When Matter Leads to Form: Material Driven Design for Sustainability

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KEYWORDS
Material driven design, design for sustainability, design process, product design, circular economy, design education.

HOW TO CITE
Bak-Andersen, Mette. 2018. "When matter leads to form: Material Driven design for sustainability". *Temes de disseny* 34: 12-33.

This article presents the argument that a conventional, form-focused design process causes a lack of knowledge regarding materials and, as a result, creates a knowledge barrier between the designer and the product – a barrier that acts not only against the implementation of so-called advanced materials and new technologies, but also ends up as a major obstacle to the creation of sustainable industrially produced products. A new type of design process is emerging, in which the material is present from the outset and can be seen as the driver of the process. This material driven design process breaks down the aforementioned knowledge barrier and has shown potential for being a design process that enables design for sustainability. However, simply starting with the material does not ensure a sustainable outcome by default.

Thus, the overall aim of the research behind this paper is to define the specifics of material driven design for sustainability with the objective of testing to which degree it is possible to design a process that guarantees results compatible with a circular economy. The research is based on constructive design research with a predominant Lab approach and elements from a field in which a new reality is imagined and built to test whether it works. This was done by running a series of five design trials in which the material driven design process was continuously tested, evaluated and adjusted through reflection-in-action. In total, the process was tested one hundred eighteen times by students with the involvement of expert designers and specialists from four different companies and institutions. This article presents the quandary in the relationship between form and matter in established contemporary design processes and specifies the cross-disciplinary field in which material driven design for sustainability is placed. The methodology and the definition of a 'design trial' as a method is described, followed by the progress of the process through the five trials. Finally, the material driven design process for sustainability is outlined step by step, including relevant approaches for the experimentation. This article presents a design process that delivers products which are compatible with a circular economy at the end of their life. The process does not necessarily have to be used as a 'standalone' design process but can be combined with others and has reached a point where it is sufficiently developed to be tested in an industrial setting.

1

INTRODUCTION

Considering that all human-made materials surrounding us are made from elements that occur naturally on our planet, it may seem paradoxical that using these same elements in materialising and building our civilization should end up being so harmful to the same environment from which they came. Nonetheless, it has become evident that we need to change the way we make things. A strategy for sustainability that is being adopted by several governments and institutions is the circular economy (Government of the Netherlands 2018; Su et al. 2013, 215-227; European Union 2018). The circular economy is a closed loop material system that encompasses the human-made world (Pearce and Turner 1990; Ellen Mac Arthur Foundation 2018). Developing the ability to design for a system in which a product must either be recycled or biodegraded at the end of its life demands a profound understanding of the composition and compatibility of materials. A lack of understanding of materials effectively creates a knowledge barrier between the designer and the product. This barrier acts not only against the implementation of advanced materials and new technologies, but also becomes a major obstacle to the creation of sustainable products.

During the last decade, variations of a material centred design process have been gradually emerging from some design professionals and researchers: a process in which the material plays a fundamental role from the beginning of the design process. It is described by most researchers involved as *material based* or *material driven* (Karana et al. 2015, 35-54; Van Bezooyen 2013, 277-286; Hansen 2010; Oxman 2010) (the latter being the term that will be used to describe the research in this article). The main difference between a material driven design process and most conventional contemporary design processes is that the designer plays an active role in designing, developing or manipulating the material that is being used for the design from the outset instead of merely selecting a material to fit the form once the design process has been finalised. A large variety of design processes intended for design for sustainability (Ceschin and Gaziulusoy 2016, 118-163) already exist, but they tend to be either focused on systemic thinking, and lack specific direction for product design as a result, or tailored after conventional design processes in which the material is a secondary element that is selected.

Applying a material driven design process makes the designer the expert on a given material (Karana et al. 2015, 35-54) and, thus, potentially provides the designer with essential knowledge when designing for a circular economy. However, although published research on material driven design processes present valuable arguments for the benefits of using material driven design, such as designing for material experiences (Karana et al. 2015, 35-54), to spark creativity (Van Bezooyen 2013, 277-286) or to achieve a more environmentally friendly outcome (Oxman 2010), results are neither sustainable nor compatible with a circular economy *by default*. To achieve the potential of material driven design as a design process for sustainability that results in products compatible with a circular economy, specific actions and considerations during the process are required. The aim of my research is to define this process and to test material driven design as a design process for sustainability and its potential contribution to a systemic change towards a circular economy.

This article presents the quandary in the relationship between form and matter in established contemporary design processes and the fundamentals of material driven design (section 2) the methodology for the research leading to development of the process is introduced (section 3), followed by results and discussion, a specification of the cross-disciplinary field in which material driven design for sustainability with examples from research and practice (section 4), then the material driven design process for sustainability, outlined step by step, including relevant approaches for the exploration of materials (section 5). This is summed up by a discussion on limitations and prerequisites (section 6) followed by concluding remarks (section 7).

2

THE FUNDAMENTALS OF MATERIALS DRIVEN DESIGN

To comprehend the prospective of using material driven design as a design process for sustainability, it is necessary to understand the underlying principles of material driven design in general and, just as important, how these differ from the present more established form focused design process. Although descriptions of material driven design vary in the literature, there seems to be a shared understanding of it as a process in which form is not prioritised over matter and the material is not merely introduced to fill a set shape, but truly defined (as in the dictionary) as: "The matter from which a thing is or can be made" (OED 2017). Material driven design is a design process initiated through the exploration of material, or where a material is designed, grown or developed in the same process that determines the form.

2.1 The quandary of material selection

Established contemporary design processes include different approaches and strategies on how to get from an initial idea to the finished product, but they rarely question the role of the designer as the creator of form and the material as an element that is selected and fitted to the form. Numerous books, articles and research projects have been published addressing the critical importance of selecting the right materials (Ashby and Johnson 2003, 24-35; Karana, Hekkert, and Kandachar 2010, 2932-2941; Van Kesteren, Stappers, and De Bruijn 2007). Likewise, there are several digital tools aimed at helping the designer in material selection (Ramalhete, Senos, and Aguiar 2010, 2275-2287). Whether these encompass nearly all possible criteria and characteristics like the comprehensive Cambridge Engineering Selector, CES, or whether they have a specific focus on cost, performance or environmental impact, they generally have one thing in common: they are predominantly set up to support the designer as the creator of the form, and the material as an element subsequently selected to fit the form. Even large materials libraries like Material Connexion (Material Connexion 2018), Materia (Materia 2018) or MaterFad (Materfad 2018) are usually set up to aid the designer in a process in which form is primary and material secondary. They display a great variety of new and fascinating materials – but typically finished, commercially available materials ready to be selected for a design.

The literature, research, tools and materials collections represent very valuable knowledge about material technology, but, in the context of designing for a circular economy, it is a drawback when the material only appears in the design process as a finished material which is selected once the design is complete.

The material can, to a large degree, be seen as a product's DNA. It is what defines both tactile and technical properties and largely what decides the production method. It is the material or the combination of materials in a product that determines future recycling options and/or the biodegradability of a product. Thus, when the material is not present in a dialogue with form and function from the beginning of the process, it can be hard for the designer to make appropriate decisions – not just regarding sustainability. Leaving the material to the very end of the process, or even in the hands of others, provokes a knowledge barrier between the designer and the end product.

A designer who does not understand or know how to work with materials for a product is in many respects as badly equipped as a chef who does not understand the ingredients for the dish she is preparing. Qualities such as innovation and sustainability are not extras that can be injected into a product at the last minute, meaning that a product not originally designed to fulfil these criteria is unlikely to ever do so. However, if materials are to be a central element in the design process with the current complexity and amount of materials, it raises the question of how they affect the field of design and the core of the design process. This question will be addressed in sections 4 and 5.

