Material Driven Design (MDD): *A Method to Design for Material Experiences*

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Materials research constantly offers novel materials as better alternatives to convention. Functional aptness is taken for granted at the first commercial launch of a new material. Nevertheless, this alone may not be enough for its commercial success and widespread use. The 'material' should also elicit meaningful user experiences in and beyond its utilitarian assessment. This requires qualifying the material not only for *what it is*, but also for *what it does*, *what it expresses to us*, *what it elicits from us*, and *what it makes us do*. In search of a proper application through such an understanding, material scientists and industries have reached out to designers to guide the development of materials by experiential goals. However, how to design for experiences with and for a material at hand has been poorly addressed to date. In this article, we propose a method, Material Driven Design (MDD), to facilitate designing for material experiences. After explaining the theoretical foundation of the method, an illustrative case is presented—where 'coffee waste' is the subject of a design effort to conceive a new product concept. Finally, possible research directions are addressed to bring new insights to the effective application of the MDD method to diverse projects.

Keywords – Materials Experience, Experience Design, Materials, Material Driven Design, Designing with Waste.

Relevance to Design Practice – 'Material' has been a central point of research and practice agendas for decades in design. Yet, how to design for material experiences has been poorly addressed to date. The MDD method presented herein aims to support designers in structuring, communicating, and reflecting on their actions in design for material experiences.

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Introduction

'Material' has been a central point of research and practice agendas for decades in product design (Ashby & Johnson, 2009; Manzini, 1986). Most of the seminal works have centralized around how to guide designers in selecting proper materials within the *shape* and *manufacturing process* limitations and/or requirements (Ashby, 1999; Ashby & Cebon, 2007; Mangonon, 1999). More recently, a newly founded research direction that scrutinizes materials' active role in shaping our experiences with products has gained attention among scholars (Ashby & Johnson, 2009; Karana, 2009; Karana, Pedgley, & Rognoli, 2014; Pedgley, 2009; Rognoli & Levi, 2004; van Kesteren, 2008; Zuo, 2010). Many influential studies have been conducted to inform how we sense materials (Fenko, Schifferstein, & Hekkert, 2010; Howes, Wongsriruksa, Laughlin, Witchel, & Miodownik, 2014; Laughlin, 2010; Rognoli, 2010; Sonneveld, 2007; Westeils, Schifferstein, Wouters, & Heylighen, 2013), how we attribute meanings to materials (Karana, 2009), and how materials elicit emotions (Ludden, Schifferstein, & Hekkert, 2008). Nevertheless, how to *design for experiences with and for a particular material at hand* remains poorly understood to date. Before moving forward, let us first explain why such an understanding is needed now at the crossroads of design and materials science.

Materials research constantly evolves to offer novel, superior materials as better alternatives to convention (e.g., bio-based materials, smart materials, recycled and/or recyclable materials, etc.). The adoption of a new material, nevertheless, is characterized by a long gestation period—typically of 20 years and above—between the technical innovation, first commercial application, and widespread uptake of the material (Maine, Probert, & Ashby, 2005). For example, the market diffusion of nitinol shape memory alloys took about three decades from their first introduction in 1962 to the first commercial applications in the medical field in the 1990s (Mohd Jani, Leary, Subic, & Gibson, 2014). Likewise, the production of early bio-plastics such as PLA, which was discovered around 1890, took until the 1960's to take off among packaging industries (Stevens, 2001). Functional aptness is taken for granted at the first commercial launch of a new material—meaning that the 'material' should make sense from the perspective of a performance or utilitarian advantage. Nonetheless, this alone may not be enough for its commercial success and widespread use. A material should also be socially and culturally accepted—or acceptable (Manzini, 1989; Manzini

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& Petrillo, 1991); thus the material should also give sense. In his well-known work, *The Material of Invention*, Manzini (1986) emphasized that new materials were characterized foremost by their functionality. Nevertheless, rather than asking "what is it?" in reference to a newly acquainted material, designers need to ask "what does it do?" The latter question reflects an understanding that a material with its properties, potential applications, and performance affects users and gives rise to unique user experiences. This is acknowledged as one of the powerful strategies to shorten the gestation time of a materials innovation (Ashby & Johnson, 2009; Miodownik & Tempelman, 2014; Wilkes et al., 2015).

In search of a proper application through such an understanding, designers may arrive at an embodiment that as far as possible not only meets the practical demands of the design but also offers *intangible sparks* (Karana, Pedgley, & Rognoli, 2015) that captivate people's appreciation and affect the ultimate experience of a product in and beyond its utilitarian assessment. An iconic example, 'plastics', can help us elaborate on the thinking behind this statement. When plastics first emerged, they stood for cheapness, low quality, and un-authenticity (Sparke, 1990). Their experience was generally unsatisfactory for people (Walker, 1989). Plastics were not brilliant, not heavy, and not as hard as porcelain or iron. One of the most popular strategies adopted by designers seeking to enliven the surface qualities of plastics was to mimic qualities of natural materials such as wood or marble (Dormer, 1990; Meikle, 1997), creating 'faux materials' from plastic. However, this approach did not last for long; plastics were still in need of an identity—a meaningful application which would bring the unique qualities of the material forward and which would elicit positive user experiences.

In the 1950s, Tupperware products introduced plastics as a flexible, lightweight, and soft to the touch material (Clemenshaw, 1989). The application perfectly qualified plastic properties on a functional level (e.g., flexibility, durability, lightness, etc.), but crucially offered a new tactile experience and way of 'closing a lid of a container' through its flexible "burping seal" which distinguished it from competitors. Consequently, Tupperware (at that time based around polyethylene) became associated with 'modern housewives' and the 'modern kitchen'. Without a doubt, the 'material' had been physically and aesthetically manipulated to embody an appropriate application unfolding a *meaningful materials experience* for the end user. That is to say, even though the principle of using materials with superior functionalities or improved environmental credentials for product design is rational, it is users' appreciations of those materials that determine their ultimate commercial success (Ashby & Johnson, 2009; Karana et al., 2014).

By acknowledging the dualist view of product materials—that they are required to contribute to satisfying both functional and *hedonic needs of people* (Hassenzahl, 2010)—it became clear that new materials development and application must necessarily be multidisciplinary. Recognizing this situation, material scientists and industries involved in the development of new materials have reached out to academics and professionals in design, art, architecture, and crafts (Miodownik, 2007). The underlying goal in such consultations and collaborations is to guide the development of materials by both experiential and functional goals (Ball, 1997; Ball, 2001; Miodownik, 2007). Design communities are continually evolving their ability to contribute scientifically to such developments, through improved knowledge and skills in 'understanding', 'interpreting', 'envisioning', and 'designing' for user experiences—where user studies and/or '*design-driven innovation*' strategies (Verganti, 2009) can be a conceptual starting point.

There are many examples in the history of design where designers have been approached by material industries (Manzini, 1986), not only to introduce those companies' materials to societies in an effective way, but also to be inspired by design interventions for the further development and/or modification of those materials. Examples range from materials made of recycled plastics, such as Neolite (Manzini & Petrillo, 1991), to Dupont's highly recognized material Corian® (Dupont, 2007). More recent examples include design interventions for stimulating the commercialization of environmentally sensitive materials as alternatives to petroleum based plastics, e.g., *CorkDesign* (Mestre & Voghtlander, 2013), *Dutch Design Meets Bamboo* (van der Lugt, 2008), *Designing with Bio-Plastics* (Karana & Nijkamp, 2014), *Designing [with] PULP-PLA* (Zeeuw van der Laan, Lindberg, Karana, & Lindström, 2014), and Natural Fibre Composites Design (Taekema, 2011).

The potential for collaboration between the worlds of materials science and design has also been highlighted in recent European projects aiming at the *co-development of semi-developed*

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Anouk Zeeuw van der Laan is an industrial design engineer. She received her BSc and MSc degrees from Delft University of Technology (DUT). In her master's graduation project, in collaboration with Politecnico di Milano, she identified 'coffee waste' as a valuable raw material, and used it as the departure point in the design process. She was nominated for UfD-Royal Haskoning DHV Best Graduate Award (2014). After her graduation in 2013, she worked as a designer and a design researcher for material driven design projects, including a project conducted for Innventia (Sweden), which is a research and development company that works with innovations based on forest raw materials.

smart materials, e.g., DiaBSmart (http://www.diabsmart.eu), DAMADEI (http://www.damadei.eu), and Light.Touch.Matters (http://www.light-touch-matters-project.eu). Common to all, material properties are manipulated and new techniques are explored and applied to ultimately '*tailor materials*' (Lindberg, Hartzén, Wodke, & Lindström, 2013; Lindström, Gamstedt, Barthold, Varna, & Wickholm, 2008) for desired applications.

