showcases several opportunities for AM in a circular economy. The digital files of the joint structure can be adjusted to fit a variety of panels or panel compositions. The joints were made with a parametric design process meaning that defined and related variables can be easily adjusted to change the design. If certain parameters are fixed, the initial state of components can be preserved for reuse. In this way, a product family can be created with generalized and product-specific components providing more opportunities for designers to design for product integrity.

Furthermore, the design of the reversible joint contributes to the overall aesthetics of the product, as the joints are a visible and integrated part of the product architecture. Designers can adjust the patterns to influence the aesthetic appearance to create a design language for product design in a circular economy.

Reuse is preferable to recycling in a circular economy. Our goal was to attain a high number of reusable components. This resulted in two main challenges. First, our specific solution for reversible joints required physical parts to be (re)connected by and during the 3D printing process itself. A condition for this approach is that AM can handle existing components onto which the joint is printed. As this is not a standard and straightforward process for FDM printing, we had to adjust the printing process. Second, we designed for dis- and reassembly, but this does not directly imply a high number of reusable components. In our case, most components can be reused and only a small number have to be recycled, but this was only achieved after several design iterations. Design for dis- and reassembly is thus most effective when it is applied in combination with high value reuse.

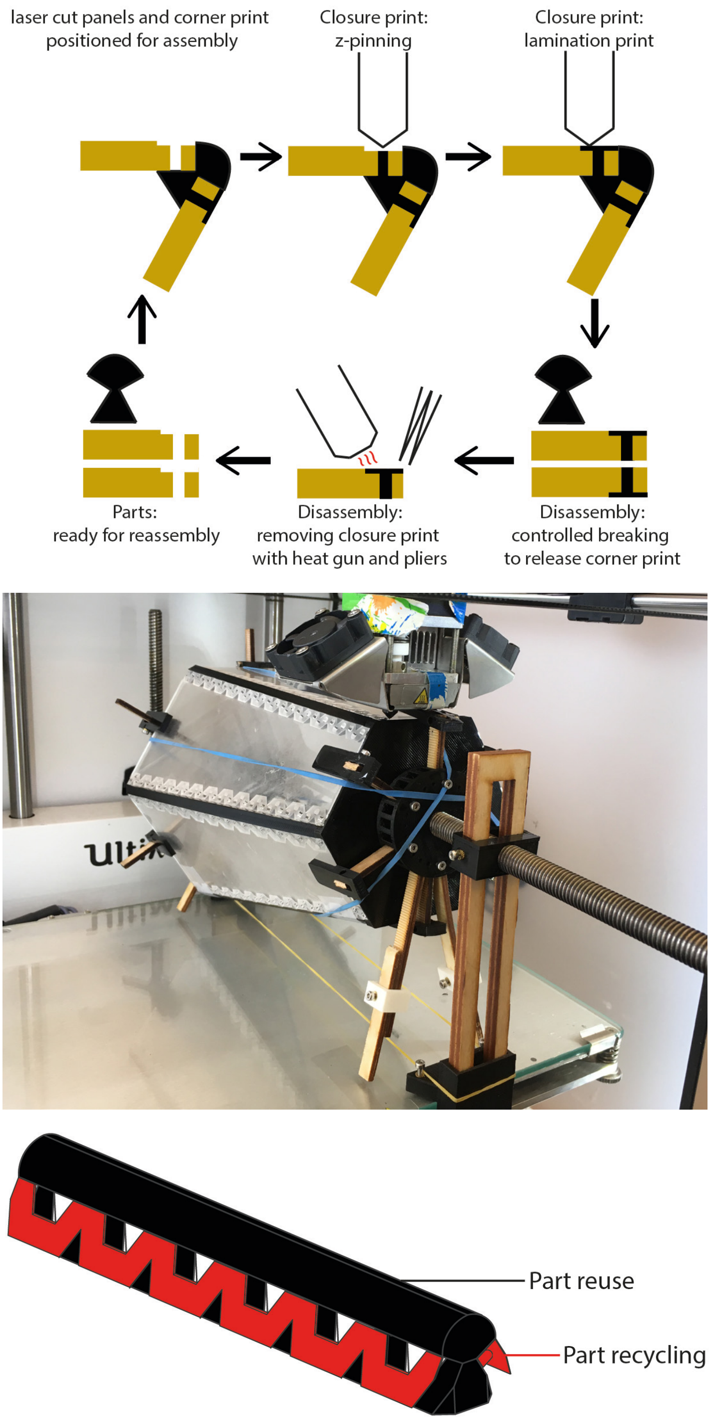

Figure 7.2. A: procedure to create reversible joint. B: parts are fixed in a clamp for assembly by 3D printing. C: Part of joint suitable for reuse (black) and recycling (red).

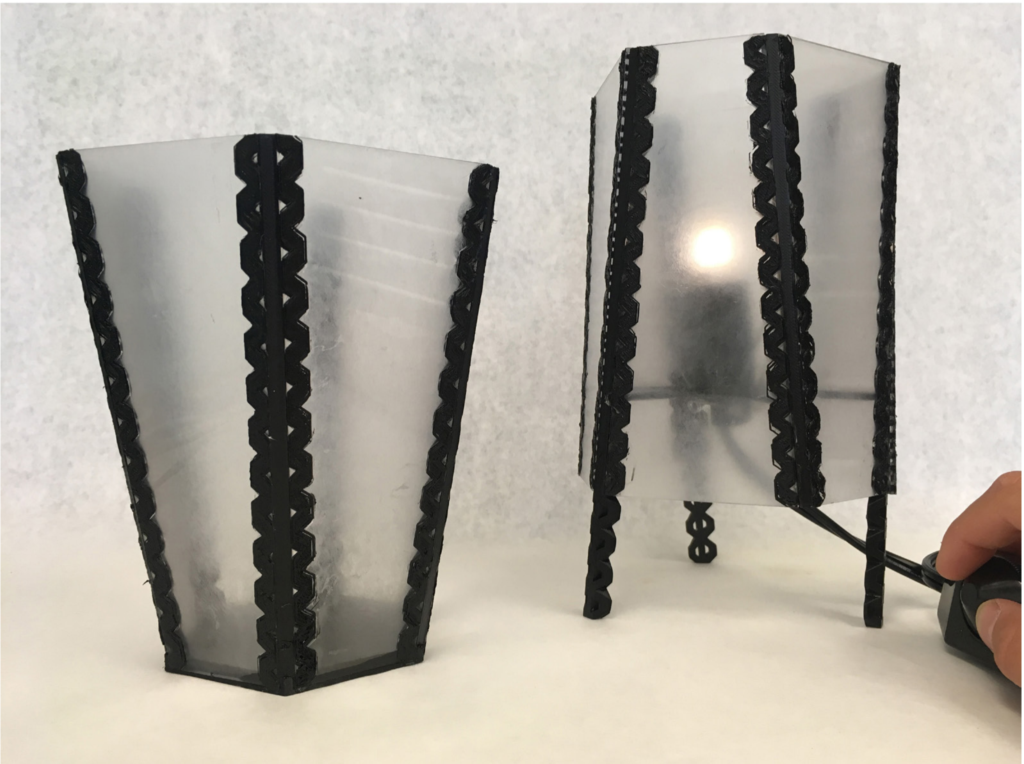

Figure 7.3. Lamp and vase with reversible 3D printed joints and laser cut panels.

7.4 Additive manufacturing and material integrity

We successfully developed reprintable materials from bio-based sources. Reprintable materials enable material recovery, because they can be reconstituted after product use to their original properties in terms of printability and functionality. In this way, the materials are kept at the highest quality level for as long as possible, i.e. a high level of material integrity. This requires a system perspective for material development as the complete material lifecycle (sourcing, production, use, and recovery) has to be taken into account. Approaching material development in such a way opens up possibilities and avenues that should be further explored in the context of a circular economy.

