Design touch matters
Bending and stretching the potentials of smart material composites

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DESIGN TOUCH MATTERS

BENDING AND STRETCHING THE POTENTIALS OF SMART MATERIAL COMPOSITES

Dissertation

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at Delft University of Technology,
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by

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1 Introduction

1.1 Introduction

Ever since the establishment of materials science, the discovery and development of new materials have largely become a scientific activity. Materials testing and mathematical definitions of their properties, such as strength and roughness, provided precise numerical data for the design and engineering of material applications. However, the dominance of science in determining the direction of materials development has also led to undesirable consequences (Miodownik, 2007), one of which is prioritizing technical performance of materials over their non-technical aspects, including their sociocultural meanings (Manzini, 1989), *sensorial-expressive* (Rognoli, Salvia, & Levi, 2004) and *performative* qualities (Giaccardi & Karana, 2015) elicited when we interact with materials in a specific context of use (Karana, 2009). To foster a more encompassing understanding of materials that pays tribute to this *experiential* side of materials next to their technical performance, collaborations between materials science, art, and design communities have escalated over the last decades (e.g., Colette, 2017; Lefteri, 2012; Montalti, 2017; Nimkulrat, 2009). These so-called 'upstream' collaborative projects strive for changing the dominant schemes of *design being downstream of technology* (Bergström et al., 2010), by involving designers in the early stages of materials development (Mani, Cutcliffe, Penã, & Andersen, 2014; Nathan et al., 2012).

The overarching aim of this PhD research emerged within the context of the EU funded project Light.Touch.Matters (LTM) (2013-2017), which is one such upstream collaborations between designers and materials scientists. The project focused on the development of a particular composition of two smart materials, namely organic light-emitting diodes (OLED) and piezoelectric polymers, i.e., the LTM materials. Smart materials are broadly defined as a group of different materials of which their intrinsic properties change, reversibly, in response to particular stimuli, including mechanical strain, changes in temperature or electromagnetic field (e.g., Addington & Schodek, 2005). In the case of LTM materials, a pressure/deformation sensing component, i.e., piezoelectric polymer, and a light-giving component, i.e., OLED, were envisioned to constitute a single material composite. In line with the incentives for developing thin and integrated composites of smart materials (see McEvoy & Correll, 2015), these flexible and formable composites aimed to provide alternative solutions to the current flat interface technologies (cf. Coelho et al., 2009; Nijholt, Giusti, Minuto, & Marti, 2012).

In this PhD research, we took an interest in 'underdeveloped' state of these smart material composites as well as their dynamic qualities in response to external stimuli, specifically human interaction. Considering the material composition as underdeveloped gives designers higher degrees of freedom concerning the unspecified material properties and experiential qualities. By building tangible representations of the underdeveloped material, designers can contribute to the discussions of the experience and impacts of the smart material, prior to its actual development (Bergström et al., 2010). In addition, the dynamic and responsive properties of smart materials can open up new design spaces, blurring the conceptual boundaries between physical and digital, matter and information, structure and membrane (e.g., Addington & Schodek, 2005; Coelho & Zigelbaum, 2011). For instance, a shape-changing material composite that responds to the humidity of its surroundings becomes both the structural component and the actuator of a building's vent (see Figure 1.1).

We coined the term 'Underdeveloped Smart Material Composites' (USMCs) to make an explicit reference to these two unique aspects of the LTM materials (i.e., their underdeveloped state and their dynamic qualities). This term helped us to organize our research beyond the specific case of the LTM materials. It allowed us to look at a broader range of smart material composites that may serve as a departure point in other material driven design processes. Accordingly, the main research question of this thesis is:

How do designers understand, explore, and unlock the potentials of underdeveloped smart material composites?

Figure 1.1 – HygroSkin- Meteorosensitive Pavilion by Achim Menges in collaboration with Oliver David Krieg and Steffen Reichert.

Based on the assumption that designers can discover new potentials of an underdeveloped material, the PhD research was aimed at understanding ***what material potentials are*** and ***what makes designers unique in unlocking those potentials***. In investigating these unexplored territories, the thesis research capitalizes on the notion of 'materials experience', which takes into account materials' active role in conditioning and influencing our experiences (Karana, 2009), and our ways of doing (Giaccardi & Karana, 2015). Acknowledging that the link between a material and actions *afforded* by it is also influenced by the design process, the thesis extends the notion of materials experience from use-time to design-time. Consequently, this conceptualization helps us to articulate the creative contributions of designers to collaborative materials development in relation to the *discovery of novel affordances*.

1.2 Challenges of Designing with USMCs

Investigating the potentials of novel smart materials and designing with them is known to be a challenge for designers (Schröpfer, Viray, & Carpenter, 2011). Difficulties can stem from the conditions of early material development, such as having no material sample to work with (Bergström et al., 2010) and having no design precedents or body of knowledge regarding the manufacturing and user experience of the new material. Additional technical and methodological challenges are expected when incorporating smart materials in the design process (Bergström et al., 2010; Bohnenberger, 2013). The design approaches that involve materials only in later stages of the design process are not apt for smart materials (e.g., Addington & Schodek, 2005; Bergström et al., 2010; Bohnenberger, 2013). As functional materials that can sense and respond to their environment, smart materials and designing with them demand an understanding of the dynamic relations between material, environment, and design rather early on in the design process (Addington & Schodek, 2005; Bohnenberger, 2013).

In his doctoral thesis, Bohnenberger (2013) motivates new design tools to overcome the difficulties of designing with smart materials, in relation to three main topics: *material thinking*, *material representation*, and *interdisciplinary communication*. The first topic concerns the differences between how materials scientists and designers think about and act upon materials. It is mostly accepted that materials science acts bottom-up, operating at the nano- or micro-level to change the material structure, whereas designers tend to operate at the product-scale and search for suitable materials, i.e., product-oriented approaches (Ashby & Johnson, 2002). In other words, rather than in the material behavior itself, which falls in the interest and expertise area of materials scientists, designers' main interest is in already specified characteristics and existing applications (Addington, 2006). The second topic touches upon a limitation of the static modes of representing materials in terms of their physical properties and functionality. The existing tools and methods, such as visual collage and verbal descriptions are insufficient to capture and communicate the complexity of materials behavior that is dynamic and reactive to its context (Bergström et al., 2010). Material representation becomes a central issue when introducing USMCs to designers in the absence of the actual materials. The final topic takes notice of the distributed knowledge between the fields of design, engineering, and materials science and a need for interdisciplinary communication and exchange. The differences and discrepancies between foci of interest, means of communication and vocabularies, and the knowledge gaps can hamper effective and fluent communication between designers and materials scientists (Ashby & Johnson, 2002).

More recently, there has been an emerging body of research, aiming to understand and mitigate the challenges of upstream collaborative projects. For instance, the studies of Wilkes et al. (2016) and Hornbuckle (2018) highlight the multidisciplinary challenges of collaboration for materials development. To facilitate communication and knowledge transfer between designers and materials scientists, respectively, they emphasize the mediating role of isomorphic material samples, which take a systematic approach to exploring the relationship between the technical properties of materials and the sensorial experiences of their sound, taste, and feel (Wilkes et al., 2016); and material liaisons, who are familiar with both worlds of design and materials science (Hornbuckle, 2018). Taking place in the context of projects with stakeholders distributed across Europe, who gathered up every 2-3 months in a workshop setting, the two studies propose solutions for facilitating interdisciplinary communication of materials.

Other researchers have looked into alternative means of representing smart materials and digital technologies that involve dynamic properties. Sundström et al. (2011), for instance, emphasize the limitations of "black-boxing" technologies when representing them to designers, favoring approaches that expose the technologies' dynamic properties in supporting the collaborative exploration of their design possibilities. Their proposed approach, referred to as *inspirational bits*, is a range of small games or investigations specifically designed to engage all the members of the development team in getting to know the working principles of a technology and its peculiar properties and limitations. Rather than aiming to achieve a final design with the technology, the focus of investigation is to open up to anything different and/or unexpected and inspirational in that technology. Directly related to smart materials, Bohnenberger (2013) shows the relevance of dynamic computational models and simulation tools, developed based on early physical engagement with smart material properties. According to his practice-led studies, a real-time simulation of the material's behavior as a function of its specified structural and environmental parameters can foster a closer discourse between designers and materials experts (Bohnenberger, 2013).

This overview indicates that exploring the potentials of smart materials might be hampered not only by the technical complexities of their dynamic properties and inappropriateness of the product-oriented design approaches, but also by how the transactions between designers and materials scientists are structured, i.e., the organizational structure of the collaborative project. While the abovementioned studies rightfully address the challenges of interdisciplinary communication and representations of smart materials, ***the understanding of what design can actually do for the (further) development of these materials remains uncertain and unexplored to this date***.

1.3 Research Context

The European Union (EU) project Light.Touch.Matters (LTM) provided a research incentive and technological platform for this thesis. However, to provide answers to our main research question and reflect on the designers' role and contribution to collaborative materials development, we made a deliberate choice to bypass the organizational structure of the LTM project and its proposed methodology.

The LTM project was carried out over four years (2013-2017) with an objective to understand and tackle the challenges designers might face in upstream collaborative materials development. To modulate the interactions between materials research and development (R&D), partners, and small and medium-sized design enterprises (SMEs), the project followed a pre-defined methodology. It prescribed three cycles of five sequential activities: "(1) generating scenario of meanings, (2) envisioning promising new experiences, (3) identifying material properties, (4) design concepts and products, and (5) analyze, evaluate and learn" (see the projects official website). Design SMEs were expected to carry out these activities in parallel to materials R&D, with occasional exchanges between the designers and materials scientists through casual meetings and official workshops. In the beginning, only a few laboratory samples of the OLED technology were available and the piezoelectric polymer was still at a concept level. To mitigate that, materials scientists prepared presentations to communicate these underdeveloped materials to the designers. For instance, a schematic structure of the eventual composition was shown to the designers (see Chapter 2, Figure 2.1), complemented with technical performance graphs, high-level descriptions of the physical features (e.g., thin, flexible) and sensing/actuating functions of the eventual composite (e.g., pressure and deformation sensitive).

Grouped under the 'creativity/design-driven' material innovation research theme, the LTM project made an explicit reference to the creative contributions expected from designers. The methodology, however, drew on a generalized outline that designers relied on top-down approaches, such as user and market studies, while materials scientists did the actual development of the materials. Both the organizational structure of the LTM project and its methodology reinforced a traditional understanding of designers' role and their creative contribution, i.e., to 'come up' with application ideas. This understanding resonates with the mainstream creativity literature, where creativity is closely associated with divergent thinking (Guilford, 1950) and having an associative mind (Mednick, 1962), qualities that good designers are expected to show in activities such as idea generation. However, recent creativity theories, such as the work of Glăveanu (2012, 2014, 2015), try to understand creativity from a socio-cultural and developmental psychology perspective, as an action outside of the designer's mind, in interaction with the material, the social situation, and over time. The organizational structure that constraints the designers to top-down approaches in understanding the material potentials, based on descriptions of the USMC and the static representation techniques (e.g., schematic structure) can compromise designers' creative contribution that may well go beyond product application offerings.

The emerging design practices at the intersection of design, materials science, biology, arts, and crafts, however, suggest that designers' creativity does not stay within the application potentials of novel materials. In identifying designers' creative contribution to materials development and exploring how they unlock the undiscovered potentials of USMCs, next to the LTM project design cases, ***we looked into material-driven design situations that involve transdisciplinary material making/developing activities***.

1.4 Material Driven Design: Designer's Shifting Role from Passive Recipient to Active Explorer

Over the past two decades, we have been witnessing a growing number of 'experimentalists' and 'makers' among artists, designers, architects, and engineers with a focal interest in materials fabrication (see Bohnenberger, 2013; Karana et al., 2015; Kolarevic & Klinger, 2008; Kretzer, 2017; Neri, 2010). Fundamental to this ongoing development is a new attitude towards achieving design intent through interrogating materiality (Kolarevic & Klinger, 2008), a return to 'making'; a shift of paradigm towards material driven design approaches (Neri, 2010). In contrast to the largely linear and standardized interface of design and materials in the twentieth century, the new generation of designers favors alternative, non-linear, non-standard design and material practices (Kolarevic & Klinger, 2008), which go beyond selecting materials and/or exploring the application potential of materials.

Material driven design refers to such design processes that depart from the material and follow its specificities, such as the properties and behavior for a design outcome that is informed by the material itself (Bohnenberger, 2013; Karana et al., 2015). In this PhD, we initiated and studied cases of material driven design that followed a systemic, step-wise design method, i.e., Material Driven Design (MDD) method (Karana et al., 2015), with an explicit focus on designing for material experiences. While the design approaches that focus on experience take their departure, typically, from psychological theories (e.g., P. Desmet, Hekkert, & Schifferstein, 2011; Hassenzahl, 2010) or analytical and phenomenological studies of situated experiences (e.g., McCarthy & Wright, 2004), the MDD method takes its departure from materials. The method motivates an understanding of materials as structural and functional building blocks of products, as active collaborators in unfolding our experiences with and through them (Giaccardi & Karana, 2015). By encouraging " ***a sensitivity to flows and transformations of materials***" (Ingold, 2009) ***through materials tinkering and processing***, and ***a simultaneous understanding of the technical and experiential qualities of materials in defining their potentials***, the method opens up novel opportunities for further development of materials.