Coming back to our underlying argument, although the design and material industries are becoming deeply engaged in the creative challenge to achieve material functionality and meaning, there is not a systematic method to date on how to define and design for material experiences when a (new) material is the main point of departure in a design project (i.e., *material driven design*). Most of the works referred to as 'material-driven' in the literature take a particular material as a starting point and explore its technical/engineering properties to embody a product (e.g., Dietz, Guthmanna, & Kortea, 2006; Jordan et al., 2013; Knauer, 2014), or they emphasize hands-on experimentations and prototyping with materials in the design process (van Bezooyen, 2013). We acknowledge these important attempts to bring 'material thinking' to the early steps of design processes and to mobilize unique technical characteristics of materials in the design process. A distinguishing feature of our stance, however, is its *experience-oriented perspective*. We aim to support designers to define and design for meaningful experiences with and for a material at hand, qualifying the material *not only for what it is, but also for what it does* (Manzini, 1986), *what it expresses to us, what it elicits from us* (Karana et al., 2014), and *what it makes us do* (Giaccardi & Karana, 2015).

Accordingly, this article presents a method—*Material Driven Design (MDD)*—to facilitate designing for material experiences when a particular material is the point of departure in the design process. In the following section, we first explain the theoretical foundation of the MDD method. We ground our discussion on many disparate but interconnected sources: existing literature and theories on *materials experience* (Giaccardi & Karana, 2015; Karana et al., 2014; Karana, Hekkert, & Kandachar, 2008); *ingredients of experience design* (Desmet, Hekkert, & Schifferstein, 2011); *methodology for material-centered interaction design research* (Wiberg, 2014); the *material learning* that was carried out at the Bauhaus and *tinkering with materials* in art, craft, and design; and on-going and previously conducted material driven design projects. We then outline the suggested steps of MDD with the help of an illustrative case, for which an environmentally sensitive material, 'coffee waste', is the subject of a design effort to conceive and embody a new product concept. Finally, we reflect upon the conducted steps and discuss future research directions to further develop the proposed method.

Theoretical Foundation

The MDD method is grounded on the following premises, which we elaborate upon through the progression of this paper:

- Whilst product experience may originate from- or be moderated by—a wide variety of sources, one of the prominent sources is the physical reality of a design, i.e., its material(s). Hence, in any (material driven) design project, how materials are expected to shape and affect the overall user experience, i.e., *materials experience* (Karana et al., 2008), should be taken into account.
- Designing with a material entails a thorough understanding of the material in order to discover its unique qualities and constraints in comparison to other materials. This can be achieved through 'tinkering with the material'—a kind of explorative process of creation and evaluation—starting from the first encounter with the material, until its final product embodiment at the end of the process.
- Designing with a particular material in mind requires action steps to be followed that are comparable to a conventional product design process: understanding the domain (i.e., research in the field, benchmarking, market analysis, etc.), creating design requirements and objectives, creating concepts, and selecting and detailing one of the concepts towards product embodiment.
- However, when 'experience' is the expected outcome of a material driven design project, a journey of a designer is established from material properties and experiential qualities to materials experience vision within a wider context (purpose of existence); from materials experience vision to experiential qualities and material properties, and to products. Action steps in this journey are organized around the *main ingredients of experience design processes* (Desmet et al., 2011).

Materials Experience in MDD

The phrase 'materials experience' was first coined by Karana et al. (2008), who defined it as the experiences that people have with, and through, the materials of a product. In its original description, *materials experience* consists of three experiential components: *aesthetic (sensorial) experience* (e.g., we find materials cold, smooth, shiny, etc.), *experience of meaning* (e.g., we think materials are modern, sexy, cozy, etc.), and *emotional experience* (e.g., materials cause us to feel amazed, surprised, bored, etc.). Giaccardi and Karana (2015) extended the original definition of 'materials experience' by adding another experiential component on a *performative level*. They emphasized that a comprehensive definition of 'materials experience' should acknowledge the active role of materials *not only in shaping our internal dialogues with artifacts, but also in shaping ways of doing and practices.* Accordingly, they defined four levels of materials experience as: sensorial, interpretative (meanings), affective (emotions), and performative. Each of these components of materials experience is highly intertwined, subject-, object-, context-, and time-dependent attributes.

A number of scholars showed the possibility of understanding and operationalizing different components of materials experience in a generic manner (e.g., attributing meanings to materials) or a more specific manner (e.g., sound of materials). For example, exploring the effects of material sounds and tastes on users' experiences of products (Howes et al., 2014); emotional bonds with materials for longevity and life long experiences (Chapman, 2014). Pedgley (2014) summarised existing approaches, tools and methods to facilitate the exploration, and application of one or more of the experiential components of materials experience: *Meaning Driven Materials Selection* (Karana, 2009), *Expressive-Sensorial Atlas* (Rognoli, 2010), *Material Perception Tools* (van Kesteren, 2008), and *Material Aesthetic Database* (Zuo, 2010) were listed as examples. These sources are particularly valuable to support designers in understanding the building blocks of materials experience, and to have a more concrete grounding for articulating 'experiential' material requirements and constraints alongside the technical. One of these tools, *Meaning Driven Materials Selection*, will be incorporated in the MDD method.

Meaning Driven Materials Selection builds on a *Meanings of Materials* model (Karana, 2009), which visualizes the dynamic action between a user and a material in materials experience. The model, which is incorporated in the MDD method (see Figure 5 under Step 3 of the MDD method), helps designers visualize the characteristics of a *situational whole* (Karana, 2009) in which materials are experienced. The overall materials experience will be (partly) based on the material's technical and sensorial properties, and is affected by aspects of the product in which the material is embodied. Each main factor (i.e., user, product, material) has a number of aspects (e.g., shape, manufacturing process, gender, expertise, etc.) that can influence how we experience materials. In addition, the context in which the material of the product is appraised may have a considerable effect on materials experience. Taken together, these aspects construct a '*materials experience pattern*' (Giaccardi & Karana, 2015). Designers who can understand these relationships between the user, product, and material within a situational whole, can more deliberately (or systematically) manipulate materials for meaningful experiences.

Understanding The Material in MDD

The relationship between materials (as the matter or substance of things) and experience (as a way to know the world and to enrich knowledge of it) has long been emphasized in pioneering philosophical works. In the field of art, Focillon (1992) and Dewey (1980) emphasized the unique role of 'material engagement' in one's process of thinking and reflecting. Physical encounters with materials (or the aesthetic experiences that derive from hands-on manipulation of materials) can positively influence the creative process. Niedderer (2012) showed how such *practical enquiries*, or *learning by doing*, is mobilized in understanding the relationship between material, process, and form with regard to the creation of elastic movement. Material engagement in craft is a means to logically think, learn, and understand through sensing and immediate experience of materials (Adamson 2007; Ingold, 2013; Nimkulrat, 2012). In his Inaugural Address at Goldsmiths' College, University of London, Professor Martin Woolley (1998) eloquently pointed out that clay on the hands of a potter alternates between being part of the potter, part of the process of crafting a ceramic artefact, and part of the end artefact itself [1]. In other words, materials are 'collaborators' (Rosner, 2012) in the craft process, enabling artisans to construct, enact, and reaffirm their identities (Tung, 2012).

In design, tutors at the Bauhaus were particular advocates of learning about/with materials. Around 1920, Itten formulated his 'theory of contrasts', which became fundamental to his educational approach for the Vorkurs (basic course) at the Bauhaus. Itten asked students to explore sensorial contrasts relevant to materials, such as smooth-rough, soft-hard, and light-heavy. The theory of contrasts gave attention to the 'nature' of materials, having the purpose of showing the essential and diverse characteristics of different matter. Furthermore, these contrasts had to be felt and not just seen. With this approach, Itten's students were able to experience and appreciate the character of materials directly through hands-on exploration (Itten, 1975).