We used bio-based resources because there is a need to transition away from oil-based resources toward renewable resources as a basis for materials in general (Bakker and Balkenende, n.d.; Ellen MacArthur Foundation, 2017). Moreover, the maker and design communities have the ambition to create non-toxic and benign materials that can be safely used. Furthermore, locally available, abundant materials can strengthen distributed manufacturing with AM and contribute to a resilient local production system. Bio-based resources for material development in AM

Figure 7.4. Lampshade (design by Joost Vette), flowerpots (design by Edwin van Tongeren), and hairpin (design by the author).

have been used before, but we explicitly introduced reprintability as an additional requirement in the development process.

We designed and 3D printed a lampshade, flowerpots, and hairpin using reprintable bio-based materials based on ground mussel shells bonded by sugar or alginate (figure 7.4). To make these prototypes, we had to develop the material, achieve printability, as well as to design the object. The materials can be recovered through dissolving (lampshade) or after reversed ion cross-linking (flowerpots and hairpin). While dissolvable materials generate products that are water soluble, ion cross-linking of a suitable binder material creates the option to use products that are water-resistant. The recovery strategy is thus controlled by the dissolution properties of the binder.

Our design processes present several opportunities for 3D printing materials in a circular economy. We used a design approach to develop materials that account for the entire material lifecycle, from sourcing, 3D printing, and use, to eventual reprinting. This gives designers unprecedented opportunities to explore the material properties and aesthetics while also aligning with circular economy requirements. There are many more opportunities to create bio-based reprintable materials with a range of properties. The alginate binder was, for example, also tested with other fillers which resulted in materials with different shrinking behaviour, colours and mechanical properties. Furthermore, we noted interesting possibilities to use other local bio-based resources, for instance waste streams like eggshells, nutshells, and sawdust that can serve as the basis for new material development.

However, some challenges also remain. Developing reprintable materials from scratch is a time-consuming process. It requires developing a material with certain use qualities and that ensure its printability, which are both iterative processes. Furthermore, developing materials with a design background is a difficult process and takes time as well. Most of the knowledge needed to execute a design approach to develop reprintable materials is available, but it is not easily understood by designers. Therefore, close collaboration with material scientists may lead to better expectations, as well as providing greater access to in-depth and valuable knowledge.

7.5 Reflection on 'Research through Design'

'Research through Design' (RtD) was the central methodology used in our research. In this methodology design plays a formative role to generate knowledge by iteratively developing prototypes (Stappers and Giaccardi, 2017). We applied RtD to better understand the design implications of using an emerging technology (AM) in a future context (circular economy). We used the prototyping process to create insights and verify new approaches. The focus on prototyping processes for knowledge generation and technical development is less common in RtD as most literature is related to user interaction. Therefore, we reflected on our process based on themes identified by Boon et al. (2020) to generate new insights. In the following section, we share the insights and learnings from our process as input for other researchers who would like to similarly apply RtD.

7.5.1 Making, artefacts, and prototypes

The prototyping process occurred in two subsequent steps: the development stage and the design stage. These two stages are typical for our RtD approach; usually the prototyping process in RtD only entails a design stage. However, in our project, technical development was required before design objects could be made. For example, in order to create 3D printed objects from reprintable bio-based materials, we first had to develop the material itself before we were able to design and 3D print an object with it. In the other experiment, we had to adjust the 3D printing process, before we could print prototypes with reversible joints. Thus, with these experiments, we introduce novel concepts to the fields of AM and circular economy. As a consequence, most time was spent on the development stage and relatively little time went to the actual prototype design stage. We consider the development stage part of the RtD process as it serves a design goal and is prerequisite for establishing the requirements for the subsequent design stage.

Artefacts and prototypes played different roles in the development and design stage. We distinguished artefacts from prototypes based on Stappers & Giaccardi (2017): artefacts are objects created during the making process and prototypes are the objects that represent the final outcome of the process. During the development stage, we created artefacts, such as test prints of simple shapes, to evaluate the process and decide on following steps. These artefacts represented the status of the progress and led to new insights that would not have been revealed without their creation. They often revealed unexpected problems that led to a better understanding of the end goal. In the development process of the reversible joints, for example, breaking artefacts led to the understanding that controlled breaking was needed to reuse parts. During the design stage, we then developed prototypes that demonstrate the current status and abilities of the newly developed 3D printing approach or material. They represent a proof-of-concept and the final outcome of an experimental study.