1.5 Research Approach and the Thesis Structure

This paper-based thesis presents four papers published or in-review/press in peer-reviewed journals and the ACM conference on human factors in computing systems (CHI' 18). In each paper, we employ various design research methods, including design case studies, Research through Design in developing the toolkit, and semi-structured interviews. The first exploratory study focused on the understanding of the new design situation, as experienced in the LTM project **[Chapter 2]**. After this study, which involved a number of design case studies and interviews with the LTM designers, the specific research direction for the following studies was chosen. The key to this research direction was to provide an understanding of the role of material tinkering and fabrication in unlocking novel material potentials, which remains unexplored when USMCs are (only) conveniently represented through fixed physical and functional properties. This research goal required a shift towards 'material driven design', referring to a design situation when a particular material (proposal) is the departure point in the design process (Karana et al., 2015). Thus, a different series of studies were conducted to identify the benefits of having access to the material and

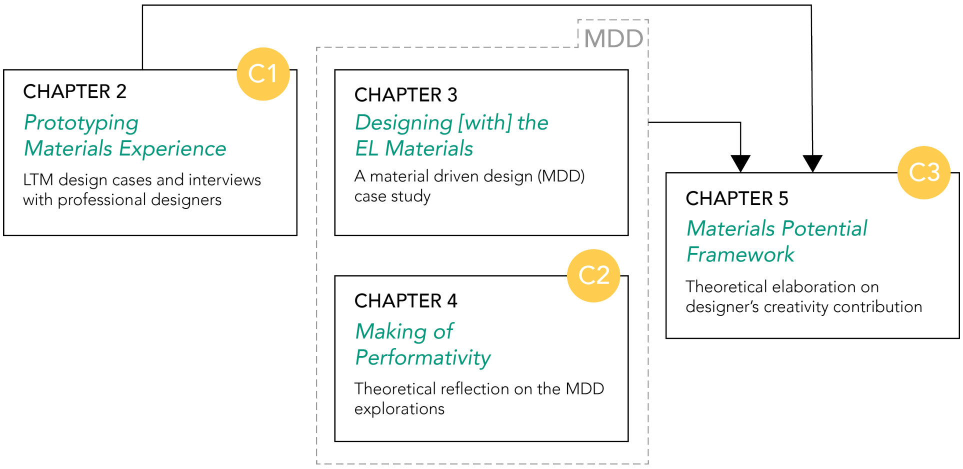


Figure 1.2 – Thesis stucture: outlining the main theme of each chapter in connection to the main constibutions of the thesis (C1, C2, and C3).

tinkering with it in material driven design processes. **Chapter 3** presents one of these design case studies, which focuses on the electroluminescent (EL) materials. Further analysis of the material driven design explorations with the EL material hinted at different strategies that designers relied on to identify the performative character of the EL samples **[Chapter 4]**. A theoretical understanding of how material driven design may expand the existing (product-oriented) conceptualizations of materials potential is presented in **Chapter 5**.

Below I will describe the goals and approach of each chapter in more detail. The four chapters had to be presented in a chronological order, even though each chapter taps into different issues related to the overall research question of this thesis: How do/can designers explore the potentials of underdeveloped smart material composites? Figure 1.2 outlines the structure of this thesis by showing how these four chapters are related. The labels indicate the main contributions of the PhD research, namely the digital tool for materials experience prototyping to explore and communicate the dynamic properties of USMCs (C1), the material driven design strategy for identifying novel action-possibilities (C2), and the conceptual framework of materials potential for articulating and discussing the designer's creative contribution (C3).

CHAPTER 2

This chapter presents two explorative studies with the following objectives: (1) to gain an understanding of the design processes that depart from underdeveloped smart material composites; (2) to understand the challenges that designers face when designing with these materials; (3) to explore the range of tools and techniques designers use to tackle those challenges.

Four master-level design projects were initiated. Students were given a generic design brief to design with the LTM materials, which was similar to the brief professional designers had received in the LTM project. The design activities in between receiving the brief and exhibiting the final prototypes were documented through students' online log, self-report, and the researcher's notes taken in weekly meetings. These included the moments in the process that the application idea was generated and fixed, shifts in design direction and concept development, as well as tools and techniques used and developed throughout the design process. A ***toolkit*** is presented in Chapter 2 that responds to the need for understanding and communicating the dynamic and performative qualities early on in the design process and for collaboratively exploring, identifying, and negotiating the design boundaries. The proposed solution consists of a high-fidelity material demonstrator and a supplementary sketching tool. The former enables the development team members to personally experience a specific fusion of material deformation and computational driven behavior, while the latter allows the designers to assimilate the new material knowledge into product design ideas.

The exploratory studies of the LTM cases further motivated a closer look at the creativity implications of product-oriented design approaches and not having direct material access. These studies are contrasted against material driven design processes. Accordingly, we initiated a number of design cases with electroluminescent (EL) materials, including four master-level group projects and one graduation project. The choice of EL was a middle ground between off-the-shelf LED's and underdeveloped flexible OLED's, providing a possibility for the designers to fabricate the luminescent component directly. It provided a different representation of an underdeveloped composite, which was not a ready-made sample (e.g., LED lamps), nor an abstract description (e.g., flexible OLED), but rather basic ingredients of possible assemblages and making recipes.

CHAPTER 3
We closely observed the activities of the students, who were provided with fabrication lab equipment, basic recipes of printing EL materials, and the support of a materials scientist. The Material Driven Design (MDD) method

guided the students through an early ‘material understanding’ phase. The material understanding phase, as such, concerns an understanding of the matter as a dynamic assemblage, yet to become. The EL design case study presented in Chapter 3 is an exemplar of how a constructive approach can offer new action possibilities that are less likely to surface in mere top-down design approaches. The chapter further elaborates on the role of the MDD method in unlocking and realizing unique material potentials as well as its limitation in dealing with the technical complexity and interactive qualities of smart materials. Leveraging on the process and outcome of the presented material driven design case, the chapter urges for an equal partnership of designers in discovering and defining material potentials and boundaries, enabled by direct (yet technically supported) processes of the underdeveloped smart material composites.

CHAPTER 4
Due to the direct mode of understanding the material, a material driven design process can showcase a broader, possibly more diverse, range of material potentials. Chapter 4 focuses on the fabrication processes of EL material samples and argues that a conceptual articulation of smart materials as underdeveloped composites may unpack new ways of bringing about the performative potential of a smart material and revealing novel affordances. To that aim, the chapter reports on a number of material driven design explorations, which take their departure from unprocessed composites of the electroluminescent material, with a particular focus on the creation of EL material samples with novel action possibilities. It further identifies a design strategy that deliberates over disrupting the light-giving functionality of EL samples at the levels of matter, structure, form, and computation.

CHAPTER 5
Even though these genuine material driven design processes and the discovery of novel potentials through making may not immediately contribute to the situation of designing with the technologies that are not yet available at the scale of human experience, they could provoke useful discussions. Particularly, with the growing interest in upstream collaborative projects between designers and materials scientists, it is crucial to scrutinize the designers’ creative contribution to materials development beyond ’coming up’ with application ideas. The involvement in both material driven design processes and the design situation with the underdeveloped LTM materials gives us a unique position to reflect on the underlying

assumptions about designers' creative contribution and the agency of the material. In material driven design, the designer's creativity is not limited to cognitive processes that rely on mapping the 'given' properties to the existing product applications to inspire, identify, and navigate the potentials (i.e., novel forms, function, and experiences). It also involves discovering novel affordances that could not have been anticipated or intended prior to material engagement. Chapter 5 elaborates on 'why' and 'how' material driven design processes require a new conceptualization of 'materials potential' that considers the process and product as a continuum rather than a means to an end. The notion of 'affordances as materials potential' is accordingly introduced and appropriated for articulation and discussion of the designers' creative contribution that goes beyond the merits of the eventual product applications.

2 Prototyping Materials Experience

Over the past years, product designers have been involved in collaborative developments of smart material composites early on in the development process, to showcase creative applications of them. In these projects, the way the material is presented to the development team and the extent to which its properties are defined affect how designers understand the potentials and boundaries of the material and envision product applications. In the context of a European project, Light.Touch.Matters, we studied the attempt of designers to understand and prototype underdeveloped composites of thin-film organic light-emitting diodes and piezoelectric polymer. Arguing for collaborative exploration of the unique experiences that such underdeveloped composites unfold, we elaborate on a challenge designers face in understanding and prototyping the experiential qualities, specifically, the dynamic and performative qualities. The paper presents our design approach and complementary tools to overcome this challenge. It further discusses the applicability and limitations of the proposed design supports in the context of collaborative materials development and outlines future research directions.

2.1 Introduction

In product design, traditionally, material considerations come at the very end of the design process where designers often act as passive recipients

Chapter 2 is based on: Barati, B., Karana, E., Hekkert, P. (in press). Prototyping materials experience: towards a shared understanding of underdeveloped smart material composites. *International Journal of Design*.

of materials with no big influence on material properties. While this still defines a majority of design projects, over the last decade, we observe an increasing number of projects in which product designers are involved to collaboratively develop new materials (e.g., the European projects Light.Touch.Matters and Solar-Design). These pioneering projects are particularly interesting for the design research community, due to the early influence that design can have on materials properties (Bergström et al., 2010). The contribution of designers to such “upstream” collaborative projects may range from exploring and showcasing the design possibilities of the new materials, to bringing market considerations and consumer perspectives to materials research (Nathan et al., 2012). However, as the materials are far from being integrated into products due to being ‘underdeveloped’, i.e., certain aspects of them including their structure, fabrication, properties, and behavior are either unknown or undefined, understanding them and exploring their potentials and boundaries can be a challenge for designers. Given that the materials information flows between the disciplines of materials science and design, the challenge is as much about how these new underdeveloped materials can and should be communicated to the designers.

In this paper, we focus on the development of smart material composites, which are composite materials that tightly integrate sensing, actuation, communication, and computation (McEvoy & Correll, 2015). Due to their intrinsic physical properties and built-in control mechanisms, smart material composites are capable of sensing their environment and responding to it in a specific, predetermined manner (Addington & Schodek, 2005; Spillman, Sirkis, & Gardiner, 1996). Adaptability, memory, and multiple functionalities are among the “smart” characteristics that these composites bring to numerous possible applications in aerospace, civil engineering, biomedicine, etc. (Kamila, 2013). More anchored to product design applications, smart material composites are envisioned to blur the existing boundaries between products physical form and digital content (e.g., Ishii, Lakatos, Bonanni, & Labrune, 2012) and dramatically change the experiences of future interactive products (McEvoy & Correll, 2015; Nijholt et al., 2012). The emotive, expressive and communicative aspects of smart materials have attracted many practitioners and researchers from the broad fields of interactive art, design and human-computer interaction (HCI) to use these materials in creating tangible and organic user interfaces (e.g., Coelho & Zigelbaum, 2011; Wakita, Shibutani, & Tsuji, 2009), responsive architecture (e.g., Lumina by Chin Koi Khoo; Penumbra project led by

Richard Blythe and Paul Minifie), and expressive and communicative wearables (e.g., Chromat Adrenaline Dress in partnership with Intel).

In the early stages of materials development, direct experiences of the underdeveloped smart material composite might be substituted with verbal, graphical and/or numerical descriptions and representations, for practical or/and strategic reasons (cf. Davis, Shrobe, & Szolovits, 1993). Despite being commonly used for communicating materials between materials scientists and engineers (Miodownik, 2007), these representations take no account of materials experiential qualities (Ashby & Johnson, 2003; Karana, 2009; van Kesteren, 2008), and have little to offer about the aesthetic, expressive and performative qualities of the novel smart materials (Vallgårda & Sokoler, 2010). In addition, researchers have argued that high-level descriptions and representations of a technology, or "black-boxing", as a strategy for reducing technical complexities can have counter-effects on designers' attention to and understanding of its distinctive properties (Sundström et al., 2011).

To support their understanding and anticipation of the experiential aspects of materials, designers often rely on physical encounters with materials (e.g., using material libraries Miodownik, 2007) and memories of previous experiences with them. The physical encounter with materials is argued to provide "an often-forgotten way" into the technical and interdisciplinary discussion of materials (Miodownik, 2007; Wilkes et al., 2016). Physical material samples, however, can hardly scratch the surface when communicating the complex, temporal, and context-dependent functions and expressions of smart material composites. Further, for new smart material composites, experiential references, and design precedents hardly exist (Bergström et al., 2010). Designers might as well find the common approach of relying on a priori knowledge and experiences of the existing materials and technologies insufficient, impractical, or not as informative. Even the vocabulary commonly used for conventional materials might not be sufficient in capturing and expressing behavioral transformability (Parkes & Ishii, 2009; Rasmussen, Pedersen, Petersen, & Hornbæk, 2012) and temporal forms of smart material composites (Vallgårda, Winther, Mørch, & Vizer, 2015).

The main objective of this research is to explore how the prototyping tools used in design processes that depart from an underdeveloped smart material composite may support understanding, exploring, and communicating of the experiential qualities. The research is part of an extensive European (EU) research project, Light.Touch.Matters (LTM), which focused on the development of a specific group of smart material composites. The LTM materials are technologically viable thin and flexible composites of an organic light-emitting diode (OLED) and piezoelectric polymer. In this project material scientists and designers have joined forces to showcase innovative applications of the LTM materials and collaboratively develop these composites. Early on in the project, there was no sample of these composites, and rather the underdeveloped composites were represented to the designers through their functions, for instance, piezoelectric polymer functions as a pressure and deformation sensor, and physical features, such as thin, flexible. Figure 2.1 shows a schematic representation of the components and the layered structure of the LTM materials used to communicate these composites. Based on such representations of the underdeveloped composites, the designers were asked to explore and showcase future application concepts.