After Itten, Moholoy-Nagy developed a course at the Bauhaus focusing on tactile experience of materials (Wick, 2000). This represented a migration away from the 'school of seeing' towards a greater emphasis on the sense of touch. In order to exercise the tactile experience, Moholoy-Nagy organized tactile tables, wheels, and ribbons onto which materials were arranged according to specific sensorial criteria, usually in the form of two line scales that could be held at the same time, for example, from smooth to rough or from sharp to dull.

Both Itten's and Moholy-Nagy's approaches emphasized the role of sensory encounters and hands-on manipulation in material understanding, whilst promoting design activity oriented to enrich desired experiences in final designs. Many designers in the history of design followed this notion and designed products by tinkering with materials and exploring their diverse texture and finishing possibilities, alongside phenomenological aspects that promoted discussion on the merits (or otherwise) of using particular materials for particular products. Today we still see such an approach in some pioneering designers' works: see for example the works of Tokujin Yoshioka (paper, glass), Piet Hein Eek (scrap wood), Paulo Ulian (marble), and Alberto Meda (carbon-fibre composites). Furthermore, in the field of Human Computer Interaction (HCI), *tinkering with materials* has been emphasized as a central practice within research (Jacobbson, 2013) to produce new knowledge and experience. In HCI, tinkering is to do with crafting interactive artifacts using physical-digital materials (Buxton, 2007; Holmquist, 2012; Löwgren & Stolterman, 2004; Sundström & Höök, 2010; Zimmerman, Forlizzi, & Evenson, 2007).

Today we also encounter several material-consulting companies (e.g., Material Connexion, Materia NL), whose services include access to physical material libraries for the purpose of material browsing and tinkering. Within University College London, the 'Institute of Making' (http://www.instituteofmaking.org.uk/about), provides design students and professionals with a creative environment to explore the technical and sensorial qualities of materials and their inter-relationships to 'making'.

Accordingly, MDD encourages tangible interaction with the material in hand, from the first encounter through to exploring and understanding the material in detail with its unique qualities and limitations. Over time, the designer who takes a MDD 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.

The Process of MDD

Product designers are educated to follow a systematic approach to conceptualize and evaluate ideas and to translate them into functions, forms, and materials embodied in a final design (Cross, 2008; Hubka & Eder, 1992; Pahl & Beitz, 1996; Pugh, 1981; Roozenburg & Eekels, 1995). They make this translation in a sequence of design phases, such as the problem formulation phase (understanding the domain, creating design requirements, and objectives), the conceptual design phase, the embodiment design phase, and the detailed design phase (Cross, 2008). Tung (2012) successfully showed how these design phases are followed in revitalizing a local craft and a material. Accordingly he suggested that first the local settings, products, and the particular material at hand should be understood. Then problems and opportunities are listed and the decision on what to design is taken. In MDD, these design phases are retained. First, the material at hand and the domain are understood to create design requirements and objectives. Existing products, which are made of the same/similar material(s) falling under the same material category, are screened (i.e., material benchmarking). Design objectives and requirements are conceptualized and finally embodied into materials/products.

On the other hand, as explained earlier, a distinguishing feature of our approach is its *experience-oriented perspective*. How can we design for experiences with and for a particular material at hand? Thus, although the main design phases have proved successful in designing with a material at hand, they do not support designers in deciding and designing experiences for the material. Accordingly, grounded on the ingredients of experience design (Desmet et al., 2011), the activities to create design requirements and objectives and conceptualize them for materials experience are gathered under the following main steps in MDD:

- *Understanding the current situation*: how the material at hand is appraised by intended users, how it is experienced on sensorial, interpretative, affective, and performative levels, and how these experiences relate to physical (engineering) properties of the material.
- After analyzing and interpreting the findings, which reveals current positive and negative experiences of the material, the designer *envisions* the design intentions for 'new' materials experience.
- *Manifesting the patterns* to evoke the envisioned materials experience, the designer *creates and materializes* concepts which make the transition from design intention to material/ product design.

In accordance with Wiberg's *methodology for material-centered interaction design research*, the organization of steps should allow a back and forth thinking between '*details*', i.e., material studies focusing on material properties and character, and '*wholeness*', i.e., a way in which the material is approached from the perspective of the user, and appraised within a *composition* (Wiberg, 2014), as well as within *a situational whole* (Karana, 2009). Accordingly, *sense-making* (Wiberg, 2014), which involves reflecting on the *material's purpose within a situational whole* is the consistent objective throughout this journey.

Material Driven Design (MDD) Method

Having worked in the materials and design domain for a considerable time, we have gained experience across a large number of MDD projects including *designing with natural fibre composites* (Lagorio, 2014; Taekema & Karana, 2011), *designing with bio-plastics* (Karana & Nijkamp, 2014), *designing with waste coffee grounds* (Zeeuw van der Laan, 2013), *designing with liquid wood* (Manenti, 2011; Rognoli, Salvia, & Levi. 2011), and *designing with computational composites* (on-going PhD research by Bahareh Barati, TU Delft). Learning from these projects, reviewing advantages and disadvantages of steps in the design process, and drawing upon theoretical foundations introduced in this paper, we developed the Material Driven Design (MDD) Method to facilitate design processes in which materials are the main driver. We envisage three scenarios where designers can apply the MDD Method.

[Scenario 1]

Designing with a relatively well-known material, which will be accompanied by a fully developed sample (e.g., oak, titanium, polystyrene, etc.). Although the material is likely to have some settled meanings in certain contexts (e.g., traditional, cosy, high-tech, etc.), the designer seeks new application areas to evoke new meanings and to elicit unique user experiences.

[Scenario 2]

Designing with a relatively unknown material, which will be accompanied by a fully developed sample (e.g., liquid wood, D3O, thermochromic materials, etc.). The material is unlikely to linked to settled meanings, affording the designer opportunity to define application areas through which unique user experiences, identities for materials, and new meanings may be introduced.

[Scenario 3]

Designing with a *material proposal* with semi-developed or exploratory samples (e.g., food waste composites, living materials made of bacterial cells, 3D printed textiles, flexible OLEDs, etc.). Since the material is semi-developed (i.e., proposal), its properties are to be further defined through the design process in relation to a selected application area, also to generate feedback for further materials development (e.g., elasticity of a food-waste composite, durability of a 3D printed textile, etc.). Furthermore, since the material is novel, it is difficult to recognize and is in need of the designer to propose meaningful applications through which unique user experiences and meanings will be elicited.

Figure 1 illustrates the MDD Method with four main action steps presented in a sequential manner as: (1) Understanding The Material: Technical and Experiential Characterization, (2) Creating Materials Experience Vision, (3) Manifesting Materials Experience Patterns, (4) Designing Material/Product Concepts. As depicted in Figure 1, the MDD process starts with a material (or a material proposal, based on the three possible scenarios previously listed), and ends with a product and/or further developed material. The method emphasises the journey of a designer from tangible to abstract (i.e., from a *material* to a *materials experience vision*, illustrated with dashed lines and lighter colours in the bubble for Step 2), and then from abstract back to tangible (i.e., from a *materials experience vision* to physically manifested, further developed *materials/products*).

The main action steps of the MDD Method will shortly be explained with an illustrative case from one of the authors' previously mentioned materials and design projects (*designing with waste coffee grounds*). Waste coffee grounds are abundant; yearly, about 15 million tonnes of coffee waste is produced. However, the waste material can conceivably be collected from coffee retailers and used as a component for new bio-based materials. *Re-worked*, a UK based company, examined the commercial potential of coffee-based composite materials. The company approached the authors with the following assignment: 'find a meaningful application area for waste-coffee ground composites'.

This illustrative case exemplifies a project falling under Scenario 3, in which the design task is not only to find a proper application for the semi-developed material, but also to further develop the material in the design process. This scenario represents a relatively novel design situation (Barati, Karana, & Hekkert, in press). As also highlighted in recent European projects (e.g., Light.Touch.Matters), we envision this situation will be prevalent in the near future. Thus it was chosen to present our design journey through application of the MDD method.