3

METHODOLOGY

The research that led to the results presented in this article is primarily based on qualitative methods. It was carried out as 'Research through design' (Frayling 1993) or, more precisely defined, 'Constructive design research' with a predominant Lab approach and elements from the field (Koskinen and others 2011). The aim of the research is to create a design process that is compatible with a circular economy. This makes the design process the object of the research and the design process can thus, methodologically in the context of the research, be understood as a research prototype. The process has evolved over more than 10 years. It initially began in my design practice with practical experimentation in which design was used, as defined by Simon, to change an existing situation into a preferred one (Simon 1988, 67-82), and from 2015 by applying systematic inquiry using constructive design research to imagine a new reality and building it to test whether it works (Koskinen and others 2011).

Fig 1. Samples from a material exploration of the fabric from jeans, in which it proves difficult to achieve material circularity as the fabric is a mix of natural and synthetic fibres (cotton and elastane). (From a pre-trial material driven design experiment in 2014).

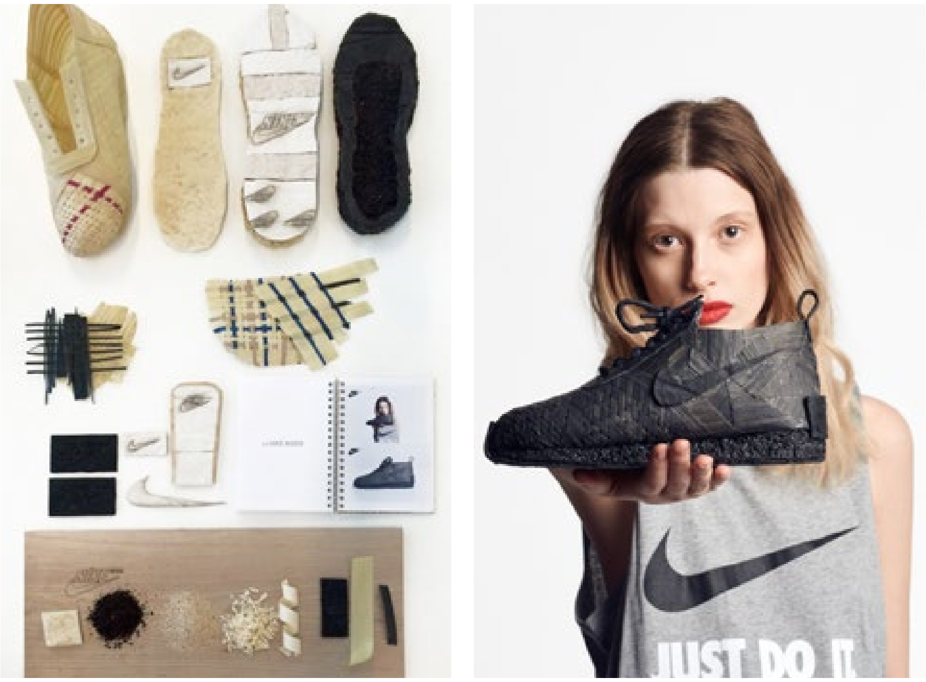

Fig 2. Image of the process and the final prototype. This participant worked with wood processed as fibres and shavings and mixed with natural rubber. The materials created show excellent properties and received very positive feedback from the designers in the collaborating company. However, the material would need to be developed further to be durable enough for a shoe. Also, because of this apparent incompatibility between material and the functionality of the product, the shoe decreases the perceived value of the material to some degree. (Trial 4)

Design for sustainability is incredibly complex and is, as such, both 'wicked' (Rittel and Webber 1973, 155-169) and messy. Schön describes a situation like this as swampy lowland and argues that only by confining oneself to relatively unimportant problems on high, hard ground overlooking the swamp is it possible to maintain technical rationalism. However, the problems of greatest human concern - in this case sustainability - are in the swamp and demand a type of inquiry that is not likely to be amenable to quantifiable methods. Rather, the problems require what he defines as reflection-in-action (Schön 2017). This affects both methods and research design.

3.1. Research design

This research is set up as exemplary design research driven by programs and experiments. The program can be seen as a structure that acts as a frame and a foundation for a series of design experiments and interventions. Binder and Redström define 'exemplary' as enabling 'critical dissemination through examples of what could be done and how, i.e. examples that both express the possibilities of the design program as well as more general suggestions about a (change to) design practice' (Binder and Redström 2006). The dialectics between experiments and program are well described (Brandt and others 2011; Redström 2017). In this research, the experimentation initially dominated and informed the program, but the program eventually took over (see table 2, A17 and B17).

The research design is centred around five design trials, each consisting of a series of experiments, in which the design process for material driven design for sustainability is tested. Schön writes about reflective research and reflection-in-action as a way to reflect on findings and decide on subsequent actions (Schön 2017). The work reported here can be understood in such terms as well and will be described in greater detail below.

3.2 The design trials

A trial is a "Test, usually over a period of time to discover how effective or suitable someone or something is" (OED 2017). The 'design trial' created as method for this research project is to some degree comparable to a scientific trial in that it includes systematic inquiry, observation and evaluation. However, it allows for a designerly approach (Cross 2006) and welcomes findings that are neither anticipated nor quantifiable, hence the term *design* trial. Each design trial consists of a series of experiments and can, to some degree, be compared to serial design experimentation (Krogh, Markussen, and Bang 2015, 39-50). However, the experiments tend to be evaluated individually and consecutively, and not set up to test the suitability of something in a specific context. The design trial was a method to test the process in action.

The early version of the process for material driven design for sustainability tested in trial 1 was based on previous practice-based design trials. At that stage, the process was relatively unsystematic and mostly focused on exploring the experiential values of the material. The results were often creative and produced with unusual materials. However, they were predominantly artistic. As a result, they were not always very functional nor were they compatible with a circular economy (illustrated in Fig. 1). The only explicit framework for trial 1 was a restriction on raw materials, which had to be locally sourced and free of charge. Subsequently, the actions and specific questions for each successive trial have been an organised response based on the findings and reflections from the prior trial(s). An overview of this progress is presented in tables 1 and 2. The execution of the five trials took place in the Material Design Lab at Copenhagen School of Design & Technology, a space designed to test, explore and design materials. Data was primarily collected from the evaluation of the results (the products produced) and, to some degree, through observation and conversations with participants and collaborating partners from the industry. Documentation was done by writing and photography and by material samples and prototypes created in the process. An overview of the trials is presented in table 1. Table 2 (at the end of the article) shows the progress of developing the process of material driven design for sustainability through a method of inquiry and analysis based on reflection-in-action (Schön 2017).

Trial number	**1**	**2**	**3**	**4**	**5**
Year / duration	2015 / 3.5 weeks	2015 / 4.5 weeks	2016 / 3.5 weeks	2016 / 4 weeks	2017 - 18 / 7 weeks
Participants	24 mixed design students, 5th semester	26 fashion design students, 6th semester	23 mixed design students, 5th semester	24 fashion design students, 6th semester	21 mixed design students, 5th semester
Collaborating partners		Nike Inc.	Biomimicry Institute and Danish Technological Institute	Nike Inc.	Aeropowder Ltd and Danish Technological Institute
Criteria for raw materials used	Had to be locally sourced and free of charge	No restriction	5 materials were provided.	Free of charge or low value biomass waste materials	5 materials were provided.
Materials used	Human hair, fish skin, LDPE (from plastic bags), algea, mycellium, coffee grounds, saw dust, potato skins, old jeans, used thatching straws.	Leather scraps, recycled polyester fabric, bamboo, wool fabric, organic cotton.	Hemp fibres, apple pulp (by-product from apple cider and apple juice production), used thatching straws, wool from meat sheep, egg shells.	Recycled nylon from ocean waste, mixed wood fibres and shavings, artificially grown snake skin (concept), fish skin, leather scraps, waste milk, hemp fibres, wool from meat sheep, wool fabric scraps.	Chicken feathers, algea, hemp fibres, wool from meat sheep, sugar beet pulp (by-product from sugar production).