The paper presents our design approach and the tools developed to support understanding, exploring and communicating the experiential qualities of the LTM materials. We develop and motivate our approach and the tool through the analysis of: (1) an interview study with professional designers and materials scientist involved in the LTM projects; (2) the prototyping tools and techniques developed or adopted by master-level students through five design processes departing from the LTM materials. Prior to the studies, the background on materials experience, smart material composites, and the existing approaches and tools for experience prototyping smart materials are presented. Next, we explain our design research methodology and present the findings from the interview and the student case studies. Introducing the proposed tools to the professional designers and materials scientist, we inquired about the applicability and limitations of such tools in the EU project. In the discussion, we bring together their feedback and our critical reflection of the tool and reflect on the generalizability of the tools to other smart material composites.

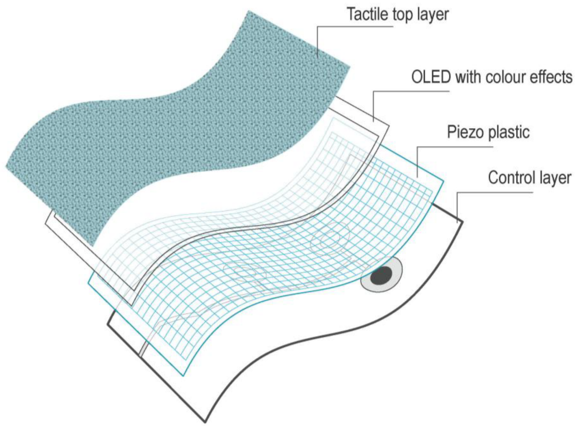


Figure 2.1 – A schematic representation of the components constituting the LTM materials (source: Miodownik & Tempelman, 2014).

2.2 Background

2.2.1 Experiences of Smart Material Composites

“Materials experience”, as a notion, was first introduced by Karana (2009) to acknowledge the active role of materials in conditioning and influencing our experiences with and through materials. The notion points to the need for a more holistic understanding of the material potentials, informed not only by the technical properties but also by the experiential qualities elicited by them in human-material interactions (Karana et al., 2015). Giaccardi and Karana (2015) specified that material experiences can be analyzed and articulated at four “experiential levels”: (1) sensorial, i.e., how the material is received through the five senses (e.g., hard, transparent), (2) affective, i.e., the emotions elicited in interaction with a material (e.g., surprising), (3) interpretive, i.e., the meanings assigned to the material (e.g., cheap-looking), and (4) performative, i.e., the actions involved in handling the material (e.g., pressing, knocking). Despite the power of language in capturing and analyzing material experiences (Giaccardi & Karana, 2015; Manzini, 1989), descriptive representations can never replace the need for hands-on experiences of materials in design (van Kesteren, 2008). Particularly, sensorial and performative qualities are bound to embodied interactions and practices with and through materials (see, Dourish, 2001; Sennett, 2008).

The designers’ understanding of materials experience is not only tied to their ‘thinking’ about materials, but rather unfolds in their making practices with them (Ingold, 2009; Nimkulrat, 2012; Schön, 1983). The role of making and fabricating in understanding composite materials (Barbero, 2011) and digital materials (Löwgren, 2015; Solsona Belenguer, 2015) has been emphasized. Barbero explains that “there is no better way to gain initial sense for composite materials than actually observing a composite part being fabricated” (Barbero, 2011, p. 1). Laboratory experience and the tutorial videos showing and explaining how the composites are being fabricated are thus advised (Barbero, 2011). Löwgren (2015) describes his relationship with the material during the design process as ‘palpating’ the material, with which he brings forth the corporeal component of the relationship. The experimental design approach, as explained by Bergström et al. (2010), allows for probing into ‘aspects of the potential or eventual expressiveness of the material’.

Given that the dynamic and responsive behavior of the smart materials can only unfold over time, temporal form becomes an important element of materials experience (Mazé & Redström, 2005; Vallgårda et al., 2015). The temporal form of smart materials largely relates to the computational structure that enables and demands a temporal expression in the resulting design (Vallgårda et al., 2015). In an experimental setting, Vallgårda et al. (2015) show how the temporal form of similar-looking compositions of textile material and actuators could elicit different experiences. The potential of this design space has been increasingly acknowledged in interaction design literature (e.g., Löwgren, 2009; Lundgren, 2013). Many artists have explored the expressive design space of temporal forms through their kinetic artwork and sculptures (e.g., Jean Tinguely, László Moholy-Nagy, Philip Beesley). There are numerous examples from stage, costume and fashion design that take a particular interest in exploring the temporal form of materials, smart materials, and light-emitting technologies (e.g., Hussein Chalayan). Related work in the industry ranges from the BMW’s shape-changing car concept to 3D mapping light projection (e.g., Mr. Beam), to one-off installations that combine shape-morphing surfaces and light projection (e.g., Parametric Space by Kollision, CAVI, and Wahlberg in collaboration with Zaha Hadid Architects).

2.2.2 Prototyping Material Experiences

In product and interaction design, the role of sketching and prototyping in supporting the designers’ understanding of user experiences and exploring the design space has been long discussed (e.g., Buxton, 2007; Lim, Stolterman, & Tenenberg, 2008). Many researchers and practitioners have contributed to the field of prototyping, by developing new ways of prototyping (e.g., Greenberg & Boyle, 2002), comparing the existing techniques (e.g., Sefelin, Tscheligi, & Giller, 2003), and identifying the types (Lichter, Schneider-Hufschmidt, & Zullighoven, 1993) and anatomy of prototypes (Lim et al., 2008). Researchers have used theatre, theatrical performance, and acting out as a means to inform and generate new insights and ideas (Burns, Dishman, Verplank, & Lassiter, 1994; Iacucci, Iacucci, & Kuutti, 2002; Oulasvirta, Kurvinen, & Kankainen, 2003). Simple animations and Wizard of Oz techniques have been extensively used for making early representations of a system's interface in action (Buxton, 2007). Some researchers are in favor of a distinction between such "sketches" of a future product and its prototypes, arguing that they serve different purposes throughout the design process, in the transition from ideation to usability testing (e.g., Buxton, 2007). Other researchers, however, argued that prototypes can be as much design-thinking enablers, not just tools for evaluating design outcomes (Jones et al., 2007; Lim et al., 2008). Such prototypes are largely used for discovering problems and/or exploring new solution directions, rather than for proving solutions, and as such are a means of "generative and evaluative discovery" (Lim et al., 2008). According to Lim et al. (2008), prototypes are "for traversing a design space" and are "purposefully formed manifestations of design ideas". The "incompleteness" of a prototype is appraised to be its primary strength in enabling the designer's traversal of design space (Lim et al., 2008).

To overcome the complexity of exploring the design space of temporal forms that are not yet built, researchers have relied on a variety of prototyping techniques, including a combination of cardboard prototypes and tools to register the duration of action and reaction (Frens, Djajadiningrat, & Overbeeke, 2003) or a combination of "music sheets" to register the patterns of color change of an interactive piece of furniture and a graphical interface connected to an Arduino board (Nilsson, Satomi, Vallgårda, & Worbin, 2011). The latter work explores the temporal form as the last part of the application design, when decisions regarding the product category, shape and patterns have already been made.

Buchenau and Suri (2000) coined the term "experience prototyping", where prototypes aim at getting a sense of the real experiences and letting the designer reflect upon them, before the product exists. The tools and techniques used for experience prototyping reinforce the attitude of 'actively experiencing the sometimes subtle differences between various design solutions' (Buchenau & Suri, 2000). The prototype's fidelity, however, remains an important issue, largely because fidelity is a matter of cost. A celebrated example of low-fidelity prototyping is paper prototyping (e.g., Snyder, 2003) but it can as much benefit from advanced technologies, such as augmented reality (Nam & Lee, 2003), due to providing a much cheaper alternative to developing the actual hardware. Some researchers argued that instead of deciding between low and high-fidelity prototyping, both may be combined in exploring different dimensions of design consideration (McCurdy, Connors, Pyrzak, Kanefsky, & Vera, 2006). It has been proposed that "the best prototype is one that, in the simplest and most efficient way, makes the possibilities and limitations of a design idea visible and measurable" (Lim et al., 2008, p. 7:3).

Researchers have argued the importance of experience prototyping in exploring and communicating the effects of materials (e.g., Bergström et al., 2010; Saakes, 2010). With the aim of bringing material considerations to the early stages of the design process, Saakes designed and developed a projection-based tool, called Skin V.2 (Saakes, 2010). The tool enables the design team to combine and manipulate physical and digital patterns, and project them real-time on the surface of early physical prototypes. Bergström et al. (2010) developed representations of an adaptive seat to support experiencing and building a common understanding of the context-dependent material expressions. Their approach involved a combination of real-scale low-tech prototypes of the seat placed in multiple households and experimental material samples to depict a process of wear-and-tear. The work of Saakes and Bergström et al. demonstrates two different functions/applications of experience prototyping in early development. The former allows for sketching and getting an impression of materials on full-scale mockups and the latter provides a contextualized representation of the material embodying a specific application.

2.3 Experience Prototyping of the LTM Materials

The literature suggests that the experience of smart material composites might be unique particularly in relation to the temporal and context-dependent qualities of these composites (e.g., Bergström et al., 2010; Vallgårda et al., 2015). Accordingly, researchers have favored experience prototyping of specific applications to help the development team with an in-depth understanding of the unique experiential qualities of these composites and their further effects on existing use practices (Bergström et al., 2010). Prototyping specific applications, however, has limitations, particularly when it comes to exploring the potential of these composites across various applications and contexts of use. Experience prototyping physical and temporal forms of these composites in experimental settings may offer ways of understanding their expanded design possibilities, beyond the limits of very specific applications. In order to identify the challenges of understanding and prototyping materials experience in the early development of smart material composites, we have conducted a set of design studies in the context of the LTM project (2013-2016).

2.3.1 Method

In order to investigate how product designers may approach the experience prototyping of the LTM materials and to identify the challenges on the way of understanding these underdeveloped smart material composites, we conducted two studies. Study #1 involved a semi-structured interview that was conducted to incorporate the experience and insights of the professional designers who participated in the LTM. To that aim, we relied on purposive sampling (Palinkas et al., 2015) and included a materials scientist (8 years of experience) to account for the complementary nature of the collaborative work. The materials scientist and three designers (6-14 years of experience) based in different European countries participated in the interview via Skype. The questionnaire consisted of a combination of structured and open-ended questions related to the participants' personal experience of the LTM project, the challenges faced and support (e.g., tools, approaches, activities) used for understanding the LTM materials (see Appendix). The interviews took approximately 45-60 minutes. All data was transcribed verbatim.

Study #2 involved five semester-long (20 weeks) master's student projects during the period of the LTM project and provided us with the possibility of observing the prototyping activities of master-level design students. Four group projects and one graduation project were defined with the same objective: to explore and communicate the design potential of the LTM materials. The information about the LTM materials was communicated to the students through the LTM project's coordinator who is an experienced academic involved in teaching courses on various topics of design and manufacturing. The group projects were part of two curriculum courses: Interactive Technology Design and Advanced Embodiment Design. Each group was composed of six first or second-year students. The method of data collection was through participant observation (Denzin, 1973), meaning that the first author was involved in the supervisory team of the projects as a coach and had the opportunity to frequently meet with the students and get updates about their activities on a weekly basis. The design activities were also documented by the design students in a written format, complemented with photos and videos of the process.

In the following, first, the challenges faced by the professional designers in understanding the LTM materials and the mitigating strategies adopted by them are reported. Second, we focus on the tools and techniques our design students used for exploring and communicating the experiential qualities of the LTM materials.

2.3.2 Result

Study #1: Challenges and Mitigating Strategies of the LTM Designers

The interview results indicate that among the three designers, only D2 had worked with underdeveloped smart material composites, prior to the LTM project. Unlike the other two, D2 mentioned that the LTM project was not very different from their daily practice, and they often work with new materials and technologies. This seemed to influence how they approached the uncertainties resulting from the lack of knowledge and definition in the LTM project. In addition to the prototypes of their proposed application concepts, D2 contributed to the project by creating a series of physical booklets that documented their material explorations with surface and light, and integration of various sensors in soft materials, to name a few. She made a distinction between her design practice and “companies that are accustomed to work with more clear technologies” and suggested that the latter might be approached when the gaps in materials understanding are bridged.

As expected, the way the underdeveloped smart material composite was introduced to the designers, through descriptions of its physical properties and sensing/actuating functions, was found insufficient and even deceiving. According to the designers, in the first round of concept design, their imagination went far beyond what actually could be done to/with the composite.

> D3: the design boundaries were not clear at the beginning until we started to push through.
>
> D2: we had the idea of LTM material being capable of doing various things mainly because the limitations were not clear to us.

The ineffectiveness of using such abstract descriptions of the material was further explained by the material scientist. According to him, despite the effort of the materials R&D team to communicate the material information, the designers ended up conceptualizing product ideas that either were not possible with the technology or did not push enough for its uniqueness.

> MS: In the beginning we tried to inform the designers of the qualities and properties of the various materials. What we learn is that apparently we didn't do well enough and that created a lot of confusion and also disappointment later in the project; a lot of ineffectiveness in the sense that people spend a lot of energy into ideas which in the end when we saw them, we could immediately say that, well sorry, this is not going to happen.

In explaining the causes of their insufficient understanding of the boundaries, designers blamed mere mediated access to the material, as opposed to directly experiencing the material and feeling its resistance.

> D2: I think it was very much connected to not having the material in the hands. We never saw the piezo material in action. The biggest hindrance was the difference between the imagination and the actual things.
>
> D1: The moment you describe the [underdeveloped] material, it exists in the mind of the designers five years ahead of the material research. This misalignment of the scale is the opportunity in this project but also the difficulty to overcome.