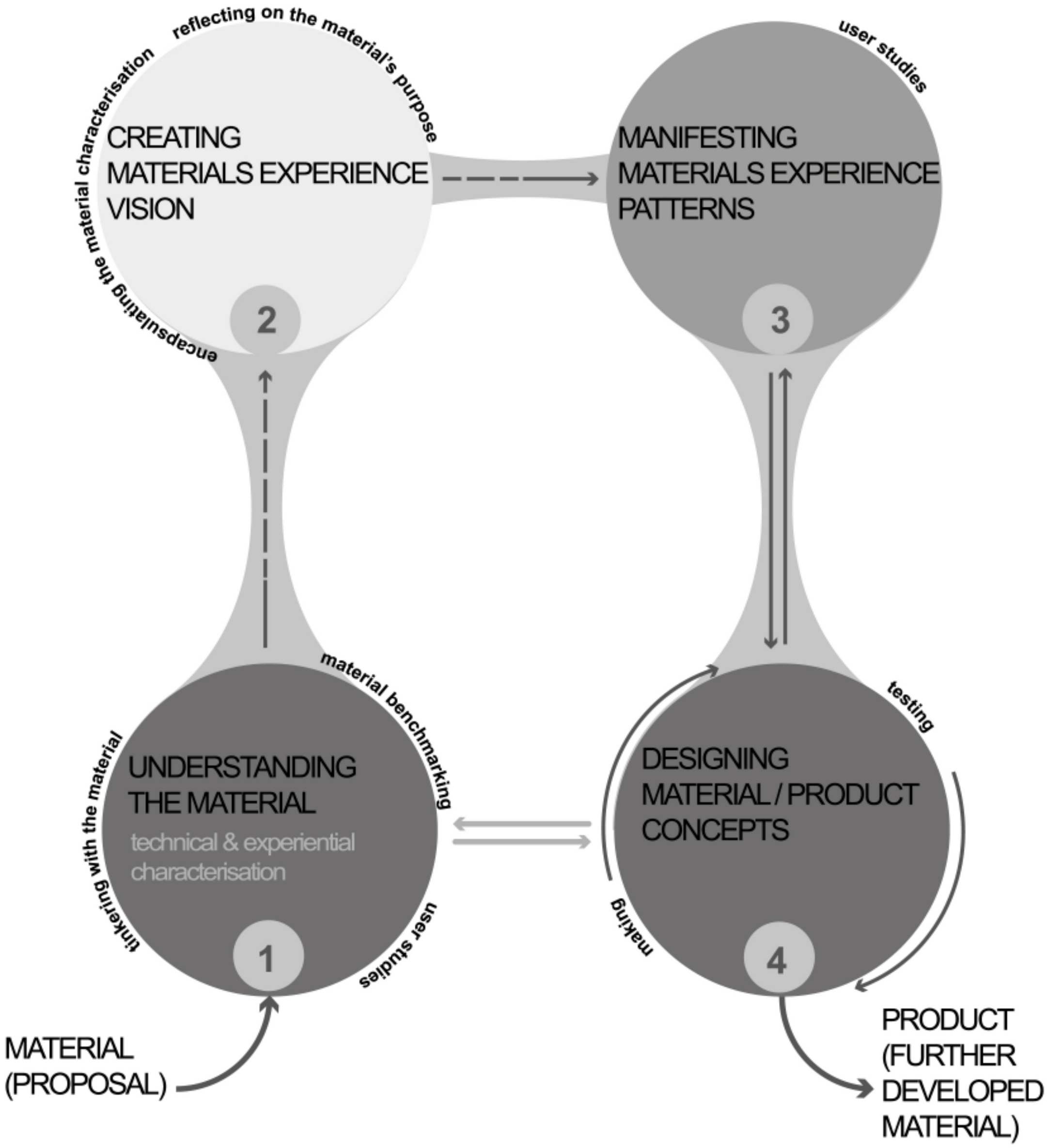

Figure 1. Material Driven Design (MDD) **method.**

[MDD Method Step 1] Understanding The Material: *Technical & Experiential Characterization*

In MDD, a designer is first expected to understand the material in hand and characterize it both technically and experientially, so as to articulate the material's unique role (in contrast to alternative materials) when applied in products. This step includes *tinkering with the material* to get insights on what the material affords, its technical/mechanical properties, as well as how it can be shaped/embodied in products; *material benchmarking* to position the material amongst similar and/or alternative materials, to generate insights on potential application areas, emerging materials experiences and other emerging issues within the design domain; and *user studies* to explore how the material is received by people, how it is appraised (i.e., experiences related to aesthetics, meanings, and emotions), as well as what the material makes people do (Giaccardi & Karana, 2015). It should be recognised that these activities, which will be further described below, are not required to be applied in a sequential manner. Rather, a simultaneous approach is preferred to create synergies and mutual nurturing.

Technical Characterization of the Material

If the material is fully developed, technical datasheets concerning its mechanical and technical properties and possible manufacturing processes to form the material can be easily accessed through material suppliers, or online material databases (e.g., CES, matweb, materia, etc.). On the other hand, if the material is not fully developed, the technical characterization should be achieved through the process of MDD. In either case, i.e., with or without technical datasheets, at this stage the designer is expected to tinker with the material—to cut it, bend it, burn it, smash it, combine it with other materials, etc.—to understand its inherent qualities, its constraints, and its opportunities when applied in products. Technical characterization of materials can also be conducted in cooperation with material labs where materials can be subjected to more stringent tests in controlled conditions. When the technical characterization of the material is completed, the following questions should be answered:

- What are the main technical properties of the material (e.g., its strength, fire resistance, etc.)?
- What are the constraints/opportunities of the material?
- What are the most convenient manufacturing processes to form the material?
- What about other manufacturing processes? How does the material behave when subjected to other processes?

It is expected that by the end of technical characterization the designer will have a clear understanding of the engineering (i.e., technical/functional and manufacturing process related) limitations of the material, as well as its unique technical properties to be harnessed in the final design.

Important lessons that we learned during the technical characterization of waste coffee grounds were that the particles in general decreased the strength of the created composite material. The particles were found to be most suited to creating bulk materials. We also learned that waste coffee grounds can be used as nutrient for plants, and that coffee particles do not set on fire but instead smoulder. How the resulting composite material will be produced depends mainly on the matrix material (e.g., PLA, latex, ABS), but because the particles are relatively small, they are not expected to constrain production processes. In Figure 2 the designer's 'tinkering activities' for technical characterization of the material are presented.

Experiential Characterization of the Material

In the experiential characterization of the material, first we recommend the designer should reflect on the experiential qualities of the material on four different experiential levels: *sensorial*, *interpretive* (meanings), *affective* (emotions), and *performative* (actions, performances) (Giaccardi & Karana, 2015). Then, he/she should delve into understanding how the material is received by people, again by using the four experiential levels as a foundational structure. For example, reactions may be recorded such as 'wow' (affective), 'it is strange' (interpretive), 'it is very soft' (sensorial), as well as observations that people may tweak the material, pat it, smell it, etc. (performative). Designers should tinker with the material to create samples of varying form (e.g., rounded, amorphous) and sensorial qualities (e.g., rough, elastic), and to collect substitute materials (in case of a not fully developed material) which would potentially elicit contrasting or complementary experiences in any or all of the four experiential

Figure 2. Tinkering with the material: varying the amount of coffee grounds in different samples to be subjected to mechanical tests (left and middle)**; fire resistance test** (right).

levels. These activities would support the designer in seeing interrelationships between intended or observed experiences and the formal properties of the material. Focus groups, online questionnaires, and interviews can be conducted in such experiential studies, from which the designer will seek answers to the following questions:

- What are the unique sensorial qualities of the material?
- What are the most and the least pleasing sensorial qualities of the material (according to users)?
- Is the material associated with any other material due to its similar aesthetics?
- How do people describe this material? What kind of meanings does it evoke?
- Does it elicit any particular emotions—such as surprise, love, hate, fear, relaxation, etc.?
- How do people interact and behave with the material?

To facilitate this process, we suggest constructing a mind-map to present an overview of the findings. Traditionally this can help the designer to discover underlying motivations of designing or using a material (or its components if it is a composite material) across a variety of forms, products and contexts. A mind-map can also effectively depict interrelationships between detected performances, meanings, emotions, and sensorial qualities. Consequently, the designer can make decisions on, for instance, aiming to retain a settled meaning of the material, or aiming to generate novel meanings in an end (product) application. The implication here is that material properties, which evoke or are particularly associated with a settled meaning, should be either kept or modified in the final design.