Table 1. Overview of the five design trials.

3.3 The evaluation

The evaluation is focused on the products produced from testing the process as the products are the main indicators reflecting the aptness of the process. The specific criteria for evaluation evolved along with the development of the process (see table 2). The following aspects are considered obligatory for the evaluation, but, depending on the focus of the brief in question and the type of project that the process is used for, different traits can be given more importance. The evaluation starts with a focus on the raw material used. One or several of the following characteristics must define it:

1. Fully biodegradable
2. Fully recyclable
3. Waste material for recycling
4. Renewable
5. Compostable
6. Abundant resource (must be combined with at least item 1 or 2)
7. Socially responsible production (must be combined with at least item 1 or 2)

When assessing the final product, the primary focus is material circularity, hence the product must be:

1. Fully biodegradable
2. Fully recyclable
3. Designed for disassembly (in components that are compatible with items 1 and 2)

Additional aspects such as toxicity, durability, weight, aesthetics, meaning and carbon footprint are also considered in the evaluation of the final product. Some criteria for the evaluation are quantifiable, for example, if it is possible to measure how long something takes to biodegrade. However, sustainability always relates to context and thus the primary goal of the material is to suit the function of the product. This means that in some cases it is a quality that the material biodegrades rapidly and in other cases, when a product is designed to last many years, it is important that the material is durable and only biodegrades very slowly. Likewise, weight can be an issue for sustainability if transportation over long distances is involved, but it can also be an important feature for the functionality of the product. A larger carbon footprint can be accepted for a spoon made from stainless steel that will last for at least a lifetime than for a spoon made from biodegradable corn starch that is likely to be used for less than an hour then disposed of. The importance of the relationship between material and function is illustrated in the following figure (Fig. 2).

Aspects which can be difficult to measure, but are extremely important to sustainability, are meaning and aesthetics. A material that might have excellent technical properties and score high on all other sustainability parameters might be considered unacceptable to users because it comes with a connotation that is offensive to them. An example of this was products made from human hair in trial one (see Table 1). By contrast, when a user finds a product aesthetically appealing or perceives the material as high value, the user will have an emotional attachment that will ensure the product's care and durability (Harper 2015).

In trials 2 and 4, which were set up to test the process with a specific brief, expert designers from the collaborating company participated in the evaluation (see Fig. 3). In the following section, a map of the field and the process of material driven design for sustainability are presented. Both are based on the theoretical foundations presented in section 2 and on the findings from the five design trials presented in section 3.2.

Fig 3. Participant presenting his final product, a shoe made from leather scrap, to the expert designers in the collaborating company, Nike. (Trial 2)

4

MATERIAL DRIVEN DESIGN FOR SUSTAINABILITY: THE FIELD

In material driven design for sustainability the creation and manipulation of the material is central. Even though different specialists might contribute to this part of the process, it is mainly performed by the designer. One could claim that this is the job of a material scientist, but there is some research indicating that the development of new materials is not exclusively a matter of highly specialised scientific research delivering pre-specified results. Influential material scientists point out that material exploration should ideally be cross-disciplinary. One example of this is the research and work by material scientist Mark Miodownik. Both at The Institute of Making (University College London 2018), of which he is the director, and in his research, he pursues the development of both physical and aesthetic properties of materials by reviving what he perceives as a mutually rewarding collaboration between the arts and the sciences (Miodownik 2003, 36-42; Miodownik 2005, 506-508; Miodownik 2007, 1635-1641). Similar ideas can be found in Cyril Smith's research into the historical interaction among science, art and technology. He documented how the art industry's interest accelerated scientific knowledge and pushed forward technological development for centuries. An important argument is that the classification of an activity as science, technology, or art is relatively recent (Smith 1970, 493-549). In a similar vein, material scientist Mike Ashby and designer Kara Johnson point out the potential that emerges when principles of materials science and technology merge with other specialities such as engineering, chemistry, biotechnology and information science (Ashby and Johnson 2003, 24-35).

Considering this, a material driven design process can be seen as inherently cross-disciplinary. This affects the field of material driven design for sustainability, both in its constitution and methods. Drawing upon the theoretical foundations introduced in this section and the findings from the trials, the field of material driven design for sustainability can be described as a cross-disciplinary field ideally involving art, technology and natural science (Fig. 4). Art brings qualities such as aesthetics, form, experiential values and tactility. Technology offers tools, techniques and a strong link to industrial production. Natural science contributes with the composition of the material itself and holds most of the answers when it comes to solving compatibility with a circular economy and technical challenges. As presented in the examples in the following section, some practitioners and researchers in the field place themselves in the centre, with a balanced representation of art, technology and natural science. Others have a strong connection with one or two constituents and lack the balance described above. (See position numbers 1, 2, 3, ...in Fig. 4.)

4.1 Examples from research and practice

Both researchers and designers work in this field. The following examples can all be seen as material driven design with the aim of creating a sustainable outcome, albeit not necessarily explicitly defined as material driven by the creator.

The work of fashion designer Suzanne Lee demonstrates how design can include knowledge from science by exploring the use of living cultures of microorganisms, such as yeast and bacteria, to grow biomaterials like cellulose into sustainable, compostable materials and products for fashion (Lee 2018) (position 1 in Fig. 4). The comparable, but more artistic designer, Carole Collet explores the fusion between biology and design in what she calls 'biofacturing' (Collet 2012) (position 2 in Fig. 4). However, the project is mainly conceptual and thus, lacks the technology component. As a result, it is not placed in the centre.

The Dutch design prize 'New Materials Award' (Het Nieuwe Instituut, Fonds Kwadraat, and Stichting doen 2018) is presented as 'on the cutting edge of science, design, art and technology'. The prize aims to challenge participants to think beyond their own discipline in applying new materials and seeking sustainable solutions for the future. Many of the nominee projects can be described as material driven design for sustainability. A good example is the 3D printed mycelium chair by Eric Klarenbeek. The basic raw material is vegetable waste with mycelium used as 'living glue' (Klarenbeek 2018) (position 3 in Fig. 4). Another researcher who is using 3D printing in a material driven design process is the architect Neri Oxman. In her 'Material Based Design Computation' thesis, she describes her process as nature's way of designing and building, a process in which material always precedes shape. She points out that early forms of craft as well as some of the most innovative new developments in materials science and engineering apply a material-based approach with the role of material as the substance of form, rather than form's progenitor (Oxman 2010b). While drawing on research on materials and biomimicry, her use of materials in the early projects seemed mostly defined by the limits of digital fabrication. An example of this could be the artistic project 'Pneuma' that is inspired by phylum porifera animals, such as sponges (Oxman 2018) (position 4 in Fig. 4). The sponge is used for structural and mechanical inspiration, but the material used for the fabrication is not related to the sponge. As a result, it lacks the natural science component and is placed outside the centre. However, Oxman has started designing materials and adapting printers to suit the material. An example of this is the 3D printer she has built with her team to suit the chitin paste made from a large quantity of crustacean shell waste (Mogas-Soldevila 2015) (position 5 in Fig. 4). Digital production can add a higher level of complexity and detail to the final product, but material driven design for sustainability does not necessarily have to be as technologically complex as the work of Oxman or Klarenbeek. A good example of this is the mycelium-based designs by designer Maurizio Montalti (Montalti 2018), which are produced simply by growing the material in a mould (position 6 in Fig. 4).