It seemed that the first round of concepts design following the initial introduction of the LTM materials surfaced some of the predefined boundaries. The designers presented posters of their product concepts to the material scientists, using refined descriptions, hand sketches, 3D renders, and story-boards. Some designers brought along materials samples and simple animations to communicate particular qualities of their proposed applications. The designers indicated that discussions about the application concepts positively influenced their understanding of the boundaries. However, they agreed that it was later in the process when they tangibly interacted with the material samples and prototypes that they developed a better understanding of the potentials and boundaries.

> D3: I think the first round of concepts was useful [...] with the prototypes and actual samples that we realize that there were a lot more constraints that should have been told to us.
>
> D1: until that point [when material samples were provided] we were talking about the properties in abstract form in graphs and descriptions [...] the material scientists were not materializing their thoughts [...] I think if anything designers are quite materialized [...] so that step to think material in a tactile way was quite a key point.

The designers emphasized that the dynamic and interactive aspects of the LTM materials made understanding of these material composites more challenging. They hinted, when combined by the performative qualities of the LTM materials, the actual behavior of the composite could not be easily imagined.

> D2: I think with the flexible OLED it was quite clear [...] but I am not sure that I still got the real understanding of the piezo component. The visual way of understanding thing is quite easy for your imagination to make a bridge between having the electroluminescent film and super flat big OLEDs... [For the piezo] you have a piece of plastic in your hand but it is so much the dynamic and interactive properties, when it is manipulated.

The materials scientist further elaborated on a variety of tools and technologies they used to communicate the potentials and boundaries of the OLED development to the designers, including a document in which they addressed designer's specific questions and explained some practical rule of thumb to be considered in application design, for instance "*if you want bright OLED you should forget about mechanical flexibility*". In acknowledgment of the designers' emphasis on physical interaction with the material, the materials scientist considered how certain representations might have supported designers' understanding of the underdeveloped OLED, by reflecting parts of its properties.

> MS: There were a number of ways, one very formalized and centralized way was this document, which was obviously not a big success. [. . .] having these materials in your hand or having some representatives that reflect part of the materials properties was very important [. . .] in the very beginning of the project we send around OLEDs, even if there were still rigid so they (designers) could see how do they look like [. . .] you can learn a lot even if it is still not transparent, not flexible, if it is only a square and so on. [. . .] we send semi-finished products or just plastic foils that don't give light but have the mechanical properties of the OLED [. . .] also broken OLEDs that we get out of our production that people can have a look at how to connect them but also how they look like in off-state.

To capture and represent the experiential qualities of the eventual composite, the design professionals relied on two main approaches, namely physical prototyping using materials that resemble the descriptions of the LTM materials, and Arduino-based prototyping using ready-made transducers.

> D1: The basic technology we used is what everyone did, which is Arduino-based programming trying to figure out the interaction.
>
> D2: We always do very physical very early, to try to understand different things [. . .] they were not actually prototypes, but to resemble the materials. about the physics of it. And I think if anything designers are quite materialized [...] so that step to think material in a tactile way was I think quite a key point.

The designers also invested in systematic explorations of the interaction and expression possibilities of the LTM materials related to their application concepts. Documenting their explorations as sketches and sample books they tapped into the discussion of how understandable those were for the materials scientists.

> D2: We also did this systematic. For instance, we had this investigation on surfaces and light [. . .] we had all these different materials to investigate how light looks like through them. [. . .] for us putting (different investigations) together in small sample books was a way to communicate different qualities.

Unlike the interactive sample book format, the 2D design sketches of the possible interactions, hardly transcended the disciplinary barriers between designer and materials scientist, when it came to discussing the dynamic behavior of the underdeveloped composite.

> D1: We made maybe hundred little sketches of different interactions on a poster, grouping them to touch interaction, physical bend twist, scale of interaction like palm-size or body size or wind [. . .] but in terms of communication it (the poster) wasn't clear, the way we (designers) talked about the interaction (among ourselves), did not work for material scientists. They don't read sketches.

The challenges, as reported above, were mainly originated form the underdeveloped state and dynamic qualities of a new smart material composite, and the need for communicating it between the two disciplines. However, the disciplinary gaps between designers and materials scientists seemed to impact beyond causing a representation and communication challenge of the interactive and performative qualities. According to the designers participated in the interview, the disciplinary differences were as much present in how designers and materials scientists thought about the future of the material and its development. Grounded in their in-depth knowledge of the material, material scientists took control over the eventual development of the underdeveloped composite, when the material knowledge gaps remained unbridged between the two disciplines.

> D3: The material scientists already had a clear understanding of where they wanted to take the material; what they were going to do with it. I think at the beginning it was very much looking at

how can our design influence the material. Towards the end, due to time constraints, it was more like: this is what we are going to be doing with this material and come up with concepts for it.

Study #2: Design Representations Developed by Design Students

Our observations and the students' self-report reveal that a variety of tools and approaches were used and developed in the design processes with the LTM materials. In previous papers (Barati, Karana, & Hekkert, 2015, in press), we reported all the design activities, explorations and tools observed in those design processes and mapped them on time-lines. In this study, we rather focused on how the design students took account of exploring and communicating the LTM material's possible physical and temporal forms. To identify an initial set of design aspects that prototyping LTM materials' physical-temporal forms might exhibit, we consider the interactions between the three elements of 'material', 'light', and 'time' (Figure 2.2). This further provided a basis for clustering and analyzing the students' prototyping attempts and specifying the gap that the proposed tools intend to bridge.

The element of material underlines the importance of physical embodiment in investigating the expressions of computational objects (e.g., Jung & Stolterman, 2012; Mazé & Redström, 2005). Particularly for the LTM materials, integration of the piezoelectric component in flexible substrates allows for an extended repertoire of physical interaction, while the formal/spatial relations between the two material components are under-defined. Integration of light into curved displays (e.g., Papillon by Disney Research) and flexible substrates adds additional experiential dimension to the experiences of the physical body. Light as an experiential element has been discussed across various disciplines, such as theatrical design and more recently textile and interaction design (e.g., Franinović & Franzke, 2015; Jansen, 2015). Accordingly, we specified three spaces based on the interactions between the material and light elements in prototyping 'Luminescent Materials', and their individual interactions with time in prototyping 'Performable Structures' and 'Dynamic Light', respectively. And a fourth space where the three emergent spaces overlap as the Physical-Temporal form of LTM materials.

Our findings suggest that the students represented and prototyped the LTM materials more or less within the boundaries of the three emergent spaces.

Prototyping Luminescent Materials

A variety of approaches and techniques were used to consider the interactions between the material structure and light elements, focusing mainly on bricolages of available physical and digital materials (Hazlewood, Dalton, Marshall, Rogers, & Hertrich, 2010). While in the early explorations, the two elements were not often combined in a single unit, the final prototypes aimed at realizing the experiences of both as an integrated whole (Figure 2.3). Figure 2.4 shows two ways of using LEDs for creating surface illumination. The actual fabrication of these composites was implemented towards the final stages of concept design and embodiment design (Figure 2.5). These detailed representations reveal that the designers invested in experience prototyping surface lighting, which could not be simply achieved using point light sources such as LEDs. Their strategy to achieve this quality through integrating a larger number of LEDs, however, resulted in a stiffer material structure, which was inevitably less representative of the material's tactile and performative qualities. In the final prototypes of the LTM product applications, the fidelity trade-offs were favored the visual qualities of the luminescent material rather than the tactile and performative qualities.

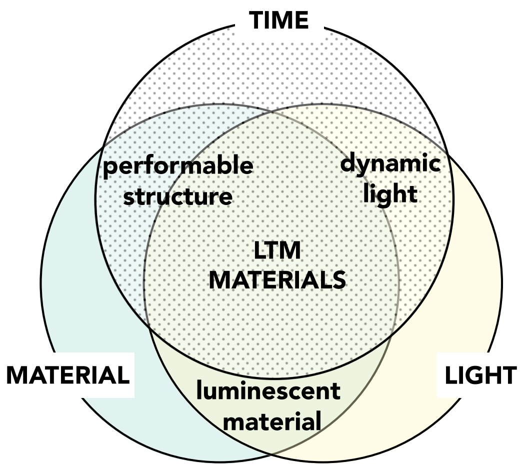


Figure 2.2 – An ontological deconstruction of the LTM materials used in analyzing the prototyping of the physical-temporal form.

Figure 2.3 – The integration of light and material elements in three final prototypes: Yoga mat (left), CPR trainer (middle), punching bag (right).

Prototyping Performable Structures

Structural movement offers a way of looking at the LTM materials as under-specified structures that require pressure and deformation to activate. A 'performable structure' is a relationship between the parts of the composite that enables certain dynamic movements (Niedderer, 2012) and encourages certain performances with and through the composite. An example of material structures that exploit the dynamic movement of sheet materials is action origami (i.e., a folded structure that can be animated). In order to achieve richer ways of interacting with physical forms made with the LTM materials, the performative aspect of the material structures becomes a key topic in both discussing the potentials and designing them.

Across the projects, we observed only a few instances, particularly in the early stages of ideation and design explorations, that material structures were made to represent the performative qualities of the LTM materials (Figure 2.6). In other instances, the students used ready-made force

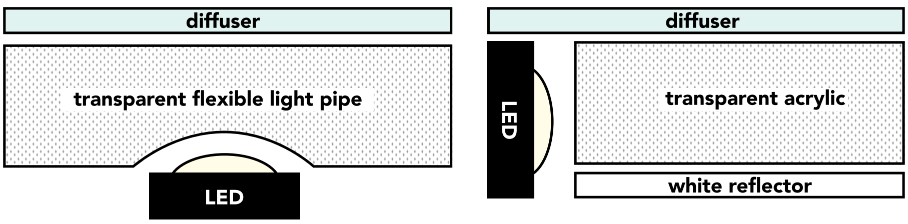


Figure 2.4 – Two ways of making thin and flexible light-emitting surfaces with LEDs: using LED strips and translucent material sheets on top (left) and using side-emitting LEDs and engraved acrylic (right).

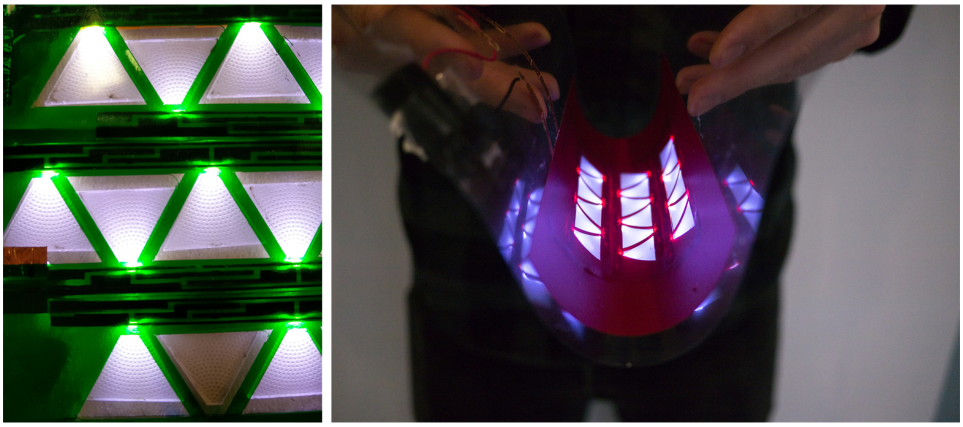


Figure 2.5 – LED edge lighting allows for a thinner structure in comparison to using top diffusers: the engraved acrylic triangles in combination with the LEDs (left), and the final light-emitting sample as a proof of concept (right).

sensors (Figure 2.7, right) to make simple representations of the pressure-sensing composite. Later in the design process, in order to achieve a higher fidelity prototype of the smart Yoga mat concept (Figure 2.3, left), the students constructed their own flexible pressure sensors using Velostat (Figure 2.7,left). Relying on these interactive prototyping techniques suggests that the LTM materials were dominantly understood as a pressure-sensing flat surface. We suspect that the urge to come up with product concepts with the LTM materials early on, and the gaps between physical materials and the off-the-shelf sensing technologies used for interactive prototyping, left little room for creative explorations of the performative qualities. Even though the concepts made use of thinness and flexibility of the composite, the possibilities for unique expressions

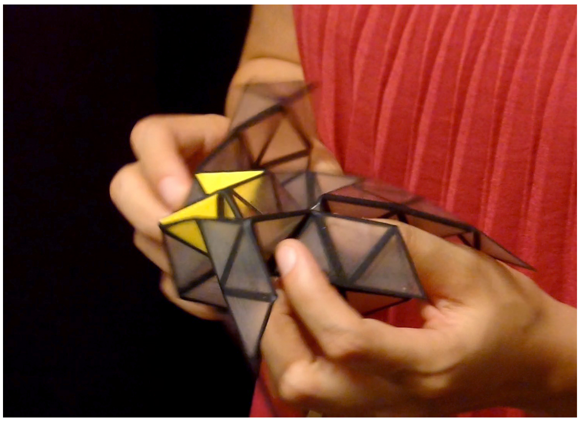


Figure 2.6 – A multi-material 3D printed piece combining soft and hard materials made in exploring the possibilities of a performable structure.

emerging from an under-specified structure remained largely underexplored.

Prototyping Dynamic Light

The interaction between time and light can also bring about different experiential qualities. Examples range from dynamics and rhythm of an expressive LED-optical fiber composition (Jansen, 2015) to the dynamics of daylight in buildings (Köster, 2004). The design students used variety of tools and techniques to explore and represent the experiential qualities of dynamic light, including projection and LEDs (Figure 2.8). Early on, they used *Wizard of Oz* techniques, such as a simple setting with a light bulb and a dimmer where they could manually control the intensity of the light and create dynamic light behavior (see Barati et al., 2015). They also used adjectives, such as *pulsating* and, *flashing*, as well as simple graphs of light intensity as a factor of time (see Jansen, 2015) to qualify the intended light output.