For the waste coffee grounds project, to explore what people did when they interacted with the material, and how they went about appraising the material, several material samples having varied aesthetic qualities were collected and used in focus group studies and interviews. The pre-settled meanings 'environmental friendly' and 'natural' were detected. Colours and scent were found as two important sensorial qualities of the material to elicit these meanings, as well as to communicate the origin of the material. We found that imperfect surface qualities of the material were embraced, as typified by one of the focus group participants: "they enhance the naturalness of the material and create authentic patterns." Furthermore, people wanted to touch and smell the samples with rough and imperfect surfaces, which were associated with 'nature and soil'. After learning the main material component, people were generally surprised, particularly in relation to the more homogeneous samples. Even though the material is a waste material, it did not recall negative associations such as 'low-quality'.

During experiential characterization of the material, the designer is also expected to position the material within a group of similar materials and their applications (i.e., material benchmarking) by delving into literature, design magazines, material websites, etc. The aim of this step is to map the potential application areas (by also reflecting back to the required technical specifications of the material for these areas), as well as to understand what kind of experiential issues are emphasized in the domain that the material is positioned, and what experiential qualities of the material can be observed or emphasized in the descriptions of other applications. Next to that, the material benchmarking is expected to reveal other issues, strategies, or values increasingly emphasized within the design domain in the last decades (e.g., design for sustainability, cradle to cradle: C2C, slow technology, etc.).

For example, if the material is a food-based composite, other food-based composites and their applications should be explored (see Figure 3 for a short overview of the products screened for the illustrative case). As depicted in the Figure, we found four application areas for food-based composites, which were shortly analysed particularly on the aesthetics (sensorial) level (e.g., scent intensity, visible fibres, etc.), as well as possible experiential issues mentioned in the description of these products (e.g., naturalness, imperfection, authenticity, Wabi-Sabi[2], and Standard Unique[3]), and other issues emphasized within the design domain in relation to the materials (e.g., C2C, local production, design for sustainability).

Note that, having completed the first step and explored what has been done so far and what the material 'is', a designer might already have an idea on a possible application area, where unique technical properties and experiential qualities of a material are incorporated or come forward. He/she may then directly proceed to Step 4, where material/design concepts are created. However, caution should be exercised since moving directly from Step 1 to Step 4 may lead to rather conventional solutions, or a re-design of an existing product, which is acceptable in some circumstances but is not within the spirit of innovation and radical design contribution. When designers (or clients) would prefer to explore the 'unknown', outside of their prior experiences and comfort zone where they can push their creativity towards new applications, then they can proceed to Step 2 of the MDD method. Alternatively, on completion of Step 1, the designer may have become inspired to express particular meanings of the material in the final application (e.g., high-quality, natural, delicate, sportive, etc.). In this case, skipping to Step 3, where the patterns to create these meanings are manifested, is recommended.

[MDD Method Step 2] Creating Materials Experience Vision

We suggest that articulation of the design intention, or as we call it the *Materials Experience Vision*, as an ultimate aim of the design process, can help designers to summarise various findings under a cohesive whole and guide their decisions through the process of design. The Materials Experience Vision expresses how a designer envisions a material's role in creating/contributing to functional superiority (performance) and a unique user experience when embodied in a product, as well as its purpose in relation to other products, people, and a broader context (i.e., society and planet). Designers should reflect on the material concerning people and products (e.g., through benchmarking and user studies) and the broader context (e.g., through literature survey), to explore what has remained constant over time in societies, what has been changing, and what values, meanings or experiences have emerged. These activities can help to recognize a visionary path through the unknown, towards a future application.

	Çurface Re-Worked	MycoBond Ecovative Design	Curran Cellucomp	Coco Dust Kokoboard	Agricola Studio Atupertu	Qmilk Qmilch	Foodscapes whomade.it	Solskin Peels Solskin designs
	Waste coffee composite with added fibres and pigments.	Mycelium packaging that grows on waste food.	Carrot fibres, comparable to carbon fibres.	Coconut fibres with natural adhesive.	Using seasonal food waste in new materials.	Silk-like material from waste milk; naturally anti-bacterial.	Reusing leftovers.	Orange peel natural process of material aging.
Applications								
Decorative	yes	no	no	yes	yes	no	yes	yes
Structural	yes	yes	yes	yes	no	yes	no	no
Packaging	no	yes	no	no	no	no	yes	yes
Food related	yes	yes	no	no	no	no	yes	yes
Experiential qualities & emerging experiential issues								
Natural colour	revealed	revealed	recovered	revealed	revealed	recovered	revealed	revealed
Imperfections	medium	high	no	high	high	no	high	high
Roughness	medium	high	no	high	high	no	medium	high
Scent intensity	low	low	neutral	medium	low	neutral	neutral	high
Visble fibres	high	high	none	high	high	none	high	high
Wabi Sabi	weak	weak	no	strong	strong	no	medium	strong
Standard Unique	yes	yes	no	yes	yes	no	yes	yes
Temporal (change over time)	yes - in time	yes - rapidly	no	yes	yes	no	yes	yes
Authenticity	high	high	low	high	high	low	high	very high
Naturalness	high	high	no	high	high	no	high	high
Other emerging issues in design	Local resources.	Cradle2cradle; Waste equals food.	High-performance but lower footprint.	Alternative to wood.	Local resources; Degrades after 10 years.	Waste equals food.	Cradle2cradle; Waste equals food.	Local resources.

Figure 3. Material Benchmarking for food-based composites.

Accordingly, in Step 2 of the MDD Method, first the designer is expected to encapsulate and reflect on the overall material characterization. The questions to be answered in the creation of the Materials Experience Vision can be listed as follows:

- What are its unique technical/experiential qualities to be emphasized in the final application?
- In which contexts would the material make a positive difference?
- How would people interact with the material within a particular context?
- What would the material's unique contribution be?
- How would it be sensed and interpreted (sensorial and interpretive levels)?
- What would it elicit from people (affective level)? Would it, for instance, contribute to the fulfillment of a hedonic need (Hassenzahl, 2010, e.g., feeling related, feeling stimulated, etc.)?
- What would it make people do (performative level)?
- What would be the material's role in a broader context (i.e., society, planet)?

Answering these questions, the designer can construct the Materials Experience Vision, which may accommodate various statements that could be interpretative (e.g., the material will express naturalness), affective (e.g., the material will surprise people), or performative (e.g., the material will require delicate use). In addition, the unique role and purpose of the material within a broader context may be defined (e.g., the material will make people aware of their consumption patterns; the material will make people to appreciate products made of 'waste' materials, etc.).

We mapped all our findings from the material characterization of the coffee grounds to encapsulate a vision for coffee waste composites. Foremost was the use of 'otherwise' waste material being transferred to a 100% bio-degradable material, as a replacement for throwaway 'petroleum based materials'. The intention was to make a solid contribution to environmental sustainability (i.e., impacts on the planet). Next to that, being different than other food-based materials, a coffee waste composite would also be food for plants, corresponding with the Cradle to Cradle (C2C) principle of "waste = food" (McDonough & Braungart, 2002), since coffee grounds are a very good fertilizer and might be used to change people's pre-judgments about waste materials. Nevertheless, it cannot be used as a structural material for high performance products as coffee particles reduce strength of the composite material. Its unique aesthetic quality is its imperfect surface qualities (i.e., its Wabi Sabi aesthetics), which can be embraced to allow unique products to be produced, even under mass production facilities. This aspect is important, because it has potential to elicit personalized materials experiences (Karana et al., 2015), which fulfill a hedonic need by making oneself feel special through possession of a unique personal belonging. The material's unique imperfect surface qualities and associations with nature can also impart high-level values to reinforce appreciation of 'waste'. The ultimate Materials Experience Vision can be formulated as: the final material application will change people's approach to a waste material through the material's unique inherent quality as a 'fertilizer' and its potential to possess imperfect surface qualities, even though it is mass produced. It will ultimately express naturalness, uniqueness, and be a personalized material.