The prototypes can also be seen as a step towards further research. In the case of the mussel shell-sugar material, for instance, a representative prototype (the lampshade) was created, but the process made clear that the characteristics of the material in combination with water solubility limited the range of applications. Therefore, a new binder dissolution process was sought that would be water-resistant, hence the introduction of ion cross-linking with alginate. The lampshade was thus both a prototype that represented the outcome of the material development process and demonstrated a possible application, as well as a means to identify directions for further research.

7.5.2 Roles and documentation

In my role of author, I conducted or supervised experiments and prototyping processes. I am trained as an industrial designer and this influenced my approach. During the research project, I alternated between the role of designer and researcher, and experienced the need to distinguish between these roles as they require different mind-sets; creative and specific versus structured and critical. However, both processes influenced each other as the goal of the prototyping process was to generate scientific knowledge. Several media were used to document the prototyping process for analysis and knowledge generation. Artefacts and prototypes played an important role as described above, but we also used other media, i.e. diaries, blogs, and annotated portfolios.

The diaries formed a rich source of information of the prototyping process and expressed both the chronological progress as well as the idea generation. The layout of the diaries differed slightly between the development and design stage. Development stage activities were mostly registered, similar to a logbook or lab diary. The design process contained more design activities, like ideation and annotated sketches. The diaries were used to verify decisions and to analyse the process. Therefore the more detailed the documentation, the better the diary supported knowledge generation at a later stage. Precise descriptions of the procedure, as well as general considerations, complimented by images were valuable means of obtaining a high level of detail.

Extracting knowledge from the prototyping process was not an easy task. It requires taking a distance from the specific solutions in the design stage to assume the analytical role of the researcher. Discussions with people close to the project but not directly involved in it were valuable, as they helped us to take distance and to reflect. To support this process and inform my supervisors, I kept a blog summarising my diary findings and illustrated with images (Sauerwein, 2019). These blogs were greatly appreciated, and provided valuable support for our discussions on the development stage.

We found annotated portfolios to be a valuable support tool when analysing and discussing the prototypes. We used this method for interview analysis at the beginning of the project to evaluate other designers' projects. The visual overview of images with annotations led to intense and fruitful discussions and contributed to a deeper understanding of the subject. The formulation of the annotations is key and requires close attention to detail, because they have to be an accurate summary of the transcript. When well executed, annotated portfolios can increase the transparency of the analysis process.

7.5.3 Assessment and contribution

Even with my background, I did not have all the necessary skills needed to develop the 3D printing equipment or materials. Therefore, I approached experts from other disciplines to help me with the necessary knowledge. Due to the design approach, I had a clear goal in mind and could ask them specific and direct questions that led to interesting input. For example, the principle of ion cross-linking is not something taught in design education, but it was suggested as a possible solution to my aim to develop reprintable and water-resistant materials. RtD thus helped me to extract the relevant information from other disciplines and make this information understandable and approachable for designers. In this way, RtD functioned as an umbrella approach that allowed me to combine input from multiple scientific fields.

The RtD process led to interesting results regarding design, material science, and engineering. However, these results cannot be considered typical for these fields; an extensive material development process is not common in product design and a lifecycle approach to material development is much broader than most material development processes. User interactions and evaluations are the most common RtD methods to evaluate processes, but our focus was on technical development. We evaluated outcomes based on the making process and the design aspects of the prototype itself. We assessed these making processes and prototypes as an interpretation of more general and theoretical approaches, like the call for inclusion of part reuse in AM. In this way our prototypes served as concrete examples that contribute to a better understanding of the general theory.

Prototypes are not only valuable for professional and academic communication, they are also meaningful when explaining research projects to a wider audience. They are concrete and accessible examples that can be shown at exhibitions, and reported in newspapers or on forums. Prototypes from our project were exhibited at the Dutch Design week and featured in two large-circulation Dutch newspapers. They bridge the gap between science and practice, because they demonstrate how theoretical approaches can be interpreted.
To conclude, we consider prototyping processes for knowledge generation a valuable RtD approach for developing technology in a new context. The design goal in the prototyping process helped us to obtain relevant information from other disciplines and for technical development in a new context. Artefacts and prototypes, as well as a detailed process documentation, play an important role in the evaluation of the process of generating scientific knowledge.