In the latest stages of concept specification, the students produced high fidelity representations of dynamic light, using animated and interactive illustrations on computer screen and light projection on physical surfaces (Figure 2.9). Programing skills play a crucial role in prototyping dynamic light behavior, enabling the designers to diversify and expand the expressions, as shown in Figure 2.9. The more sophisticated light behavior was prototyped after decisions concerning the application and function were already made.

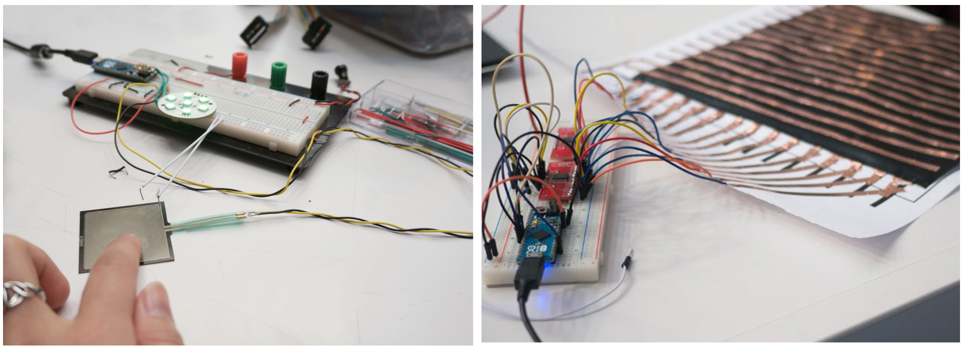


Figure 2.7 – Two prototyping approaches throughout the design process focusing on the pressure-sensing function of the LTM materials: using an off-the-shelf force sensor in early explorations (left) and a Velostat-based pressure sensing matrix, constructed by the students in prototyping the Yoga mat concept (right).

The exploration not only confirmed that the interaction between the elements has been of concern in experience prototyping the LTM materials, but also pointed at complexity of representing the dynamic and performative qualities of LTM materials simultaneously. The Arduino-based approach using off-the-shelf LEDs and pressure sensors, even though is straightforward when it comes to handling and programing, was not optimized for representing unified physical and temporal forms.

2.4 Proposed Approach and Tool for Prototyping the LTM Materials

The results of the observational study complement the interview results in specifying when and how in the design process designers explored the experiential qualities of the LTM materials. It indicated that except for early explorations concerning the LTM materials' performable structure, most of the prototyping activities intricately corresponded to the evolution of the application design ideas. The interview results highlighted the role of material samples and prototypes in facilitating the early discussions of the potentials and boundaries of the material. By externalizing designers' idea of the material and its qualities in some kind of "physical" manifestation, the prototypes let the world "speak back" (Schön, 1983) in helping designers verify their assumptions. On the other hand, when substitute materials and technologies are used to simulate an underdeveloped composite, further discussions between the designer and the materials expert are needed to clarify how the underdeveloped composite may be processed or behave differently from the designers' initial assumptions.

In order to support the LTM team in an early exploration and discussion of the LTM materials' experiential qualities, our first step was to make them

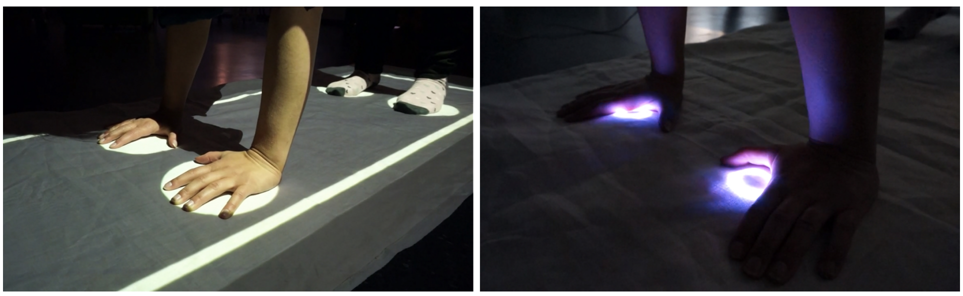


Figure 2.8 – Two techniques used for experiential prototyping the Yoga mat concept: projection (left) and LEDs connected to an Arduino board (right).

Figure 2.9 – Software developed for simulating sophisticated light behavior: interface of the HTML file (left) and screen-shots of the graphical simulations (right).

aware of the richness of the forth (overlapping) space at the intersection of luminescent tangible, performable structure and dynamic light (see Figure 2.2) through a material demonstrator. This section first presents our material-driven experimentations with electroluminescent (EL) materials, aiming at fabricating and engineering this material demonstrator (Step 1). The demonstrator was however not intended to support early prototyping of the dynamic and performative qualities. To that end, the second step was to develop a hybrid sketching tool aiming to enable designers to further explore the design space beyond the limits of a specific design exemplar (Step 2). The tool is proposed as a practical way to facilitate projections of the material's dynamic and performative qualities across various applications and situations.

2.4.1 Step 1: Electroluminescent Material Demonstrator to Represent the LTM Materials

Instead of using ready-made EL devices and manipulating their forms, we used unprocessed inks and made EL material samples in our university lab. Our approach to understanding the luminescent matter through direct engagement with its chemical and physical properties is similar to Olberding, Wessely, and Steimle (2014) and Franinović and Franzke (2015). According to Franinović and Franzke (2015) such a shift from electronics-oriented hardware to physical experiments with smart materials sheds new light on 'the inherent interactive properties of matter' and thus can lead to 'novel design ideas and creation processes'. To guide our experimentation, we followed the materials understanding step of the Material-Driven Design method (Karana et al., 2015).

Electroluminescent (EL) materials in the form of thin-film displays have been used in various commercial products, such as watches. Many artists and designers have pushed the expression and application of these materials by creating exclusive lighting furniture and architectural pieces (e.g., *Butterfly Nightlights* by Soner Ozenc and John Wischhusen; *Blumen Wallpaper* by Loop.pH) and interactive on-off installations (e.g., *Sonumbra* by Loop.pH; Lumibolic by Steve Lee and Meredith Sattler). Recently, researchers have proposed that EL materials are suitable for prototyping thin-film custom-printed displays (Olberding et al., 2014). Unlike OLED's complex fabrication which require high-end lab equipment, the chemical inks for making EL materials can be easily processed, using screen-printing method. The in-house processing facilities offer more 2D and 3D design freedom to design custom-made demonstrators, in comparison to standard EL displays.

To get a better understanding of the experiential aspects of the LTM materials in a single *smart material demonstrator* (Barati, Karana, Jansen, & Hekkert, 2016), we printed the EL materials on a transparent, thin and flexible polymer substrate. The screen-printing process followed a standard method of sequentially depositing and curing multiple layers of materials, including phosphor, dielectric, and conductive materials (see Franinović & Franzke, 2015; Olberding et al., 2014). This fabrication technique results in a high-fidelity representation of the surface light and tactile feel of the flexible OLED component. We then applied *Kirigami*, which involves cutting techniques to obtain 3D shapes from 2D sheets. The technique enabled not only changes in shape, from cylinder to sphere, but also a broader, more sophisticated range of actions (e.g., rotating hands in opposite directions), and expressions. Finally, to relate the structural performances to the dynamic behavior of light, a light sensor was incorporated in the demonstrator. The deformation of the structure from fully close to open changes the amount of light received by the light sensor. Hacking a standard DC to AC driver used for EL wires, the intensity of light was mapped to the analogue input from the light sensor (Figure 2.10).

The smart material demonstrator allows designers to experience the dynamics and performative qualities of a thin luminescent material as it actively elicits certain performances, influenced by the concurrent changes in light behavior and structural deformation. A video of the demonstrator and the tutorial of making it were uploaded on Instructables[1]. The prototyping process, from screen-printing and shaping, to connecting,

[1] https://www.instructables.com/id/Interactive-Electroluminescent-EL-Device-TFCD/

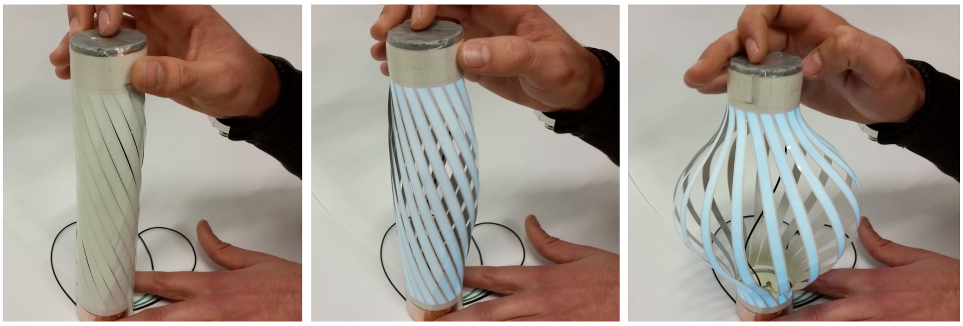


Figure 2.10 – The demonstrator features a dimming effect corresponding to structural deformation.

incorporating the light sensor and hacking the EL driver provided us with a practical understanding of the boundaries in designing with the EL materials. The final EL demonstrator is designed to represent an instance of the overlooked space in experiential prototyping the LTM materials and to let the development team experience, discuss, and explicate the subtle differences between the LTM materials and other existing materials and technologies. Nevertheless, such a demonstrator is not meant to actively enable further explorations of the overlooked design space. To support such explorations beyond the definitive form of this specific demonstrator, we suggest a supplementary generative tool. This step is motivated by the interview results, specifically the challenge of communicating the dynamic and performative qualities of the application concepts through design sketches. The generative tool aims to facilitate the assimilation of the outcome of the experimental design step into the design and development process.

2.4.2 Step 2: Hybrid Tool to Sketch the LTM Materials' Physical-Temporal Form

Our criterion in choosing a technique for experience prototyping the LTM materials was to get high-fidelity representations of the physical-temporal forms through simple, quick and efficient way, drawing on the *economical principle* of prototyping proposed by Lim et al. (2008). Requiring too much investment in time and resources and the unnecessary complexity could become a hindrance in the early stages of design where ideas need to be quickly sketched, prototyped and perhaps discarded (Buxton, 2007).

Many interaction design researchers have addressed a similar challenge since 1990s in connection to user-interfaces (UI) (e.g., Landay & Myers, 2001). In order to represent dynamic behavior in early sketches, an early solution was to scan the paper-based sketches into a computer and then script the behavior, using multimedia tools (Wong, 1992). Electronic sketching systems, such as SILK (Landay & Myers, 2001), let UI designers produce free-hand sketches that could be automatically recognized as the standard widgets, such as buttons, with attributed behavior. Currently, there are numerous design tools to create Wireframes and high-end user interfaces, such as Balsamiq and Sketch. Despite the interactive and animated features of the 2D sketches, these tools do not seem to offer much when it comes to experience prototyping the experiential qualities of smart material composites, at the performative level.

Our criterion in choosing a technique for experience prototyping the concurrent structural deformation and dynamic surface light was to get high-fidelity representations with minimum means. Various methods, including augmented reality and spatial augmented reality (i.e., augmentation of the real world through the addition of digital graphics onto physical objects) exist that allow for fusion of physical structure and digital surface augmentations. Applications of these methods range from product customization (e.g., www.vizeralabs.com), collaborative development (e.g., www.spark-project.net), and education (e.g. *Shaping Watersheds*, S. Reed et al., 2014). While most of these methods require sophisticated algorithms and high-end tracking devices to contour the physical object and track the changes, Chroma-key offers a much simpler solution for representing dynamic changes of color, lightness, and even texture on specific areas of kinetic and moving objects.

Chroma-key is a special effect for layering two images or video streams together based on color hues. The technique has been used heavily in news-casting, movie-making and videogame industries to create a simulated world for the user. It allows for creating a realistic illusion of alternative conditions, without actually being engaged in them. Application of Chroma-key in simulating the behavior and operation of real-world system over time has been mainly to extract a physical object from its color-marked environments and place it within a virtual environment (e.g., Coles, John, Gould, & Caldwell, 2011). The same technique can be used to digitally augment physical samples or mock-ups that are being moved or deformed. Existing software programs, such as Adobe After Effect, enable designers to manipulate recorded video footages and create color-changing effects (Foole, 2016). In post-process Chroma-key, the physical deformation

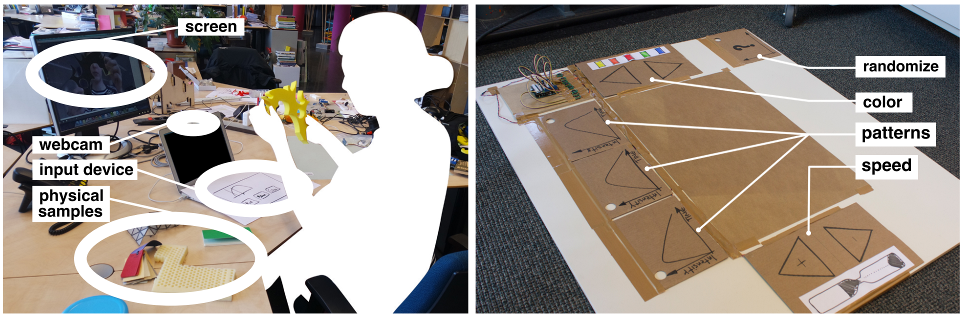


Figure 2.11 – The Chroma-key setup and components: the setup consists of four main components, a screen, a webcam, an input device and physical samples and mockups (left) and features of the input device to control the dynamic behavior of light (right).

and dynamic surface effects are co-located (on the screen) but are not concurrent. Our sketching tool benefits from real-time Chroma-key to approximate concurrent experiences of the LTM materials at sensorial and performative levels.