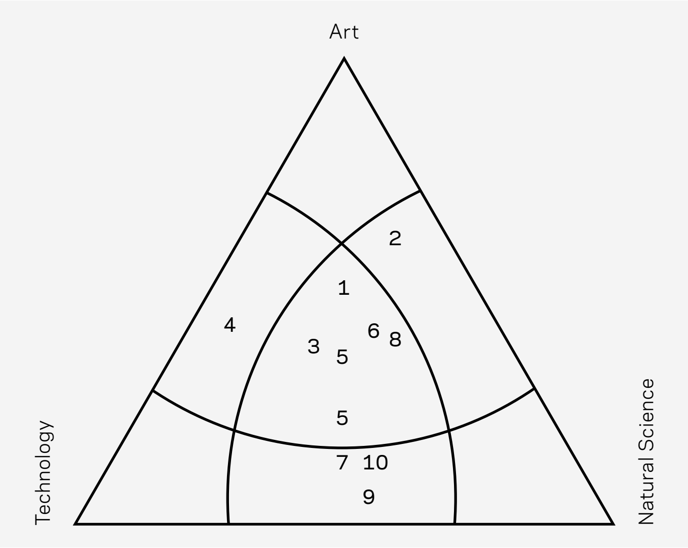

Fig 4. The cross-disciplinary field of material driven design for sustainability involving art, natural science and technology. The numbers indicate where the different examples of material driven design, presented in section 4.1, are placed.

Some of the most avant-garde research on design and materials that has been published over the last few years did not come from design, but from biotechnology; research on creating materials by the means of synthetic biology and research on material design in biology (Weiner, Addadi, and Wagner 2000, 1-8); and scenarios where biotechnology is entering the field of design and in some cases are getting close to material driven design for sustainability. Examples of this are the synthetically grown honey-bee silk developed by Tara Sutherland and her team from CSIRO in Australia (Sutherland et al. 2010, 171-188) (position 7 in Fig. 4) and the "Grow Your Own – Life After Nature" exhibition in which various design trials starting with the implementation of DNA in bacteria and coding the material to grow the final product were displayed (Dublin Science Gallery 2017) (position 8 in Fig. 4). The Bio Academy or 'How to grow almost Anything' is a course on synthetic biology directed by George Church, professor of Genetics at Harvard Medical School (Church 2018). This could potentially be the stepping stone to a very advanced version of material driven design for sustainability. However, despite the fact that the program is rooted in the FabLab community, at least for now, it appears to lack the component of Art (position 9 in Fig. 4).

Similar thoughts and approaches to materials and design are seen in various smaller bio-hack labs like New York City's Community Biolab 'Genspace', where professionals from biotechnology and programmers have started working with materials and design at a very advanced level (Kean 2011, 1240-1241). Biotechnology makes it possible to use living systems, organisms and almost any source of biomass to develop or make products. This is widely applied in agriculture, food production and medicine. When employed to develop new materials, this could hold considerable potential for advancing the field of material driven design. The value of *tinkering* with design and materials is well-described (Wilkinson and Petrich 2013; Rognoli et al. 2015, 692-702). The activity in some of the less established bio fabricating labs and spaces can be defined as tinkering with biotechnology to create new materials.

As these examples have shown, an ideal example of material driven design for sustainability strikes a balance among art, technology and natural science. When art is overrepresented, the outcome can lack function and usability (e.g. position 2 in Fig. 4). When art is absent, the result lacks experiential values and becomes indifferent and hard to apply in practice (e.g. position 9 in Fig. 4). When natural science is too dominating, the result tends to be incomprehensible to designers and industry and, thus, difficult to apply to mainstream products. However, when it is missing, the result is rarely compatible with a circular economy (e.g. position 4 in Fig. 4). When technology takes precedence, the products – even though they might be highly complex – can appear indifferent and mechanical. However, when technology is missing the results tend to lack potential for industrial production. Thus, a balance between these three fields is important in material driven design for sustainability. Based on this, the theoretical foundations presented in section 2 and the results from the five design trials presented in section 3, the following design process has been developed.

5

MATERIAL DRIVEN DESIGN FOR SUSTAINABILITY: THE DESIGN PROCESS

Karana et al. describe how "Over time, the designer who takes a MDD [Material Driven Design: a Method to Design for Material Experiences] approach is expected to become a master of a given material: he/she will know how the material behaves under different circumstances or how it reacts when subjected to different making techniques or manufacturing processes" (Karana et al. 2015, 35-54). This can be seen as a shared advantage for a design process in which "the material has been moved from the very end of the design process to the very first step and through hands-on exploration and prototyping with the material evoking and concretizing ideas" (Van Bezooyen 2013, 277-286). Thus, irrespective of the motivation for using a material driven design process, almost by definition, such a design process, in which the material is present and explored from the beginning, eliminates the barrier of ignorance described in the introduction to this article. Nevertheless, this kind of process will not automatically ensure a sustainable outcome, even if it is as thorough and well defined as MDD, by Karana et al.

As can be seen by following the progress from D1 to D17 in table 2, it requires explicit actions during the process to guarantee the compatibility of the product with a circular economy. The main constituents of the process related to sustainability are the initial circularity check (5.2.1), requirements about research into social and environmental impacts of the raw material, before deciding if the raw material is suitable for the process (5.2.2), research of the chemical composition (5.2.3), designing for biodegradability, recycling and/or disassembly in the material manipulation (5.3.1) and other more subjective issues like understanding the value (5.2.5) and the cultural and historical meaning of a raw material (5.2.4), something that is not quantifiable but very important as a product made from a material perceived as low value or culturally unacceptable could result in a lack of emotional attachment from the user and, consequently, affect the product's longevity (see F9 – F11 in table 2).

5.1 Variations

The process can be used in different ways. In most cases, designers are likely to work with a specific brief. In this situation, the material research, exploration and design should be carried out in relation to the function the end product must comply with (see table 2, B13). Using the process with a specific design brief was tested in trials 2 and 4 in collaboration with the company Nike. Examples of the results from this variation of the process are illustrated in Figs. 2, 3, 8 and 9.

Fig 5. Participants from trial 3 are being introduced to the raw materials (see Table 1 for details).

It is also possible to use the process in a more open and explorative way, in which the qualities of the material largely define both function and form in a suitable product. This variation can be relevant when the objective is to explore the value and use for certain materials. This could be from waste materials as tested in trials 3 and 5 (see table 2 B14 – B16 and Fig. 5). In these trials five specific local by-products were used for raw materials. In the continuation of both trials, the Danish Technological Institute provided additional technical support to students who wanted to continue with their material and product. An example of this was Hannah Michaud (2018) from trial 2 (Fig. 6). Naturally using the process in this way could also be used to explore other types of materials, such as new materials created in laboratories. In the following sub-sections, the process of material driven design for sustainability is introduced step by step.

5.2 Step one: material research

From the outset it is essential to identify if the raw material at hand is suitable for the process. The material needs to be biodegradable and/or fully recyclable. Likewise it should not contain toxins from previous lifecycles.

5.2.1 Circularity check

From the outset, it is essential to identify if the raw material at hand is suitable for the process. The material needs to be biodegradable and/or fully recyclable. Likewise, it should not contain toxins from previous lifecycles.

5.2.2 Source

The material research requires studying the source of the material: how the material is excavated, grown, or produced – and by whom. This information is essential in deciding whether the material is appropriate for the process, from an ethical, social and environmental point of view. For practical reasons, it is also necessary to study supply, especially if the availability of the material is seasonal. Studying present use will help understand what potential it might have for the future. This often means looking at other industries such as the food industry, agriculture or the medical industry. In the case of new materials or new material technology, relevant information might still only be at research level and it may be necessary to look for information in scientific journals outside the field of design.