7.6 Contribution to science

This research project has been a detailed exploration of the opportunities offered by AM in a circular economy. An important finding is that, in spite of all the optimism about the way the use of AM can accelerate the transition to a circular economy, there are currently few applications of AM that actually support and enable this economy. Positive examples are, for instance, databases to digitally store and 3D print spare parts (My Mini Factory, 2020; Spare parts 3D, 2020) and filament from recycled plastic (Reflow, 2020). But on the whole, we find that it takes in-depth knowledge and understanding of the AM production technique to successfully print for both product integrity and material integrity. In order for circular economy research to evolve, it is important to develop balanced assessments of the opportunities that AM offers and the threats it may pose. Our research, for instance, shows that the opportunities AM offers will only come to fruition if product integrity and material integrity are considered from the very early stages of the design process – and this is currently not commonplace.

Based on the answers to the research question we present the main contributions of this project:

- We contributed to establishing of a new research direction by exploring design approaches for product integrity and material integrity in a circular economy.
- We developed a circular AM process flow for product integrity. We demonstrated this process flow by showing that the digital and additive character of AM can be harnessed to develop reversible connections that enable products to be dis- and reassembled without loss of quality.
- We established a design approach for developing reprintable materials. This was demonstrated by creating reprintable materials from locally available bio-based resources.
- We contributed to the domain of 'research through design' by using the prototyping process for knowledge generation; a less commonly used process. The design goal in the prototyping process was used to obtain relevant information (from other disciplines) for technology development in a new context. This resulted in an iterative process between experimental prototyping processes and scientific knowledge generation.

7.7 Practical recommendations for designers and makers

Designers and makers who design for a circular economy cannot just design for manufacturing and use, but also need to integrate product integrity and material integrity in their initial design. from our research, we gained the following insights into the use of AM in a circular economy:

- Use the complex geometries and adaptable digital design files enabled by AM to extend product lifetime:
    - Use the flexibility of digital files for repair and upgrades to extend the lifetime of existing products.
    - Use reversible connections.
    - Use parametric design to create more flexibility and adjustability for part reuse.

    - Use AM's abilities to contribute to a design language for product design in a circular economy.

- Use reprintable and bio-based materials:
    - Use reprintable materials made from locally available and renewable sources.
    - Incorporate all life cycle stages from resources, production and properties, to recovery when developing materials.
    - Use open source platforms, like Materiom, to share recipes and extend the range of accessible sustainable materials.

7.8 Future research

This project was an initial exploration into the field of additive manufacturing and design in a circular economy and therefore there is ample room for future research. Below we discuss a number of directions:

- *Expansion of approaches for product integrity and material integrity in AM*
  We introduced approaches to integrate product integrity and material integrity in the AM process to design products for a circular economy. These approaches should be further expanded to investigate their use in the broader context. Possible directions are to extend the exploration into solutions for reversible connections, to develop approaches that combine product integrity and material integrity more closely, and to explore the approaches for other digital fabrication processes. These directions demonstrate that further research is needed to come to a more comprehensive development of opportunities for design for product integrity and material integrity in AM and digital fabrication.

- *Design-inspired material development*
  Design increasingly contributes to the development of sustainable materials. This increased interest is, for example, demonstrated by the emerging field of biodesign in which the design is for, with, or about biology (Myers, 2018). Our material development process demonstrates that a design-driven approach based on in-depth knowledge from material science and a lifecycle perspective can be successfully employed to achieve materials for design in a circular economy. Stimulating an interdisciplinary approach that integrates design and material science, will bring new perspectives to material development and provide in-depth material knowledge to designers.

- *Improvement of reprintable paste-based materials*
  The reprintable paste-based materials reported in this thesis show promising properties, but need further development to allow reliable use and reuse in product manufacturing. Elaborate testing and determination of physical and mechanical properties is needed with (re)printed samples to improve our understanding of material integrity after recovery. Finally, material printability and quality is likely to benefit from research that combines material development with process parameters related to digital design files and printer settings.