When the designer desires to go beyond initial findings, dig deeper to unfold the 'un-seen', and elaborate on how the user-product interaction would be (if there is no strict time concerns in a project), then he/she can progress to a supplementary step. Vision in Product Design (ViP), developed by Hekkert and van Dijk (2011), is one possible method to support a designer wishing to take such a journey. In ViP, within a set domain, findings are clustered so that they form unique and original insights. Structuring the clusters reveals coherence and focus, and ultimately leads to a vision statement, from which a user-product interaction is defined. The designer may ultimately use anecdotes, metaphors, or mood-boards to communicate the intended vision.

We clustered and structured our findings so that we could show how they complemented or challenged each other, and how together they formed new and original insights relevant to the application context (see Appendix 1). From that, our final vision statement was: 'I want people to desire to experience the material and be captivated in the course of emotional bonding with the material, like a tempting exposure in a cathedral'. The metaphor illustrates both desire and captivation. Tourists are eager to see what is happening: they desire to see what they are there for. The captivation is found in their mass-presence and lack of sight but persistence to witness the event.

Up to this point, possible end users of the material (or materialized products) have only been involved in the MDD process to understand how they appraise the material (Step 1, user studies). Now that the designer has a new Materials Experience Vision, they should understand the commonalities and contradictions among end users with respect to intended materials experiences and material qualities. To illustrate this in the next step, we continue with our materials experience vision created through the application of the ViP method.

[MDD Method Step 3] Manifesting Materials Experience Patterns

In Step 2, the Materials Experience Vision—including a metaphor showing the aimed interaction between the user and the material—was created. The designer was guided to analyse and cluster the results from the material characterization, reflect upon the material's purpose, and finally used his/her intuition and creativity to generate a vision statement. In order to decide on the formal qualities of the application and provide feedback for the further development of the material (if needed), now the questions to be answered are what are the interrelationships between the created materials experience vision and the formal qualities of materials and products? What are the characteristics of a situational whole when the aimed materials experience vision is elicited? That is, how can materials experience patterns be manifested? (Giaccardi & Karana, 2015; Karana, 2009). The designer, at this stage, is expected to understand how/when other people experience or interact with materials in a way he/she envisions, rather than using intuitions and guesstimates on possible experiences and interactions.

Nevertheless, it can be difficult to link a created vision to formal qualities of new materials and products. Therefore, herein first the vision and the interaction is further analysed to obtain 'meanings' (such as feminine, familiar, high-tech, etc., under the interpretative level of materials experience), which can be more easily operationalized in user studies (Karana, 2009). For example, relating certain material properties to the meaning high-tech would be much easier than detecting material properties that make people desire to experience a material.[4]

Accordingly, we first distilled two meanings from the created vision to be further explored. In order to do that, we sought examples of the envisioned interaction (including tempting exposure and emotional bonding) from daily life, existing products, and existing materials. In a brainstorming session, we identified two meanings that evoke the aimed interaction as 'modest' (i.e., in relation to those things that create an emotional bonding across a longer time span) and 'provocative' (i.e., in relation to those things that will entice or provoke interaction, like a tempting exposure in a cathedral).

In order to find patterns to evoke the aimed meanings, another supportive method, the *Meaning Driven Materials Selection (MDMS)*, is incorporated in MDD. Developed by Karana (Karana & Hekkert, 2010), the method familiarises the designer with key aspects (such as shape, user, manufacturing processes, etc.) playing an important role in attributing meanings to materials (e.g., a material might be appraised as cheap because of its transparency or easily stretchable surface qualities, and its sharp-edged shape). Most importantly, the method supports the designer in understanding other people's understanding of preferential meanings. In MDMS, a group of people are approached to participate in a study where they are given the following three tasks: (1) select a material that you think is 'X' (such as high-quality, feminine, modern, etc.), (2) provide a picture of the material (embodied in a product) you selected, and (3) explain your choice and evaluate the material against a set of specially devised sensorial scales[5]. The results are evaluated both qualitatively (by analyzing the provided images and descriptions from the participants) and quantitatively (by performing a statistical analysis of sensorial scale ratings).

At the end of this phase, the designer is expected to summarise the findings of the study, to use his/her own intuition to interpret the findings, and formulate the relationships between the formal properties of materials/products and the explored meanings. He/she can also find other meanings/values/associations, which are stated by participants to describe the explored meanings. In order to illustrate the overall findings as a cohesive whole, the designer can benefit from the Meanings of Materials Model (Karana, 2009). With the presented visualisation of the data set, the designer is expected to draw his/her own conclusions, which he/she thinks relate to the attribution of the intended meanings to materials.

We used The Meanings of Materials Model to visualize data sets for the meanings 'modest' (Figure 4, above) and 'provocative' (Figure 4, below) as '*materials experience patterns*'. The results of the MDMS study for the waste coffee grounds project, as *collages of materials (embodied in objects)* selected by users and *results from sensorial scale gradings* are presented in Appendix 2.

Our interpretation of the patterns and our material/design decisions are as follows: 'Modest' materials are often derived from nature and widely accessible/available for use. The materials are easy to manipulate. Colours are neutral and sober and imperfect patterns are embraced. Products embodied with the selected materials have functions such as protecting or covering. The materials are cheap. Respondents mentioned the openness or honesty of the materials and described modest materials as common. Modest materials are opaque, non-reflective, and warm. 'Provocative' materials collected by respondents were high-performance materials. The raw material usually undergoes extensive processes to reach its final state. Touch is very important for provocative materials: textures and finishes are used to invite touching, and products embodying the materials are often used close to the skin. There is a sense of mystery or hidden messages with provocative materials, which makes them exciting to interact with. Provocative materials are strong, opaque, and glossy.

As seen above, the aspects eliciting the two meanings 'modest' and 'provocative' turned out to be contradicting, but there were also opportunities found where they enhanced each other and elicited the intended interaction of tempting exposure. For example, the appearance of both provocative materials and modest materials is opaque, with grey and sober tones. Modest materials are often imperfect and related to nature, which matches well with the main component of waste coffee grounds. Provocative materials, however, are reflective and shiny, which could be engineered to some extent by using special finishes or adhesives.

Another finding was that the modest materials gathered through MDMS were usually embodied in products that are used for the purpose of protecting or storing other products (e.g., iPhone case, protective packaging, etc.), while provocative materials were embodied in products necessitating high mechanical performance. However, during technical characterization, waste coffee grounds