5.2.3 Composition

Part of the initial exploration must be a more scientific examination to acquire a fundamental understanding of the composition of the material and its circular compatibility with other materials. It is necessary to study chemical composition and it can be useful to examine the material with scientific tools to identify patterns and structure.

5.2.4 Historical and anthropological research

An important part of understanding the material is to look into how the raw material has been used in earlier times, in different cultures and how it used to be manipulated, processed and treated. Inspiration from traditional techniques and processes often results from this and can be useful when translated into a modern manufacturing context. Often, there are historical narratives about the use of the material and these can represent an emotional value to both the designer and the user.

Fig 6. Hannah Michaud was a participant in the 2nd trial and continued by forming a company around the material and products that she designed. She initially struggled with the fact that she was trained as a fashion designer and, thus, insisted on her material being used for fashion products. Finally, after more than a year, she accepted that by changing her focus to packaging, her material had a much higher value. In 2017, Michaud was rewarded with the Danish start-up award 'Iværkst' for her work.

5.2.5 Value

It is, of course, important to identify the monetary value of the material, but just as important is the value perceived by a potential user. Certain materials that might have good technical properties can, because of tradition or culture, be perceived negatively by the user.

5.2.6 Hands-on Exploration

The exploration in this first step of the process includes a thorough hands-on exploration of the material to see how it behaves and changes in all conceivable situations, both from a technical and a sensorial perspective. Describing the experiential experience of the material, such as a soft touch or a distinctive smell, is just as important as defining the measurable technical specification, such as fire resistance, biodegradability or water resistance. Both form part of identifying the inherent qualities of the raw material.

5.3 Step two: material manipulation and design

Applying as many relevant techniques, tools and processes as possible gives a comprehensive understanding of the material's potential and enables the designer to creatively manipulate the material's design to suit specific requirements for function, form or aesthetic expression.

5.3.1 Manipulation

With the information acquired about the material in step one, the designer has the basic knowledge necessary to start the manipulation and transformation of the material into something new. This requires both utilising mechanical and chemical processing to achieve good material properties, and often involves the challenge of finding sustainably compatible binders as well as adapting or building tools to suit the material. The material and product must be designed for biodegradability, recycling or disassembly. Once at this point, it is often evident which of these it should be. It is possible to mix biodegradable materials in a composite without jeopardizing the possibilities for biodegradation, but working with materials for recycling generally means working with mono-materials or design for disassembly.

5.2.4 Enhancing the strengths

The worth of the material is in the strengths – both the technical and the experiential - and these are later going to play an important role in the quality of the product, thus it makes good sense to try to enhance them. This will add to the both the factual and the perceived durability of the end product.

5.3.2 3D sketching

The value of sketching in the design process is well documented (Cross 2006; Goldschmidt 1991, 123-143). Ideally, sketching in material driven design for sustainability should be done in the material and will consequently be 3-dimensional from the outset. Designing the material is the first step towards form and the sketching at this stage of the process should be centred on the different possibilities of transforming the material into a three-dimensional structure or form.

5.3.3 Challenging weaknesses

Different materials have different inherent properties, but it is important not to accept unnecessary weaknesses. Thus, identifying and addressing issues such as fragility, unappealing aesthetics or smells is crucial at this point in the process.

5.3.4 Enhancing strengths

The material's worth is in its strengths – both technical and experiential - and these will later be important for the product's quality, thus an effort should be made to enhance them.

5.4 Step three: product development

The material driven design process is not strictly linear, but can be seen as an ongoing dialogue between material, function and form. Therefore, the material is rarely 100% finished before product development

Fig 7. Participant exploring plant textures, structures and strategies for survival at the botanical garden in Copenhagen. (Trial 3)

starts and is still likely to need minor adjustments to suit function and form.

5.4.1 Form & function

At this stage the actual product starts taking form. At this point, the material should meet the requirements of the design brief. If the process is used more openly to explore the value of a material, this is the moment to decide on a suitable function for the material.

5.4.2 Handmade for digital manufacturing

Designing a physical object using a material driven design process requires the same laborious consideration of form, function and usability as other design processes. However, as the designer in this process also designs and manipulates the material, there is an opportunity to simplify and optimise the path from raw material to finished product. Depending on the physical installations available, the prototype, to a large extent, might be handmade. However, when it goes to production it will likely be industrially produced with the means of modern technology, and therefore typically improved in terms of finish, and the production time will be shortened considerably. This is important to remember in the making of the prototype: a woven prototype hand made on a homebuilt loom will potentially be manufactured by means of CAD/CAM 3D-knitting technology in industrial production.

5.4.3 Presentation of the prototype

When the material driven design process is finished, the design is presented in scale 1:1 in the material. This will give the truest picture of the technical, sensorial and functional properties of the product. In some cases, if the product is very large, a fragment of the product can be presented. In this case it is important to choose a fragment that demonstrates the material's suitability for the product.

5.5 Three approaches to the exploration of materials

As described in section 4, material exploration is ideally cross-disciplinary. This affects the approaches in material driven design for sustainability. Thus, both phenomenological sensory-based methods that more traditionally are found in art and design, and scientific methods involving experimentation, measurement and systematic observation should ideally be applied. From the early trials it became clear that this balance did not come naturally to most participants. As a result, this guideline including three suitable approaches was finally defined after trial 3 (see E1 – E17 and D6 – D10 in table 2 for details regarding the development).

5.5.1 The phenomenological approach

There is perhaps a tendency in the artistic professions to take a phenomenological approach, even when it is not explicit or if the participant is not introduced to the method. The testing and exploring of the material is often based on subjective experiences and the immediate perception of the material. Such a process can be systematic, but it is more often based on freely studying and developing both tech-

Fig 8. Image of the process and the final prototype. This project was based on studies of the properties of snake skin and how to grow it artificially. Despite this having a strong connection to natural science, the project ended up far from natural science in the field map simply because the participant did not have the means or facilities to explore the potential for growing this type of material. As a result, the project ended up in what might be deemed a thought-provoking statement, but not strictly a result of a material driven design for sustainability. (Trial 4)

nical and sensorial properties through handling and creatively exploring the material using all senses. The reflections in the design process will typically address experiential issues like how the material smells, how it behaves and feels and which associations this might provoke in the user. It will make the designer consider aspects such as the aesthetics and cultural perception of the material, and it is typically through the phenomenological approach that the designer starts to tinker or play. Mistakes and unexpected results are common and can be very useful. Initial exercises to encourage a phenomenological approach can include blocking vision when introducing materials, for example blindfolding designers, presenting them with various materials and asking them if the materials they have in their hands are sustainable or good quality. Both characteristics depend to a large degree on how the material is used, but the exercise makes us realise how subjective and biased our experience of a material is.

5.5.2 The scientific approach

There are many things that cannot be measured and described with data. But being systematic and recording all steps enables a much more efficient process. It provides the information required for repeating or elaborating on earlier tests and the data necessary for technical comparative assessments of different material samples. Most scientific inquiry during the process will typically be related to issues such as the performance or the characteristics of the material and how it can be measured. For example, if the biodegradability of a material is an important feature for the product, how can this be tested and improved by adjusting the chemical composition? Or, if the tensile strength is vital for the function of the product, how will different lengths of fibres and the ratio between binders and the fibres affect the result? Measuring and documenting every step of a trial or a process seemed unnatural to most participants in the trials, and apart from lectures and demonstrations, it proved useful to introduce practical tools such as lab diaries and requirements about labelling to ensure systematisation and accuracy in the development of the material.