V.01: Chroma-key Station

The Chroma-key station supports the prototyping activities through generating the dynamic light behavior, replacing it on the screen instead of the color-marked surfaces, and letting the team members modify the light behavior real-time. Figure 2.11 shows the main components of a real-time simulation setting, namely a webcam, a screen and an input device in addition to the Chroma-keyed objects. The Chroma-keyed objects are physical mockups that are color-coded at the parts that the designer intends to show dynamic surface lighting. This can be done by simply adding vinyl or velvety stickers on the surface of the physical mockups (Figure 2.12, left). To produce the Chroma-key effect (Figure 2.12, right) and the dynamic light behavior we used, respectively, a default and a custom-made function in MAX/MSP/Jitter, which is a visual programming language and environment for music and multimedia development. As the hands of users are interacting with the object, we decided to let the users control the light behavior using their feet (Figure 2.11, right). Given that the deformation of the objects and the modification of the light behavior are both manual, making the coupling between the dynamic behavior and the deformation is the matter of a live, performative exploration.

The specific design of the Chroma-key tool requires the members of a

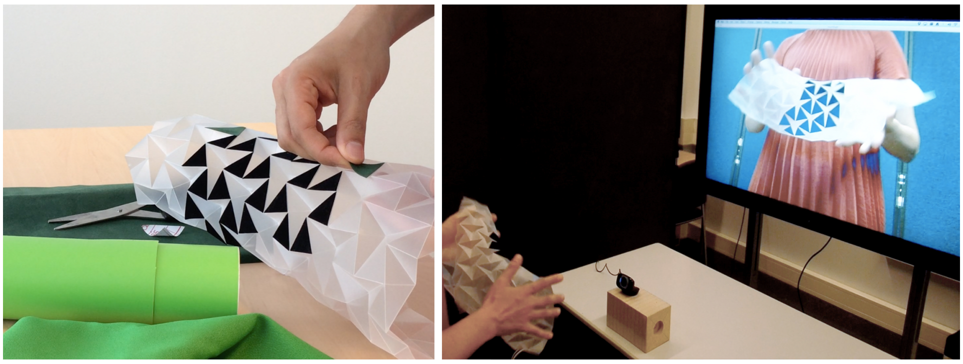


Figure 2.12 – Preparation and augmentation of the physical mockup: adding velvety stickers (left) and the appearance of the real-time Chroma-key effect on the screen (right).

design/development team to stand in a dedicated prototyping station, so that they would be more active in exploring a wider range of hand-gesture to full-body interactions. The control over the light behavior made available to the users through a physical input device. The feet-controlling input device, as shown in Figure 2.11, right, included eight touch-sensors connected to an Arduino Uno microcontroller board. For this early version, we consider a limited number of dynamic light controlling features, namely, color, three fade-in/fade-out patterns (one symmetric and two asymmetric intensity variations), and speed, to generate repetitive light rhythms. A randomizer button allows for random combinations of the features (color, patterns, speed). In addition to simple sheet materials, a collection of performable Origami and Kirigami probes was made with polymer and paper sheets to showcase a variety of structural movements.

Figure 2.13 – The real-time Chroma-key app: a snapshot of the interface (left), the user can select the color by touching it on the screen and use the slider to fine-tune the threshold (right).

V.02: Chroma-key iPad App

The idea of the app was to complement the Chroma-key station and give the designers a dedicated platform to further develop the coupling of light behavior and deformation in relation to specific interaction scenarios. Using the app, the deformation videos and the dynamic behavior parameters, namely intensity-change pattern, color and speed, could be recorded and linked to a specific interaction scenario (e.g., "storage of the mat"). In addition, the Chroma-key app allows for specifying the coupling type (e.g., feed-forward, feedback), tagging and documenting the Chroma-key videos (e.g., "activating the mat"). Having the option to launch the real-time Chroma-key, the app lets its user quickly perform the sketched coupling between the action and the simulated dynamic light output and record the augmented videos. Other existing frameworks such as the Interaction Frogger framework (Wensveen, Djajadiningrat, & Overbeeke, 2004) can benefit the exploration process, by identifying more expanded characteristics of the coupling (e.g., location, direction).

2.5 Feedback of the LTM Project Members on the Proposed Tools

We asked the opinion of the designers and the materials scientist we involved in the first interview about the Chroma-key tool and the demonstrator. Even though they had seen and tried the earlier version of the tool (V.01) in the closing exhibition of the LTM project, they were provided with a video of the EL demonstrator, the Chroma-key tool and its features to refresh their memory. Their direct involvement in a collaborative materials development project provided us with valuable insights regarding applicability of the tool and possible limitations in such projects.

Our four participants agreed that the electroluminescent (EL) demonstrator was clear in communicating its core idea.

> D2: ... you twist and the structure is completely different from cylinder to sphere and then you have the interactive light started [...] not only dynamic but also shape changing [...] you have the direct understanding of what is happening [...]

They collectively acknowledged that the Chroma-key station is a sketching tool with clear advantages for communicating and discussing the boundaries early on in the project.

> D1: It is a very quick and easy way of showing the potential concepts. It is like paper prototyping without actually committing too much or prototyping beautiful coding very quickly.
>
> D2: I think it is very nice tool and the whole idea of a tool is fruitful [. . .] it is a kind of tool that demonstrates what is possible.
>
> D3: I actually do think it is useful, you saw my reaction when I tried it. What I liked about it is that is as simple as painting things with black... it is not a really kind of like glossy thing... it is not aiming to completely replace ...it is not like a CG [computer graphics] kind of thing that you could probably render very realistic effects [. . .] for me your demonstrator is a sketching tool and I think as such there is clearly benefit.
>
> MS: It [the video] is very instructive and it shows nicely how such a tool could have enhanced the experience and the search for new ideas... and it is a bit of a pity obviously that it was presented within the LTM so late, I mean there was no way to do it another way, but I think it is very useful to have such things from the very beginning [. . .] you can simulate lots of things that are either technically not yet there, or in real-life costs a lot of money and effort that can be spent better otherwise.

D3 identified three moments when the tool might be used in a collaborative setting: (1) when designers are briefed, (2) when presenting initial ideas, and (3) when developing the application concepts.

> D3: The first is when we [designers] are briefed. So we get the power points of this materials and the properties, then we have your demonstrator there and we could just have some sheets of black and we can start playing with this. One is the kind of exploration of the properties and understanding of the time-based design and design for behaviors. So this is like basic understanding, understanding the framework of the time-based design. The second is to present our initial ideas. So if I could show my building concept, this little pieces...scale model with the actual behavior this could have been much more powerful than

> trying to explain the concept with sketches with two pieces of this thing. People do not get it! You need to be quite an imaginative person to imagine the effect, and talking about the behavior is a lot about the effect. The third would be in the communication between the development team and the designer [...] in a way very practical way to describe interaction, and have this scripted. So you could translate and add a layer to your demonstrator.

The designers and the scientist warned that considering the tool as ‘a simulator’ could raise false expectations. They touched upon the limitations of the tool in terms of not offering new information about the material and not including its limitations.

> MS: You also need to be very careful if you use it for communication of the properties that you need to make sure that it also includes the limitations.
>
> D1: I think as simulator of the product that you are designing it could be a powerful tool but I don’t think that I can learn a lot from it.

The designers also mentioned the necessity of looking at a screen as a limitation that would narrow down the interaction scenarios for which the tool could be used.

> D3: A scenario that might not happen in front of the camera, or is difficult to do it in a quite direct positioning, also in scenarios that involve multiple, longer, and more complicated interactions.
>
> D1: I think you still look at a screen to show what it is doing, so if there is something on the person, you are still looking at screen to see how it works.

2.6 Discussion

In this paper, we focus on the experience prototyping of underdeveloped smart material composites in collaborative projects, aiming at further developing these novel materials. We have described our approach to identifying the challenges in understanding and communicating the experiential qualities of a specific smart material composite, namely the LTM materials. Analyzing five student design processes and interviewing three professional designers and the materials scientist involved in early development of these materials, we could relate most of these challenges to the LTM materials' dynamic and performative qualities.

In order to support the design process, we proposed (1) an approach, which advocates the understanding of the luminescent matter through direct engagement with its *chemical and physical substances to create a material demonstrator*; (2) a tool, which supports *early sketching of the physical-temporal form so that the potentials and boundaries of the underdeveloped composites* can be collaboratively explored and discussed. The expert feedback, presented in the previous section verified the relevance of such a simple sketching tool in the instances where designers and materials scientist exchange material information and initial ideas. The findings seem to be in favor of the proposed tool development direction and its appropriateness. Both the professional designers and the materials scientist made positive remarks about the scope and the means of support. As elaborated before, the scope was the dynamic and performative qualities of the material and applications, and the means was the direct and tangible interactions with the underdeveloped composite, particularly using a combination of material experimentation, physical and digital prototyping.

2.6.1 Reflection on the Experience Prototyping Tools and Approach

Our experience prototyping approach involved the identification of an initial set of design aspects in relation to the LTM's distinctive physical-temporal forms, which involved the specification of four spaces emerging as the three elements of material, light and time interact. To support the development team in understanding and exploring the overlapping design space between these three elements, our approach combined a smart material demonstrator (high-fidelity) and Chroma-key sketching tool (low-fidelity). This "mixed-fidelity" prototyping approach (McCurdy et al., 2006) aimed to bring the development team's attentions to the distinctive properties of the LTM materials, namely their performable structure and dynamic surface light, by providing a direct understanding of the experiential qualities. Neither the demonstrator nor the Chroma-key tool was intended to inform about the accurate behavior of the smart materials composite, assuming that such knowledge might not yet available in early stages of the development. Instead, the resulting prototypes, as noted by the designers, were deliberately “incomplete” (Lim et al., 2008), to encourage further discussions among the development team concerning the limitations of the real composites and other boundaries of the collaboration (e.g., time and resource constraints). and further discussions among the development team were necessary did not inform on the limitations of the real composites and other boundaries of the collaboration (e.g., time and resource constraints).

The appropriateness of the Chroma-key sketching tool in terms of being simple to use and low-cost is indeed bound to the specified needs for exploring and communicating the experiential qualities and boundaries in early stage of collaborative materials development. The tool, accordingly, enabled quick and direct experiential prototypes of the design ideas, which need to be further discussed within the team for their appropriateness, creative contribution and so forth. As pointed out by the interviewed designers, the “generative stages of design thinking” (Sundström et al., 2011), can be leveraged as an opportunity to collaboratively explore the composite’s unique potentials and boundaries. The proposed tool is found useful as a communication means in the discussion and definition of the temporal and performative qualities of a yet-underdeveloped smart material composites. Nevertheless, both the designers and the materials scientist believed that the tool is most useful to complement, rather than replace other means of communication, such as 3D rendering, live or video tutorials of the fabrication process, engineering rules of thumb. Further research would be necessary to assess usability and effectiveness of the proposed tool in the context, or to compare it in those terms with other interaction design sketching tools and low-fidelity prototyping techniques.

2.6.2 Limitations and Implications for Collaborative Materials Development

But how do the presented design research work and findings contribute to the overall discourse between design and materials science and to what extent the findings can be generalized to other smart material composites?

An important implication of our approach for collaborative development team is to reserve dedicated times within the project to build material demonstrators, which will support the team to explore the materials’ potential and communicate this to all members of the team. We suggest creating material demonstrators to be a collective process where individuals and groups within the development team retain skills and knowledge around particular aspects of the underdeveloped composite. In the making of our demonstrator, direct engagement with ELs *chemical and physical substances* and the hacking of the EL driver helped us understand the EL's working principle and its design boundaries. In other words, by getting outside of our disciplinary boundaries and comfort zone, we could reveal novel possibilities that were not initially imagined in designing [with] the EL materials (Barati, Giaccardi, & Karana, 2018). Further, the prototypes created through such a material-driven design process could satisfy the informational requirements of both designers and material scientists (Lee, 2007; Wilkes et al., 2016). The demonstrator thus may act as effective 'boundary objects' (Lee, 2007; Star & Griesemer, 1989) in collaborative discussions of the LTM materials' potentials and boundaries. Boundary objects are objects that can coordinate the perspectives of different communities, by being plastic enough to adapt to their needs, yet robust enough to maintain a common identity across sites (Lee, 2007). As mentioned by one of the designers, the 2D sketches of the interactions created by the designers were too abstract and ambiguous for material scientist, making them ineffective boundary objects.

Nevertheless, the actual demonstrator and tool are to a large extent bound to the specific features of the technology they represent. Such links to the LTM materials was, in fact, the key motive for investing on and making the electroluminescent (EL) demonstrator in the first place. Other smart material composites most likely involve different compositions and ways of interactions, compared to what presented in this paper. It is important to note that the demonstrator is not a neutral representation of the smart material composite, rather provides a frame of reference, a specific way of looking at its unique aspects and qualities. For instance, a similar kinetic structure might be used in representing a shape-changing smart material composite (Qamar, Groh, Holman, & Roudaut, 2018). Our demonstrator, however, brought forth the performable structure as input, to reach beyond traditional controls, which was largely determined by the LTM materials. The application of the Chroma-key technique can be generalized to other smart material composites that feature surface changes, including color, light and texture. The technique is, however, sensitive to surrounding illumination and surface glossiness of the physical mockups. This might limit the type of materials that can be used in physical prototyping, particularly if they cannot be effectively color coded and prepared for Chroma-keying. Further, as pointed out by one of the designers, the tool requires its users to look at the screen, which limit the type of application ideas and use scenarios that can be effectively prototyped using the tool. We aim to explore the usability and effectiveness of the demonstrator and the sketching tool in actual multidisciplinary workshops between the designers and materials scientists in a next study.