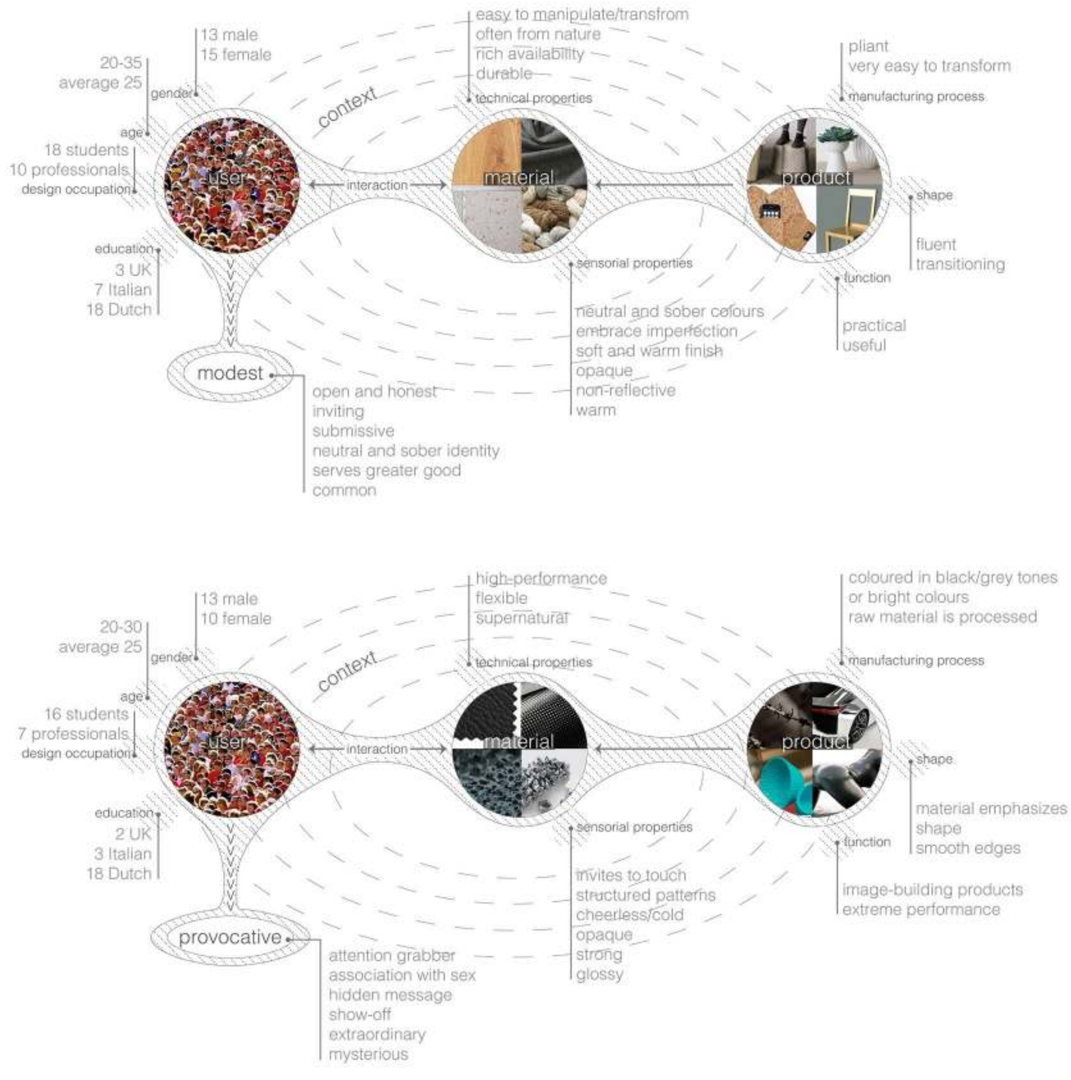

Figure 4. Visualisation of 'modest' (above) **and 'provocative'** (below) **data sets as 'materials experience patterns' based on The Meanings of Materials Model** (Karana, 2009)**.**

were found to decrease the performance of the overall composite material; therefore it is not probable that a 'high-performance' application for the material would result in success. On the other hand, we concluded that both modest and provocative materials could be tempting for physical interaction when imperfect surface qualities were kept, which would create a rather mysterious texture, holding a hidden message to be explored or revealed by the user.

[MDD Method Step 4]
Creating Material/Product Concepts

Herein Stage 4, the designer integrates all his/her main findings into a design phase. It may not commence exclusively here; for example, even after just Step 1, the designer might already have an idea for an application (product) domain. In such cases, material considerations and product concept creation go hand in hand, and the material is shaped accordingly. Alternatively, if at the arrival at Step 4 no product idea has been contemplated, the designer now starts to make material concepts incorporating results from Step 3 and his/her experience through tinkering with the material gained from Step 1. In both cases, the performance of the concepts with greatest potential is tested through mechanical tests in a number of iterations, whilst the material experiential qualities are evaluated through interviews and focus group studies, etc.

Note that, in the material concept creation, if the material is fully developed (reflecting previously mentioned Scenarios 1 and 2), the opportunity for the designer is mainly to manipulate sensorial qualities. This can be achieved by applying different surface treatments, different forms, and experimenting with different manufacturing possibilities. In Scenario 3, the designer might have a semi-developed material in hand, or for example a composite material for which one of the components is still open to development and improvement (e.g., waste coffee grounds, computational composites). From any of these starting points, the designer uses the material's core idea as it is (e.g., making a composite out of coffee waste), but manipulates the components of the composite material to find optimal combinations, particularly using the results from the material experience patterns. He/she tinkers with the material, plays with its structure by using different resins for binding the coffee grounds (i.e., leading to property changes such as more/less flexible, more/less transparent, more/less rough, etc.) to reach the aesthetic (sensorial) qualities associated with the intended Materials Experience Vision, as revealed in Step 3.

In Scenario 3, a specific challenge can be faced by designers if the material is a smart composite. In such cases, the designer might not be able to create the ultimate material, but create or find different material samples to exemplify or mimic the sensorial qualities, or physical behaviour of the material envisioned. Then the designer can use these similar materials, or their modified versions, to test and verify the concepts in mind and to facilitate the material development by communicating with material engineers. At the end of this step, the created material concepts are analysed and the most promising and diverse materials are selected to be used in the product concept creation.

Accordingly, we created several material samples by incorporating the Step 3 results, combined with our know-how from initial tinkering activities (see Figure 5, our material creation environment). Finally, three promising samples that differed from each other with regard to technical properties and experiential qualities—which all aimed to deliver a comparable materials experience—were selected to be used in the product concept creation: CapPurcino (left), Cofflexi (right), and Café Maché (above) (Figure 6).

The process of arriving at a product concept is shortly presented below.

We conducted a creative session with 50 Master's level design students at Politecnico di Milano, Italy. In groups of two or three, the students were given a material package including (Figure 7):

- One of the material concepts as a physical sample
- Technical data-sheet about the given material concept
- Materials Experience Patterns for 'provocative' and 'modest'

The students were asked to design a product with the given material concept by using the given technical data sheet and materials experience patterns; thus the ultimate product was expected to express the meanings 'provocative' and 'modest'. In total, five product ideas for each material concept were created. Some of the ideas were for products concerning a 'coffee ritual' (i.e., drinking or making). In most cases, there existed a strong link to nature. The aesthetics of the material, such as its dark brown colour, imperfect patterns, and texturization, were used to

Figure 5. Our material creation environment.

emphasize and enhance this link. Surprisingly, several gardening products were developed for all three material concepts (see Figure 8 for two of the created ideas).

We further analysed the ideas against their fit to the intended Materials Experience Vision; their feasibility (for cost and production); and their technical performance (whether the material can fulfill the required function). As a result, Cofflexi was found to be the least sustainable and feasible, due to excessive production processes, even though it was considered the most provocative and modest. The most successful concept was found to be Café Maché, especially considering the rapid transformation that the material can undergo. CapPurcino was also a good fit to the vision and had the most promising commercial potential.

Accordingly, we developed our final product concept using two of the material concepts (Zeeuw van der Laan, 2013). It is a set to grow greens at home, Cof2Grow (Figure 9). Café Maché was

Figure 6. Three selected samples to be used in the product concept creation: CapPurcino (below left)**, Cofflexi** (below right)**, and Café Maché** (above)**.**

Figure 7. The material package used in the creative session.

Figure 8. Two of the created ideas of the creative session.

used for the packaging as well as a nutrient for tablets that contain seeds of preferred greens. The seeds sprout rapidly after adding water and the coffee grounds provide nutrients. The material changes quickly due to the growth inside, and after the seeds are fully grown and consumed, the entire tablet can be disposed of as organic waste. The tablets come with a pot that is made from CapPurcino, which can be reused. Taking into account the natural course of maturing of the material, it will change over time slowly due to the influence of UV and touch. Anticipating the process of curing the material, the pots are designed to have unique design features (e.g., different textures, different colour tones, etc.) for each cast. The product concept was carried to the next step to be tested in the lab and in the field, before final embodiment and detailing were completed.

Figure 9. Final product concept 'Cof2Grow' (right) **consisting of a tablet made of Café Maché, which contains seeds of preferred greens** (left above)**; a pot made of CapPurcino, which will change over time slowly due to the influence of UV and touch** (left below)**.**

In the MDD Method, we particularly emphasize that a selected concept should be prototyped with the final material choice and tested not only under controlled conditions (e.g., mechanical tests, user perception tests, etc.) but also in the field (e.g., putting the concept within its actual context, observing peoples' reactions, interviewing end users, etc.). It is expected that the designer will refer back to the initial material characterization as a reminder about where he/she started and what was aimed and envisioned for the material. The measure of success at this stage is related to confidence—the material and its embodied concept should demonstrate all the qualities intended of it, at which stage there is a 'green light' to progress to final development and embodiment in a final product.