- *Distributed manufacturing and recovery*
  The availability of a broader range of locally sourced and renewable materials can contribute to distributed manufacturing and remanufacturing. The development of bio-based reprintable materials demonstrates this potential, but further research is needed to better understand the implications and opportunities of these materials regarding distributed manufacturing and remanufacturing for AM in a circular economy. Interesting research directions are on environmental assessment, value chain organization and required infrastructure, such as the facilitation of distributed remanufacturing with locally available materials and dealing with scale in relation to sales and use.

- *Beyond extrusion printing*
  All experimental work in this thesis was performed with extrusion 3D printing. While we consider the main findings of this thesis applicable to AM in general, further research is needed to verify the findings for other AM processes that use other technologies to build objects. This leads to questions regarding both the implementation of material integrity and product integrity for non-extrusion AM technologies. For product integrity, the nature of AM systems that work with a powder bed, for example, poses challenges to printing onto or around existing components for high value reuse. For material integrity, as different AM technologies use varying physical and chemical processes for building objects, a large diversity of approaches for reprintability will be required.

- *User research*
  The studies in this thesis focussed on the development of AM to find production solutions for a circular economy. The final outcomes were not rigorously verified with the target group; the design and maker communities. We received informal input on our outcomes through publication on the digital platform Materiom and by exhibiting at the Dutch Design

Week. However, user studies are required to fully understand the needs of designers that work with locally available and renewable materials.

To conclude, additive manufacturing is a promising method for manufacturing in the circular economy, as long as product integrity and material integrity are part of the design and production process. In this thesis, we demonstrated possibilities for product integrity with reversible connections enabled by the complex geometries and adaptable digital design files of AM and the possibilities of material integrity through locally sourced renewable and reprintable materials. We developed prototypes and examples to show future opportunities and to invite researchers and designers to embrace the mind shift needed to achieve sustainable production with additive manufacturing in a circular economy.

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List of publications

Under review

Sauerwein, M. & Peek, N. (under review). Incorporating Sustainability in Digital Fabrication Workflows: Reversible 3D Printed Joints for Part Reuse. TEI'21

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Sauerwein, M., Karana, E., & Rognoli, V. (2017). Revived beauty: Research into aesthetic appreciation of materials to valorise materials from waste. Sustainability, 9, 529. https://doi.org/10.3390/su9040529

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Sauerwein, M. & Peek, N. (2019). Integrated Connections: Workflows for Hybrid Digital Fabrication, Poster proceeding at Symposium on Computational Fabrication (SCF), Pittsburgh, USA

Non-academic exposure

Mussels in the 3D printer: a surprising look at recycling. Exhibition at Mind the Step, Dutch Design week 2018.

Als design en wetenschap een eindje met elkaar oplopen, krijg je slimme producten die er nog goed uitzien ook. De Volkskrant, 20 October 2018.

Het tweede leven van iets dat eigenlijk kapot was. NRC handelsblad, 4 April 2020.

Living Matters. Up close and personal. Research event at Mind the Step, Dutch Design week 2020.

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About the author

Marita Sauerwein was born on the 13th of October 1989 in Vorden, the Netherlands. She studied Industrial Design Engineering at Delft University of Technology (TU Delft) and graduated in 2015 on the aesthetic appreciation of bio-based materials. After her graduation she worked as a freelancer for a year before starting her PhD at the same faculty in the summer of 2016. During her PhD, she explored the use of 3D printing for design in a circular economy as she wants to contribute to a sustainable future. She has developed both her research and design skills by creating prototypes with the purpose to generate knowledge. Next to scientific publications, this has resulted in prototypes that have been featured at the Dutch Design Week, two major newspapers in the Netherlands (de Volkskrant and NRC handelsblad) and on online platforms. Her research was embedded in education through the supervision of various student projects both on a bachelor and master level. Furthermore, she has been a visiting PhD student at the University of Washington with dr. Nadya Peek for which she received a Culture grant from the Prins Bernhard Cultuurfonds. In her free time, Marita likes to climb high in the strict sense of the term as she is an avid rock climber.


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