5.5.3 The biomimicry approach

Biomimicry, as understood here, is learning from then emulating nature's forms, processes, and ecosystems to create more sustainable designs (Baumeister 2014). Nature is a treasure trove of sustainable solutions for material design and the structure of organisms, optimised for their environment by evolutionary selection over millions of years. If only we knew how to read it entirely, nature would be the perfect design guidebook for a circular economy. However, even with the limited knowledge available, it is relevant to include biomimicry as an approach in material driven design for sustainability. A well-known example is the Japanese bullet train inspired by the kingfisher bird. However, the relation to nature does not make the bullet train considerably less harmful to the environment than other trains. This is because biomimicry is used to mimic nature for mechanical qualities and form but it ignores material composition and structure. Examples of biomimicry focusing on the material would be studying how nature makes sharkskin antibacterial or how the nanostructure on a butterfly wing catches light in a way that makes it

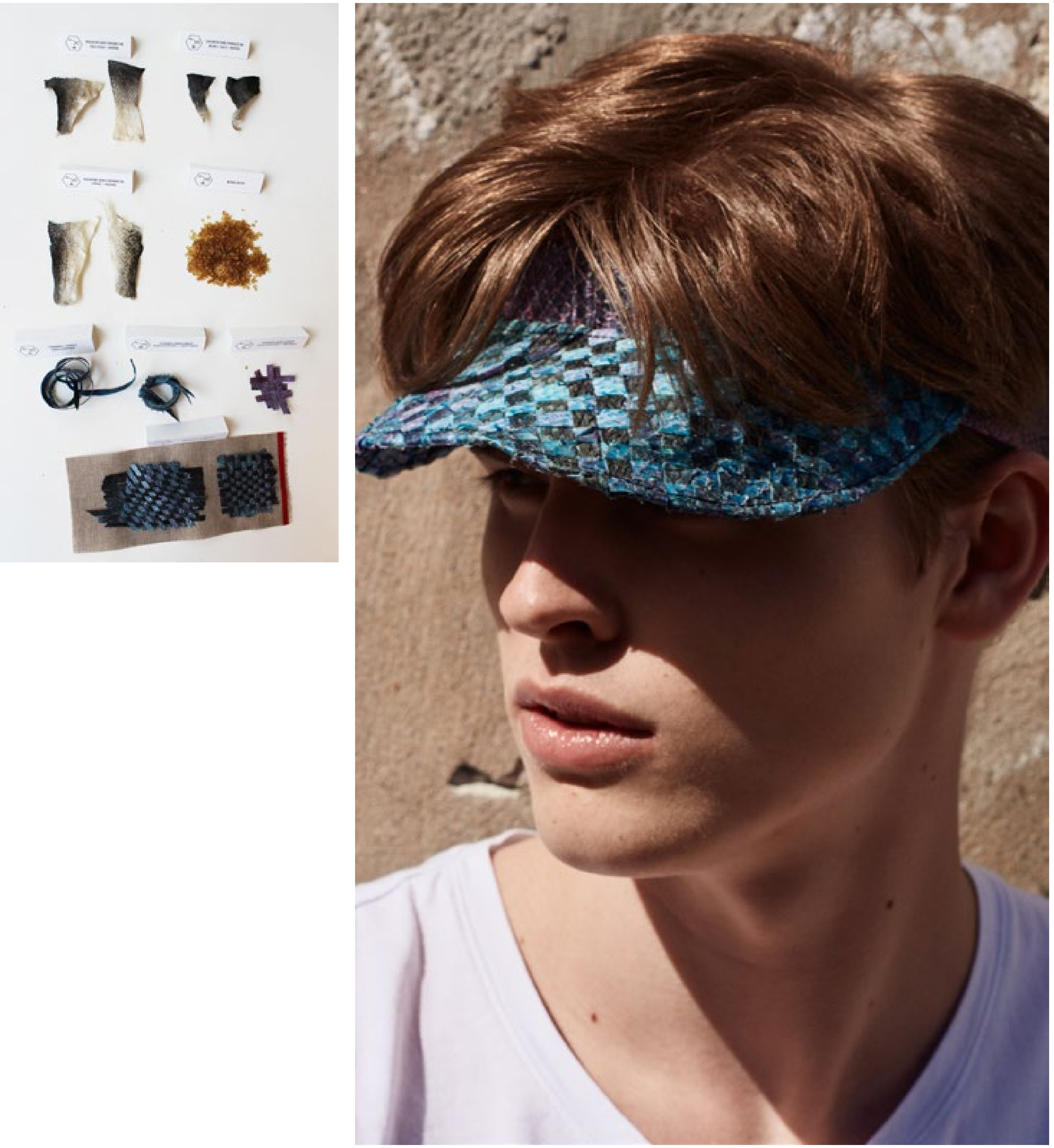

Fig 9. Samples from the process and final prototype made from salmon skin, a waste product from the fishing industry. The skin has been tanned with urea (from urine) and dyed with natural dyes. The result is a fully biodegradable cap made for Nike. (Trial 4)

look bright blue. Biomimicry as an approach is relevant for material driven design when studying material composition and structure is primary and large-scale form is secondary. The approach was tested and included from trial 3 with the help of The Biomimicry (The Biomimicry Institute 2018) and a biologist. Amongst other activities, this resulted in field trips to study plants (Fig. 7) (see table 2, D6 – D10).

Until these approaches were introduced into the process, the quality of the results from the trials were uneven. A lack of a systematic approach would result in sloppy results, and a lack of creativity in the material exploration would impede innovation in material, process and product. As a result, from trial 3, the approaches were introduced and the participants were asked in their presentation to be explicit about which approach they were using in which situations. In trial 3, the requirement of using lab journals to record all data and actions was introduced. This made the material exploration and development more methodical and easier to repeat.

6
LIMITATIONS AND PREREQUISITES

As presented in this article, material driven design for sustainability, both in the design process and the approaches, has been developed through design trials involving design students as participants. Expert designers might not necessarily have a more profound understanding of the circular economy, but they are likely to have a more solid foundation of skills, knowledge and experience to draw from and will perhaps quickly be able to internalise the approaches presented in the previous section. The following subsections will discuss limitations that have been exposed through the research, different variations of using material driven design for sustainability and prerequisites required for using the design process.

6.1. Limitations

Material driven design for sustainability opens up a different variety of resources that are not habitually used by designers: resources that are often abundant and at present have little value or are considered waste, or new resources made by means of biotechnology that are just leaving the laboratories. However, a considerable part of the materials that are considered waste or by-products at present are a mix of biodegradable and synthetic materials. These are hard or impossible to separate and, as a result, there are waste materials so polluted or mixed that today's technology cannot separate them. Thus, they are ill-suited as raw materials in material driven design for sustainability. Furthermore, the technical circle of recycling is not perfect. Some recyclable materials, like most thermoplastics, will deteriorate when recycled many times. This means that, in a future where a circular economy is established, we will need to consider if materials such as non-biodegradable plastics should even be produced or if they could be substituted by biodegradable alternatives.

Finally, the knowledge and skills of the designer and the characteristics of the physical space in which the process is conducted represent both possibilities and constraints for the process and the results. Depending on the facilities, some materials are more suitable than others. Some materials will perhaps even be impossible to work with, despite the fact that they are fully recyclable. This could be due to the lack of a furnace for melting aluminium or glass, or an insufficient biosafety level when growing live materials. The result of a situation like this is exemplified by a result in Fig. 8.