2.7 Conclusion

The main objective of this paper was to provide an approach and a tool to enable specification and discussion of the boundaries and potentials of underdeveloped smart material composites in collaborative material development. We particularly focused on the dynamic and performative qualities of these composites, which were found challenging to explore and communicate in the design process. The paper reported the interview results with design professionals and a materials scientist, and variety of tools, techniques and design representations design students developed in five design cases to represent the dynamic and performative qualities of the LTM materials. According to the interview results, the application concepts and prototypes have been a turning point in staging discussions between the designers and materials scientists to communicate the material boundaries. The findings from our analysis of the design cases supported the interview results.

Identifying a gap in relation to the early representations of their performative qualities, we conducted a number of material-driven experimentations with electroluminescent materials and developed a material demonstrator to enable experience of dynamic light on performable structures. This way, we could expose a particular design space through a material demonstrator that could clearly represent the core idea of the LTM materials: the dynamic light is tied to the performable structure. The second step of our approach focused on the development of a Chroma-key sketching tool to enable the designers to explore the design space beyond the limits of a specific design exemplar and possibly across various applications and situations. In the discussion, we elaborated some aspects of our approach that might be generalized to other smart material composites and collaborative development projects. These include an identification of the design aspects linking to the physical-temporal form of a specific smart material composite, and a mix-fidelity solution of combining material demonstrators and hybrid sketching tools for an early exploration of the experiential qualities boundaries, collaboratively. It was discussed that sensitivity of Chroma-key to the surrounding illumination and surface glossiness of the physical mockups and viewing the interactions on the screen can respectively impact the tool's usability and limit the type of application ideas and use scenarios that can be effectively prototyped. The issues related to usability of the proposed demonstrator and tool in actual workshops between designers and material scientists should be further investigated.

3 Designing [with] Electroluminescent Material

Designers are becoming increasingly involved in upstream collaborative projects to create meaningful applications for emerging materials and inform their further development. At such early stages, descriptive and schematic representations, developed mainly by materials scientists, are used to communicate the underdeveloped material to designers. We argue that these representations are far from equal replacements of direct processes with the material in supporting designers' creative contribution and unveiling material potentials in relation to novel material experiences. To better understand the experiential aspect of material potentials, we looked into a design process, supported by Material Driven Design (MDD) method. The paper reports on the key activities performed by a trained product designer in the process of creating unique material experiences with electroluminescent (EL) materials. Unpacking the theoretical foundation and action-steps of the MDD method and substantiated by practice-based evidences, the paper alludes to a design space that is less likely to be revealed when the underdeveloped materials are communicated through representations or even ready-made samples.

Chapter 3 is based on the following publications:
Barati, B., Karana, E., Jansen, K.M.B., & Claus, S. (in press). Making 'a drop of light': an illustrative case of designing for electroluminescent material experiences. *International Journal of Design Engineering*.
Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Matarial Driven Design (MDD): A method to design for material experiences. *International Journal of Design*, *19*(2), 35-54.

3.1 Introduction

A large portion of all technical innovations directly or indirectly relate to innovative materials (Magee, 2012). Among these innovative materials, smart materials and "smart material interfaces" (Nijholt & Minuto, 2017) are anticipated to radically change the appearance, behavior and experience of our surrounding products and environment. Product designers play an important role in transforming emerging materials to products that people find meaningful and take pleasure in using them (Ashby & Johnson, 2002; Manzini, 1989; Miodownik, 2007; Nathan et al., 2012). To enable the transformation, material potentials must be explored and embodied with an explicit view on how users might perceive and experience the outcome (Nathan et al., 2012). This involves aspects and qualities of materials that are not, disciplinarily, of concern to materials science and engineering, such as experiential qualities elicited by those materials. Experiential qualities encompass what people sense, feel, think, and do in their experiences *with* and *through* materials (Giaccardi & Karana, 2015). As such, they are not simply affected by the material properties but rather "the whole complex of physical, biological, psychological, social and cultural conditions that constitute any experience" (Giaccardi & Karana, 2015).

Scholars have argued that designers' perspective and approach towards materials can benefit materials research and development (Nathan et al., 2012) and even lead to more "culturally-aware" and "innovative" science (Miodownik, 2007). European-Union commissioned projects Light Touch Matters (LTM) and Solar Design are two recent examples of upstream collaborations between materials scientists and product designers. Involving designers in early stages of developing new materials, these collaborations hope to positively influence the development trajectory towards innovative and meaningful product applications in one run. Possible contributions of designers in early materials development stages are mentioned as "identifying new routes to market and lines of scientific enquiry", "challenging the research direction", and "exploring, demonstrating, and communicating potential future applications" (Nathan et al., 2012, p. 1493).

The instances of designers' finding creative links between the gaps in consumer markets and the enabling qualities, i.e., (design) potentials, of new materials are numerous in the history of design and inventions (see Manzini, 1989). However, the situation of designing with smart materials in their early development poses at least two additional challenges. The first one is concerned with the nature of these materials. Unlike conventional materials of design such as metals and plastics, smart materials feature “transient” physical properties (Coelho, 2007), which account for their dynamic and responsive behavior (Addington & Schodek, 2005). The second challenge is concerned with uncertainties in early development, due to lack of knowledge (i.e., facts that are not known, or are known only imprecisely), and definition (i.e., things that have not been decided or specified) of the system (McManus & Hastings, 2005).

Abstract representations developed by the scientists, even though offer a practical solution to mitigate the inaccessibility of an underdeveloped technology, unavoidably focus designers’ attention on aspects of the technology that scientists believe to be relevant (c.f., Davis et al., 1993). Let us elaborate with an example. In the LTM project, the underdeveloped composites of thin-film OLEDs and Piezo-polymers were abstractly represented to designers, through descriptions of the basic functional principle (e.g., the composite registers pressure and deformation inputs) and physical characteristics (e.g., thin, flexible). As expected, the situation encourages top-down design approaches, starting with the bigger picture: product *vision* and concept (Barati et al., 2015). However till the very end of the project, the designers lacked sufficient material understanding to go beyond, let alone challenge the pre-existing “technological frames”. Technological frames are concerned with the assumptions, expectations and knowledge that different groups within an organization (e.g., users, technologists) use to understand the technology (Orlikowski & Gash, 1994). These are used to explain the significant differences between users’ and technologists’ understanding of the technology and the consequential difficulties associated with the technology implementation (Orlikowski & Gash, 1994). We argue that in a true harmonious collaboration, designers and materials scientists must get an equal chance to project their own understandings of the material potentials. The limitations of working directly with the material and relying solely on second-order understandings of the potentials, through the eyes of scientists, might undermine designers’ creative contribution to upstream material development.

Studying a methodical design process, in which the potentials and limitations of an underdeveloped smart material are understood and (re)framed in direct *conversations* with the material (Schön, 1983), this paper elaborates on the limitations of top-down approaches in unlocking creativity contribution of designers in early materials development. The design process presented in the paper departs from basic ingredients of an electroluminescent (EL) material composite, namely, phosphor, dielectric, conductive and substrate materials, and involves making/fabricating of the EL composites. Facilitated by a recently proposed method, Material Driven Design (MDD) (Karana et al., 2015), designer's contribution goes beyond *finding* applications for the EL materials, towards proactively partaking in creating unprecedented experiences with and through them.

Prior to analyzing the case in relation to the activities and decisions made during the process, the theoretical foundation and action-steps of the MDD method are discussed in Section 2. This discussion provides the necessary background on how materials and their potentials are understood and approached in MDD projects, particularly, when *designing for material experiences*. Section 3 specifies the design assignment and the research method. Subsequently in Section 4, the main findings of the case study are presented. The findings are discussed in Section 5 to substantiate the theoretical background and reflect on the MDD method. Further, relevant implications are drawn on how collaborative materials development might benefit from un-mediated understanding and approaches towards material potentials.

3.2 Material Driven Design Method

Many design researchers are convinced that materials are not passive entities waiting to be acted upon, rather active collaborators in unfolding our experiences with and through products (Rosner, Blanchette, Buechley, Dourish, & Mazmanian, 2012) and even shaping our habitual practices around them (Giaccardi & Karana, 2015). Recently, Karana et al. (2015) have proposed the MDD method that instructs and supports designers in understanding material potentials not only in relation to the engineering performances, but also in relation to materials active roles in eliciting experiences. The MDD method is affiliated with "design for experience", a thread of humanistic approaches to designing products and services with an explicit emphasis on enhancing human experiences (e.g., P. Desmet et al., 2011; Hassenzahl, 2010; McCarthy & Wright, 2004). While these design approaches take their departure from psychological and social theories (e.g., Hassenzahl, 2010) or analytical and phenomenological studies of situated experiences (e.g., McCarthy & Wright, 2004), the MDD method takes its departure from the materials.

The MDD method suggests a blend of bottom-up (e.g., hands-on experimentation with materials) and top-down approaches (e.g., user studies, analysis of current trends), in designing for material experiences. The process can result in informed suggestions for the further development of the material at hand (or even new material proposals), as well as product application concepts. Coinciding the development of material and product in a single design process can be interpreted as if an artist simultaneously and mutually constructs the painting composition and the canvas. The material is seen at first as an underdeveloped, raw ingredient, which can unlock variety of development trajectories as the process of understanding evolves. The step-wise method instructs the designer to manipulate the material (e.g., alter the ingredients, the composite structure) and to characterize the material in relation to both engineering performances and experiential qualities. In addition to specifying and organizing the design activities in four steps (Fig. 3.1), the MDD method provides an explicit theoretical lens to investigate the experiential qualities (Giaccardi & Karana, 2015), as well as an auxiliary list of questions to trigger further reflection (e.g., how do people describe this material?). So far, the method has been applied to conventional materials to create new sets of characteristics, as well as novel materials, whose potentials are yet to be explored, e.g., mycelium-based composites (Blauwhoff, 2016).

The MDD method, as depicted in Fig. 3.1 organizes a number of activities necessary for transforming the material to a meaningful material application, in the four steps of (1) *understanding the material*, (2) *creating materials experience vision*, (3) *manifesting materials experience patterns*, and (4) *creating material/product concepts*. In the following, an overview of the activities and sub-activities in each step is provided.

3.2.1 Step 1: Understanding the material

Understanding the material and its potentials according to the MDD method, is not only in relation to its technical characterization, but complemented by “experiential characterization” and contrasting these with how the material potentials have been framed over time and by other designers/technologists, i.e., “material benchmarking”. Three major design activities are thus considered to accomplish such an understanding: (1) *tinkering with the material* to inquire about and reflect on what the material affords (e.g.,

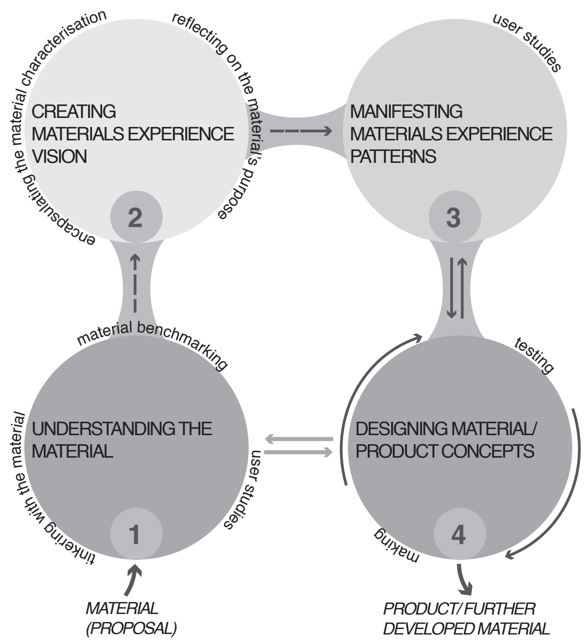


Figure 3.1 – The four steps in the MDD method (Karana et al., 2015).

technical performances, experiential qualities, shapes); (2) *material benchmarking* to position the material (and its existing applications) amongst similar and/or alternative materials and contemplate on potential application areas; (3) *user studies* to identify *patterns* in how others (potential users) appraise and handle the material. Karana et al. (2015) highlight that materials can be characterized in relation to the reoccurring *patterns*, what Giaccardi and Karana (2015) referred to as "materials experience patterns". Materials experience patterns affirm that materials have the potential to transcend and "escape" the intentionality of its maker and impose its own conditions on activity (Glăveanu, 2014). It is thus crucial to meticulously explore for existing and emerging patterns and interrogate their accuracy, temporality, intersubjective-ness, and boundaries, when experientially characterize the material.

The theoretical tool for experiential characterization is borrowed from "materials experience framework" (Giaccardi & Karana, 2015). The framework elaborates the elicited qualities and performed actions in human experiences with the material at four experiential levels: "sensorial", "affective", "interpretive" and "performative" (Giaccardi & Karana, 2015). Sensorial descriptors such as *transparent*, or *slippery* (sensorial level), emotions such as *boring* or *surprising* (affective level), and meanings such as *high-tech* or *masculine* (interpretive level), as well as actions evoked by material properties and embodiment such as *makes me caress* or *makes me hold it gently* (performative level) allow to address and articulate the materials experience patterns.

The practical knowledge acquired through tinkering processes (e.g., fabrication, dismantling, manipulation) when combined with experiential characterization and material benchmarking prepares the designer to proceed to Step 2, creating and formulating “materials experience vision”.

3.2.2 Step 2: Creating Materials Experience Vision

“Vision creation” is a normative step in top-down design approaches (e.g., Hekkert & Van Dijk, 2011), and requires designers to formulate the overall effect and intended experience of a to-be-designed before it is materialized. Vision creation in the MDD method takes inductive reasoning from the materials potentials to a novel experience description. This is in contrary to redesign and “close” problem-solving design briefs (Dorst, 2011), in which the basics of a product such as its main function, production facilities, and the context of use are likely to be known up-front.