In our final product concept, the selected materials were subjected to more in-depth technical tests. For the pot, we required several attempts to find a suitable component-ratio that resulted in correct sensorial qualities and sufficient mould fill. Sprouting seeds from the Café Maché tablets was a process of trial and error, to be further explored in the final embodiment and, ultimately, marketed product. Our reflection on the final experiential qualities of the material/product was as follows:

- Placing Cof2Grow under daylight will increase UV damage and transform material aesthetics; revealing hidden messages and a process of creating captivating patterns (link to 'provocative').
- Using the natural curing process of CapPurcino and insufficient mould-fill creates modest imperfect edges for each pot—this brings authenticity and an invitation to be touched.
- Sprouting the tablets deforms and darkens the Café Maché; a provocation and a captivating process that 'the user' wants the tablets to survive (after being deformed/sprouted).

Discussion

This paper has presented a method for *Material Driven Design (MDD)*, which aims to support designers to gain competences in exploring, understanding, defining and mobilizing unique material properties (as such that it will make sense), and experiential qualities (as such that it will give sense) in design. It is important to emphasize that the MDD method has been rationalized from our observations through a number of material driven design cases and supported by theory with the purpose of helping designers to see the structure of the activity, so that they can extend their capabilities, communicate, or reflect on their own or other's actions [see Daalhuizen (2014) for Method Usage in Design]. The success of the method should therefore be scrutinized based on how it eases one's process of structuring and organizing his/her ideas and on how one understands an unfamiliar situation when the process is completed; rather than on concrete end results (Daalhuizen, 2014).

In this paper, we showed how the MDD method has proved successful in a particular project focusing on 'designing with waste coffee grounds'. The MDD method has also been effectively applied to other material driven design projects (see for example Lussenburg, van der Velden, Doubrovski, Geraedts, & Karana, 2014; Zeeuw van der Laan, 2014). The method will be further operationalized within dedicated courses on 'materials and design' given by the Faculty of Industrial Design Engineering in Delft University and Technology and The School of Design in Politecnico di Milan. In this way we aim to demonstrate the usability of the method in diverse projects falling under the three different scenarios explained in this paper (i.e., designing with a *well-known material*, a *fully developed new material*, a *semi-developed new material*). These projects will shed light on some material specific challenges, which we did not tackle in the project presented in this paper.

For example, we acknowledge two possible challenges to be faced by designers in designing with semi-developed smart materials. We anticipate that the characterization step of such materials would be rather different from what is discussed in this paper. The reason is that designers' knowledge about the material must be accumulated not through direct benchmarking or tinkering but by making references to other materials or technologies (e.g., existing user interfaces, sensors, etc.). In this paper we have not discussed any tools or strategies that can support designers in exploring and understanding the unknown characteristics of such novel materials.

The second challenge arises from a higher risk of designing a product that can fulfil the functional affordances of a novel smart material (proposal) without creating a real value for people or society. The newness of such materials might give designers the impression that a mere transformation of a new material to any product is of value and might. This can be a dangerous assumption—and could hinder a deeper investigation of the possible impacts of the material on societies, or of how it will be received and experienced by people. In order to create a meaningful application, designers need to move from material characterization to a holistic vision (Step 2 of MDD). They also need to enable unprecedented experiences by crafting the vision into a meaningful application (Steps 3 and 4 of MDD). How these transitions can be facilitated for semi-developed smart materials (or composites) should indeed be further explored, and is the basis of current work (on-going PhD project by Bahareh Barati, TU Delft).

In the illustrative case, we have incorporated two other methods (ViP and MDMS) as sub activities of MDD to help formulate Materials Experience Visions and manifest materials experience patterns. There are many other tools and methods of potential use within MDD that could not be introduced within the scope of this paper. For instance, the *Expressive Sensorial Atlas* by Rognoli (2010) is a useful tool to tinker with materials (for both Step 1 and 4 in MDD), facilitating understanding of sensorial qualities of materials in relation to underlying technical properties and the concept of inter-subjectivity (i.e., to what extent people agree that a material possesses certain sensory qualities). On the other hand, certain aspects of the MDD Method itself should be further refined, whilst additional tools and methods should be further developed to ease the four Steps. For example, developing tools and methods to support designers in tinkering with materials for experiential characterization, and a more refined method to create a Materials Experience Vision will be two crucial subjects for future research.

Informal discussions with potential end users showed that the envisioned materials experience for our final product was realized to a considerable extent. However, it should be recognized that a thorough assessment of the final design concept in an experiential level will require an additional set of studies with end users in the lab and real life contexts. As success of a design method is not judged with a concrete end result, in this paper the detailing of the action Steps and showing how these steps guided the designer through their journey was our primary concern, rather than assessing the final product.

The MDD Method suggests a sequence of steps to be conducted in the design process. However, the nature of a design project (e.g., large or small scale production, time concerns, limited budget, redesign of an existing product, etc.) might alter the way in which the steps are conducted or the depth to which they are explored, or even might result in omission of one or more steps. For example, if a client (i.e., project owner) requires a redesign of their existing product (e.g., coffee machine) made of a new material (e.g., a natural fibre composite), then a designer will have the application in mind from the beginning of the design process, and inevitably will consider the material within its future context throughout the material characterization process. In other words, design requirements that come along with the context of ‘coffee machine’ will be merged and compared with ‘independent’ material qualities and limitations. The designer might also skip Step 2, where the Materials Experience Vision is created, since completing Step 1 he/she might have some ideas on what would like to be expressed (i.e., meanings such as high-quality, natural) with the final material embodiment within the given context. In such cases, a transition directly from Step 1 to Step 3 might be appropriate to find patterns to evoke intended meanings. As explained earlier in the paper, Step 1 of the method may lead to rather conventional solutions as it is grounded on the merits of existing products, materials, etc. It is the designer’s responsibility (and a MDD project requirement) to explore the ‘unknown’ and push creativity towards new material applications for the future.

Finally, as with any proposed method, an effective use of MDD will be seen through enhancements with practice, and use by multiple designers. We are certain that designers will invent their own ways of conducting the steps, add new steps, and use new supportive tools having had some experience of MDD.

Conclusion

This paper has been concerned with how to proceed when a ‘material’ is the explicit point of departure in the design process and ‘experience’ is the expected outcome. We have presented a design method entitled Material Driven Design (MDD), which represents our first attempt to facilitate such projects, considering both technical properties of materials and their experiential qualities in relation to how they are received by users. The method suggests that when a material is the point of departure in the design process, the designer takes a journey from material properties and experiential qualities to materials experience vision, from materials experience vision to experiential qualities and to material properties, and finally to products. Activities to support this journey are organized under four main steps as: (1) Understanding The Material: Technical and Experiential Characterization, (2) Creating Materials Experience Vision, (3) Manifesting Materials Experience Patterns, (4) Designing Material/Product Concepts. The method is explained with an illustrative case on ‘designing with waste coffee grounds’, which ends with the creation of a product concept. The presented case illustrates one of the possible scenarios we envision for MDD projects, where a material is not yet fully developed. Applying the MDD method to projects exemplifying other scenarios will bring new insights and help us to refine the method’s steps to a greater level of detail and application.

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Endnotes

1. Wooley, M. (1998, May 5). Inaugural lecture given. Goldsmiths College, University of London, London, UK.
2. Wabi Sabi is a continuous search for beauty in the truths of the natural world, using nature and its flows and flaws as an inspiration, but without revealing the truths of nature, i.e., keeping its mystery and qualities (Juniper, 2003).
3. Standard Unique is a principle that deliberately embodies imperfections that are a result of production processes, assembly, and/or material properties to have unique objects as an outcome (Rognoli & Karana, 2014).
4. Note that if we had continued with the first vision statement we created before we applied the ViP method, we could proceed with the meanings which we mentioned in the vision statement, such as natural, unique, personal, etc.
5. After conducting a number of studies in recently done PhD research by Karana (2009), a set of sensorial qualities grouped under different sensory modalities was listed and promoted as the qualities that are more commonly used for attributing meanings to materials. See Appendix 2 for the list of sensorial qualities.

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Appendix 1

Clustering and structuring of findings to show how they complemented or challenged each other, and how together they formed new and original insights relevant to the application context. Two axes were identified: the horizontal axis represents the influence of the individual and whether this is intentional or impulsive, whereas the vertical axis describes the relationship between the user and the material. The distinction is between a physical and intangible (sentimental) relationship.

Appendix 2

The results of the MDMS study for the waste coffee grounds project: as *collages of materials (embodied in objects)* selected by users and *results from sensorial scale gradings*.