6.2 Prerequisites

Even though material driven design for sustainability begins with the material, it does not mean that form is insignificant. Form is inherent in all three steps of the process: from the form of the molecular bonding, the form of the texture on the surface and the form of the structural components to the overall form of the product. A fully biodegradable and/or recyclable chair still needs to be comfortable or it will be discarded very quickly. Likewise, it must be aesthetically pleasing in a way that lasts and not too dominated by the whims of fashion. Otherwise, the design will soon be perceived as obsolete. This is a reality for a material-driven design process as well as for any other design process (Harper 2015). Thus, a designer who does not have skills, techniques and experience with designing three-dimensional forms, is at a disadvantage, even in a material-driven design process. An example of a participant who managed to strike a good relationship between form, function, aesthetics and material qualities is illustrated in Fig. 9.

7
CONCLUDING REMARKS

As described in the introduction, the aim of my research was to test material driven design as a design process for sustainability and its potential contribution to a systemic change towards a circular economy. The process was tested and developed through five design trials and has reached a point where it is fully advanced within the given framework defined by the type of participants and the physical installations. Therefore, it is now sufficiently developed to be tested in other settings. To get an idea about suitability and potential impact, it would be ideal to involve expert designers and the design departments of companies that have stated an interest in sustainability – such as IKEA, NIKE, Patagonia, etc. To test the scope of the process, it would also be relevant to test it in an environment dominated by technology or natural science. Presumably, the process will continue to evolve as the field of material driven design expands, technology advances and we gain a greater understanding of how nature builds.

For now, however, it can be concluded that the process has shown potential in the following respects regarding sustainability:

Material driven design for sustainability enables the designer to work with sustainability in a material reality that is already quite cross-disciplinary at present.

Material driven design for sustainability makes the designer aware of alternative, readily available resources, such as large amounts and variations of cheap biomass by-products from the industry.

Material driven design for sustainability makes the designer a specialist in the material in question. This prepares the designer to make qualified decisions regarding sustainability in the manufacturing process.

Regarding the contribution to a systemic change towards a circular economy, the trials have shown that following the process of material driven design for sustainability will result in a product that is recyclable and/or biodegradable. However, following the process does not guarantee that the user will indeed recycle a product designed for recycling when it is no longer wanted nor does material driven design question whether a design problem can be solved in a non-material way via service design, reusing, sharing and so forth. To change the way we make things requires holistic thinking and a systemic design-for-sustainability approach. But these very general schemes have a flaw: in their complexity and magnitude all specific instructions for the product designer are lost. By contrast, the scheme of material driven design for sustainability presented in this paper is not a systemic design-for-sustainability approach, but it does offer specific instructions for the product designer.

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Reflection and action

Design Trial	Main theme	Findings	Reflection	Action	Question
1	**Raw materials**	A1) A wide range of waste biomaterials were used in novel ways.	A2) This could be a result of restrictions on raw materials	A3) To test what happens if there is no restriction on the raw materials used	A4) How will it affect the results if there is no restriction on raw materials?
	Usability	B1) The process is tested based on open exploration of materials that leads to the definition of a product according to the characteristics of the material. This is does not reflect how most designers work.	B2) The process should be tested with a specific design brief as it will be hard to evaluate the suitability for the industry without one.	B3) To test the process with a design brief from a company, providing a more realistic situation. (Collaboration with Nike set up).	B4) How can material driven design for sustainability be used with a specific design brief*?
	Student Educational environment >< Expert Professional environment	C1) The participants in the trial are students and some of them have very limited skills and knowledge compared to what can be expected from a professional designer.	C2) An educational setting with students offers a good, flexible environment for testing and developing the process, but, ultimately, this should not just be used for teaching. It should also be a process that can be applied by designers in the industry.	C3) To involve companies and external experts in the development of the process (Collaboration with Nike set up**).	C4) How will involvement by design experts from the industry affect the results?
	Sustainability	D1) Not all results are compatible with a circular economy	D2) Participants do not have sufficient knowledge about the circularity of materials.	D3) A circularity check is introduced in the process at the very beginning, to discard any raw material that is not compatible. (5.2.1)	D4) How will the circularity check affect the results?
	Approach	E1) Results are in general artistic rather than functional. Many are not fully developed and several participants have had trouble repeating successful experiments. Some participants used trial and error sheets in which they reported their process.	E2) Participants have no or little experience in exploring and working with materials. In their exploration, they intuitively seem to be dominated by an phenomenological approach and lack logic and order. Several had difficulties in repeating experiments that resulted in good material samples.	E3) To observe the exploration in more detail in the following trial in order to specify direction for how the exploration should be done.	E4) Which specific approaches to the exploration of materials could be beneficial to the process?
	Evaluation	F1) The evaluation criteria and procedure is too loosely defined.	F2) The evaluation criteria for the results must be defined according to the objective of the research. In this way it will be possible to achieve data that can be used in the development of the process. The evaluation procedure would be more objective if it includes opinions from other professionals.	F3) Evaluation criteria is set according to the objective of the research and the brief* defined by Nike. The products will be analysed according to principles of LCA and Nike's tool 'Making', that provides data on different materials Nike uses in their production.	F4) Is it possible to measure and make a comparative analysis of the results?
2	**Raw materials**	A5) The materials used were, in general, standard commercially available materials.	A6) Nearly all materials were standard materials bought by the yard and the majority of participants chose traditional methods of fabrication. This 'default' could be a result of the free choice of materials and participants therefore choosing what they know or it could also be a result of the evaluation method (they chose materials that were represented with data in the evaluation tool).	A7) Restrictions to the raw materials that can be used in the process should be made in teaching situations to ensure material exploration.	A8) What happens if there are 5 pre-chosen suitable*** materials from which the participants have to chose?
	Usability	B5) The participants delivered products according to the brief, but the process has mostly been used as an add-on for inspiration.	B6) There are various interconnected reasons for the results (See A6). But it appears that if the process does not give specific step by step directions, the participants will by default follow a form-driven design process to meet the design brief.	B7) Specific directions for the material exploration are introduced (5.2.6 and 5.3.1). Decision to wait to repeat B4 until the process is better defined.	
	Student Educational environment >< Expert Professional environment	C5) Expert designers gave valuable guidance and feedback to the participants and their involvement worked as a motivational factor. In the development of the process they acted as a sounding board representing the industry.	C6) If the expert designers are not experts on material driven design for sustainability or at least have very specific direction on how to use the process, it is not necessarily beneficial for the development of the process that they guide the participants. Collaboration that can provide technological expertise and more advanced equipment could perhaps be useful at this point.	C7) The process needs to be defined in detail and written down step by step before expert designers are involved again. Collaboration with the Danish Technological Institute is established to provide access to technological expertise and collaboration with the Biomimicry Institute is set up. (See D6)	
	Sustainability	D5) The circularity check did ensure compatibility with a circular economy for the raw materials used. But not in the final results. The results are, in general, based on traditional manufacturing techniques.	D6) Circularity is important throughout the process. The typical error appeared in in assembling.There is little literature providing good guidance on how to design products for a circular economy. Biomimicry is being considered as a tool to meet this demand.The process should question labour intensive production methods and aim for the simplest path from raw materials to the end product.	D7) Design for disassembly is introduced in Material manipulation (5.3.1) and 'Handmade for digital manufacturing' (5.4.2) is introduced in product development.	

	Approach	E5) Trial number 2 drifted too far away from material driven design to substract valuable findings regarding approaches.	E6) This could partly be a result of the facts mentioned in A6 and B6, but it could also be a result of not being explicit about the approach to material exploration. The approaches need to be explicit. The trials consist of a series of experiments. Some of these should be designerly and open, but some must also be set up in a systematic way to test a specific hypothesis.	E7) Specific direction on how to use both a phenomenological and a scientific approach for the exploration is established. Furthermore lab journals with requirements for recording everything are handed out.	E8) How will specific guidance on the approach to material exploration and development affect the results? Can Biomimicry be used as an approach? (See D6 and C7)
	Evaluation	F5) All participants chose materials with data available in Nike's 'Making' tool. In this way, it was possible to measure and compare to a certain degree.	F6) The data provided by the tool can only be used as an indicator because the data is based on Nike's providers and not the material sourced by the students. Both the tool and using a LCA in the evaluation to some degree pushes the focus to finding measurable data. In the end, much of the data must be based on assumptions.	F7) An initial set of guidelines based on the circular economy and the principles of LCA are set up as parameters for evaluation.	

Design Trial	**Main theme**	**Findings**	**Reflection**	**Action**	**Question**
3	**Raw materials**	A8) By choosing a limited number of suitable materials, it was possible to compare different results made from the same material.	A9) Seeing the same materials manipulated and used in different designs is valuable for understanding the potential of different raw materials. Several companies in the industry produce biomass materials that are considered waste at present. The companies that provided materials for the trial showed an interest in the possibility of turning these in to new materials and products. (See A14) Choosing a limited number of materials saves time and ensures suitability to the process, but the participants also lose the discovery of the amount and variety of materials available.	A10) Material must be locally sourced, considered waste or of very low value at present. All other considerations regarding the choice of raw materials must be defined in the initial steps of the process.	A11) How do the actions in the initial part of the process affect compatibility with a circular economy and sustainability in general?
	Usability	B8) All participants have followed the process and all have produced a new material and a product.	B9) Process is defined with more details, specific steps and approaches and is ready to be tested with a company and a design brief again.	B10) Collaboration with Nike is set up again and a new brief**** that specifically mentions material driven design for sustainability is set up.	B11) Is the process sufficiently developed this time to include a specific brief and what happens when the process is used with a design brief?
	Student Educational environment >< Expert Professional environment	C8) The results are of varied quality. After the trial finished, one student continued to work on her material and product with the Danish Technological Institute.	C9) The results reflect participant skill level and knowledge and also, to some degree, the physical installations available for manipulating the materials and producing the prototype.	C10) Design experts are again involved for initial presentation, midway Q&A (webinar) and the final presentation.	
	Sustainability	D8) All products are compatible with a circular economy. The participants have used Biomimicry as an approach to varied degrees.	D9) Biomimicry can be used as an approach. The Asknature.org tool can be useful in some cases.	D10) Biomimicry is included as an approach in the process.	
	Approach	E8) The approaches have ensured rigor and systematisation in the process and gave the participants a language to describe their actions. The quality of the recordings in the lab journals are varied.	E9) These specific approaches might not be necessary for experienced designers.	E10) See D10.	
	Evaluation	F9) Results live up to the guidelines set. Some products are made out materials that are culturally perceived as unappealing and low value.	F10) Aesthetics and perceived value are important aspects for sustainability. A higher degree of understanding of a material's perceived value is necessary.	F11) Requirements about historical and anthropological research is introduced to the process (5.2.4) as well as considerations about value (5.2.5). (See also A11- A14)	F12) (See A11)

Design Trial	**Main theme**	**Findings**	**Reflection**	**Action**	**Question**
4	**Raw materials**	A12) Decisions made in the initial part of the process regarding raw materials are decisive for the end result being compatible with a circular economy and sustainability in general. The materials used are in many cases unusual and processed in novel ways.	A13) A comprehensive initial material research and exploration is vital for the end result.	A14) In addition to the circularity check introduced after trial 1 (5.2.1), 3 different actions have been identified as central in the initial search for raw materials: Researching the source (5.2.2), Composition (5.2.3) and Value (5.2.5). (See also B14)	
	Usability	B12) The process is compatible with a design brief.	B13) The brief frames the different steps in the process and makes it more focused. All steps are carried out according to the functions the end product will have to comply with. This adds direction to the experimentation. The results are the best so far. This could partly be because of the design brief.	B14) To follow up on companies contacting us to get design support in changing their waste into valuable materials and products. The following trial will be based on using the process in this way (see A9). 5 different materials are preselected. The company Aeropowder will participate as collaborating partner providing material.	B15) Can material driven design for sustainability be used to create value out of waste?

	Student Educational environment >< Expert Professional environment	C12) All participants have followed the process and all have produced a new material and a product according to the brief.	C13) Including expert designers from Nike has worked as a motivational factor and provided feedback from professionals.	C14) (See B14)	
	Sustainability	D12) All products are compatible with a circular economy and aesthetics have been improved considerably.	D13) The suitability between the function of a product and the material is to a large degree determining for sustainability. Broader evaluation criteria of the material's characteristics, not just based on sustainability aspects, are necessary.	D14) Assessment sheets are provided to the participants based on the information provided on the materials in the Material Connexion materials library.	D15) How will the assessment sheet affect the material's development?
	Approach	E12) Irrespective of approach, the participants have a tendency to create small, flat material samples.	E12) Flat material samples only inform the designer about limited potential production methods as they do not show how they behave in curves and corners.	E13) A sub-section on '3D sketching' (5.2.2) is introduced in the process.	
	Evaluation	F12) (See also A12) The results are in general better than what has been seen before. Mostly there is good coherence between materials and the function of the product. The results are detailed based on thorough material research. Two products end up being conceptual, with prototypes made in a material merely representing an idea.	F13) The results can be a reflection of the process now being developed in greater detail. Other things that might influence the results can be the brief (See B13) and the influence of the expert designers (C13). Two products end up being conceptual. This is largely due to the limitations of the installations in the workspace.	F14) Restrictions on the material used in the final prototype presented are introduced in the process (5.3.3)	
Design Trial	**Main theme**	**Findings**	**Reflection**		
5	**Raw materials**	A16) (See A8)	A17) The materials for the trial have been selected, to some degree, to suit the physical installations. The potential of the present research program based on design trials in this physical location has been exhausted.		
	Usability	B16) The process can be used to create value out of waste material. Several of the results show how it is possible with relatively simple means to use waste for new materials and products. (Such as ground up chicken feathers used for making egg trays, hemp fibre scrap used for making inlay soles).	B17) Even though the results are mainly positive, they also lack finish, the materials are in some cases not fully developed and the quality of the design is irregular. It is obvious that the participants are students (none from product design and only a few from fashion). As a result they lack skills and knowledge of production methods. The potential of the present research program based on design trials with this category of participants has been exhausted.		
	Student Educational environment >< Expert Professional environment	C16) The process appears to be very challenging for the participants.	C17) (See B17)		
	Sustainability	D16) All products are compatible with a circular economy. The assessment sheet works both as an evaluation tool and as a guide in the material exploration.	D17) The process is suitable for design for a circular economy and sustainability. It can be adjusted to have specific focuses regarding different aspects of sustainability.		
	Approach	E16) The restrictions introduced in F14 limit the materials usable to physical installations available.	E17) Perhaps this restriction should in some cases be optional as it might block innovation.		
	Evaluation	F16) (See D16, and section 3.2 for final evaluation criteria).			

* The brief was to design a product that would fit in to Nike's collection with a focus on aesthetics, performance and sustainability.
** Nike is involved in the initial presentation of the project (physically present), for a midway Q&A session (via webinar) and for the final presentation and evaluation (physically present).
*** Suitable meaning having the potential for being fully biodegraded or recyclable, but also suitable to physical installations and tools available.
**** Use material driven design for sustainability to produce a product for Nike's collection with a focus on aesthetics, performance and sustainability.

Table 2 shows the progress of developing the process of material driven design for sustainability.