Accordingly, the second step instructs the designer to summarize various findings of the understanding step under a cohesive design intention/vision, that can guide the design decisions through the process. Being formulated as a written statement (although often complemented with anecdotes, metaphors, or mood-boards), materials experience vision, in the MDD encapsulates what the material, through its potentials can offer to people. As such, it expresses how the designer envisions material multifaceted role, such as functional and symbolic (Boesch, 2007) in contributing to a unique user experience when embodied in a product. This step is supported by a list of questions to make sure that the relationship between the material and various elements of the broader context are considered. A few example are cultural values and norms, social use of material application in relation to other products (e.g., Forlizzi, 2008), activities, built environment, etc.

3.2.3 Step 3: Manifesting Materials Experience Patterns

Even though vision creation is a crucial step, products are not the result of merely abstract thinking. To create the material application means to simultaneously “materialize” it and make it “meaningful” (Glăveanu, 2014). The MDD method instructs the designer through an intermediate step between the created materials experience vision and its tangible manifestation, such as a developed material or product demonstrator. In this step, the designer investigates the appropriate characteristics that contribute to realization of the vision. To that aim, the vision is further analyzed so that the qualities in interactions between human and envisioned material/product are distilled. The designer’s activities are, hereafter, dedicated to strategizing how to couple formal attributes (e.g., shape, mechanical properties) and those distilled experiential qualities.

In design literature, at least two strategies are differentiated corresponding to cognitive and ecological perspectives on how human make sense of things. The former relies heavily on cultural references (e.g., meanings), product semantics and metaphors as mechanisms to support shapes and value creation (Cila, 2013; Krippendorff, 2005). For instance, to encourage a surprising effect, the designer may consider incongruity between look and feel of the embodiment (Ludden, 2008). The latter takes an account of “affordances”, as “action-possibilities” of an environment (Gibson, 1979), bringing the relationships between appearance and action to focus (e.g., a doorknob affords grasping and turning). Researchers argue that a combination of both strategies are necessary to create aesthetic experiences with products (Petersen, Iversen, Krogh, & Ludvigsen, 2004; Wright, Wallace, & McCarthy, 2008).

3.2.4 Step 4: Creating Material/Product Concepts

The last step instructs the designer to modify the material samples according to findings of the third step, generate and combine application ideas, and embody application concepts that are loyal to and representative of the overall materials experience vision. Accordingly, the application ideas are assessed in terms of foregrounding the intended vision as well as their feasibility (e.g., cost, production facilities) and meeting the functional requirements of each specific application.

3.3 Electroluminescent Materials Case Study

EL materials make an interesting technology case for our research, given the increasing attention to smart materials and smart material interfaces

(Nijholt & Minuto, 2017) in collaborative materials development (e.g., thin-film OLED lighting; Light-Touch-Matters). Smart materials provide the material foundation necessary for designing objects and spaces that can dynamically respond to use or context, blurring the common boundaries between physical and digital, matter and information, structure and membrane (Addington & Schodek, 2005; Coelho & Zigelbaum, 2011). In addition to research-related motivations, practical considerations were also influential in choosing EL materials as a focus. Those include the known development trajectories ever since the EL materials were introduced in 1960s and the possibility of fabricating EL materials in-house.

EL materials have been recently used for prototyping customized thin-film displays, because of the rapid and inexpensive fabrication techniques such as screen printing and conducive inkjet printing, made available to non-experts (Olberding et al., 2014). Even though the manual fabrication is not ideal for producing durable and robust displays, it is perhaps the best for exploring potentials in terms of novel and unprecedented aesthetic qualities and expressions (e.g., Franinović & Franzke, 2015). Appropriateness of craft techniques in handling the transient physical properties of smart materials has also been acknowledged by Coelho (2007), particularly in contrast to the possible limitations of computer-aided design and manufacturing technologies.

3.3.1 Design Assignment

The design project, presented here is one of the three strands of work with EL materials, focusing on double-sided illumination and transparency. The other two explorative works, respectively, focus on flexible illumination and 3D-form illumination, which are discussed elsewhere (Barati et al., 2016). The designer was naïve with respect to the EL materials and the MDD method, before joining the project. The design objective was to create a meaningful material application concept that communicates the potentials of EL materials.

Note that such open-ended design brief is radically different from the problem-solving design briefs that product design students are familiar with (e.g., supplied by third-party companies). In that respect, the MDD method aims to provide a flexible frame to guide the design process, through posing questions, listing necessary activities and investigations, and supporting an implementation of designing for materials experience. The technical challenge of “making transparent lighting” was given as an objective to guide the hands-on exploration. Even though giving such explicit directions to the tinkering process is not advised in the MDD method, we suspected that a complete open search given the project time constraint could be overwhelming.

3.3.2 Research Methodology

The analysis of the case is based on the authors’ direct involvement and close observations of the design activities, the material samples and design representations made through the process, as well as other documentations. The latter includes the documents, intended to facilitate the process of making, exploring, troubleshooting, and transferring the experiential knowledge. The main design activities were listed and compared to the activities highlighted by the designer as essential in exploring, framing and embodying the potentials.

3.4 Results: Analysis of the Designer’s Journey

During the six-month project, the designer explored the material potentials through both theoretical and practical investigations. Providing the raw ingredients and screen-printing facilities in our lab, the designer was encouraged to make EL samples and manipulate the ingredients and the processing techniques to create new EL versions. He carried out several experimentations, varying material-related design variables, namely, ingredients and structure. Understanding about EL materials and their behavior under various conditions and getting inspired through the process of making and discovering, he formulated a materials experience vision. He further developed the material and a product that, according to the research team, to a good extent manifested the intended design vision. The presented analysis focuses on EL materials and their (experiential) characterization during the understanding (Step 1) and concept creation steps (Step 2, 3, and 4 of the MDD method).

3.4.1 Understanding the potentials of EL materials

As presented earlier, the first step of the MDD method is to characterize the materials in hand from both technical and experiential point of view (Karana

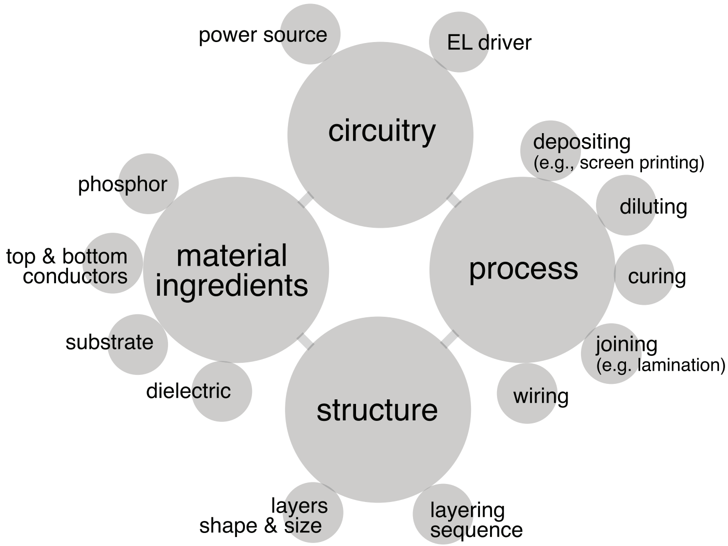


Figure 3.2 – Designer's taxonomy of the important variables affecting the ultimate qualities of EL materials.

et al., 2015). Having no previous knowledge about EL materials, the student carried out multiple concurrent activities to obtain a basic understanding of how EL material systems work. Understanding the basic working principle of a functional material as such might not be a relevant activity in characterizing conventional composites. Nevertheless, it was one of the key elements of understanding the relationship between the structure and multiple components constituting an EL material system. In the following, the key activities of the designer on understanding the EL materials and their potentials (Step 1) are discussed under four categories: theoretical study of the basic working principle, eight sessions of tinkering with the EL materials, experiential characterization, and benchmarking the existing applications.

3.4.2 Basic working principle

According to the designer, his understanding of EL basic working principle encompasses an understanding of electroluminescence phenomenon and the logic of how ingredients and structure bring about a basic yet functional EL material system. For example, understanding that luminescent effect depends on phosphors and an electric field, the designer rationalized that electroluminescent strips or panels can be printed on a variety of different substrates (as long as the layering sequence is intact). Inquiring theoretical

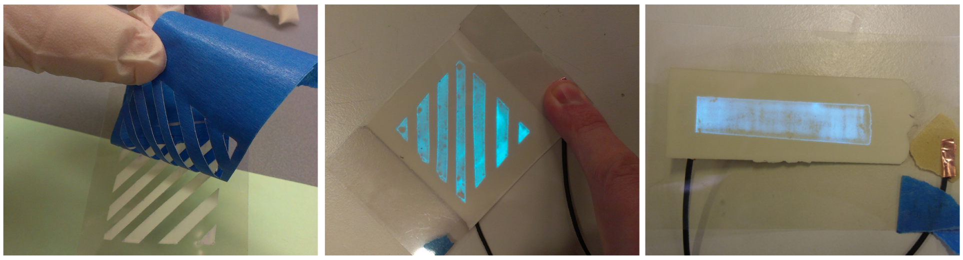


Figure 3.3 – Quick-and-dirty depositing techniques: masking with the paper tape (left), painting with a brush (middle), depositing with a scoop (right).

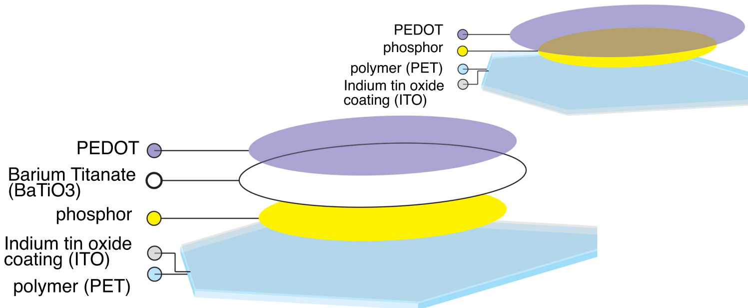


Figure 3.4 – The two sequences experimented in the first tinkering session: the standard sequence (left), a hypothetical sequence that did not function when implemented (right).

knowledge from various sources (educational websites and textbook) and practical knowledge through making processes helped the designer in identifying the important design variables, depicted in Fig. 3.2. The basic variables influencing the material qualities encompass material ingredients (e.g., phosphor paste, top and bottom conductor), process (e.g., screen-printing), structure (e.g., layering sequence, shape, size) and circuitry (e.g., EL driver, wires).

Eight sessions of tinkering with the EL materials

The tinkering activities with the EL materials were carried out in eight sessions, each motivated by a primary goal related to the identified design variables (mainly material ingredients and structure). The experiments were consulted with an internal materials scientist as well as an external expert in the field of EL and OLED materials.

The first session of tinkering aims at understanding the EL materials and

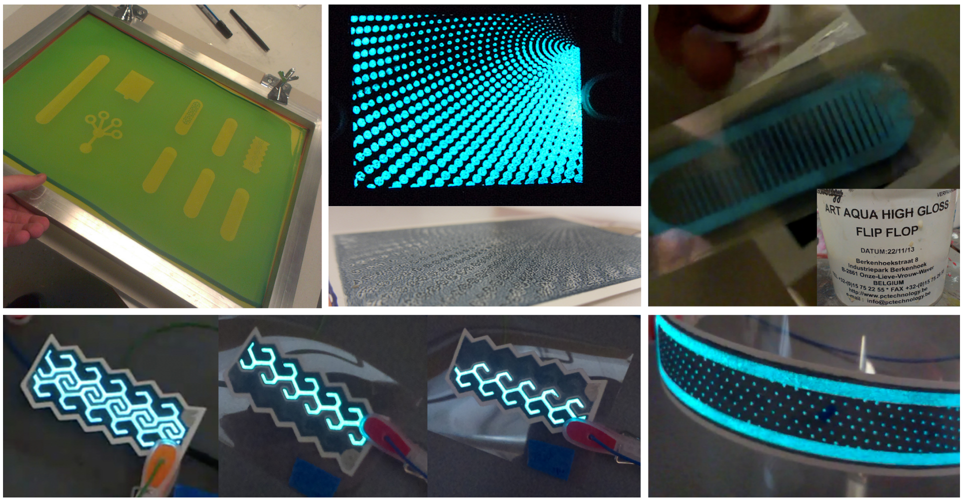


Figure 3.5 – Experimenting with screen printing fabrication technique: preparing the screen using photo emulsion method (top-left), the screen-printed surface quality and light output (top-middle), using alternative dielectric liquids and the light output (top-right), creating entangled patterns that could be controlled individually (bottom-left), playing with the length of the samples (bottom-right).

their potentials based on the theoretical principles of electroluminescence. In this session EL samples are made, using :quick-and-dirty processing techniques, such as painting and scooping, as shown in Fig. 3.3. Even though these processes did not result in high precision and fine detailed samples, they enabled a direct and practical way to get familiarized with the ingredients and layering sequence and structure. In this tinkering session, two different sequences were tested. The first sequence was a standard layering sequence for transparent ITO sheets (Fig. 3.4a), where the top conductive ingredient (PEDOT) and the ITO coating were connected to the power source. The second sequence was an ambitious trial to remove the non-transparent dielectric layer and flip the ITO sheet so the PET substrate faces up (Fig. 3.4b), which totally failed.

The second session of EL samples made by the designer aimed at mastering screen printing technique and exploring the possibilities and limitations of processing EL materials with this technique. The designer organized the information he hoped to obtain through a list of questions, for instant, “what is the finest detail that is printable?” (Claus, 2016). In this way he developed assumptions about the technical boundaries that could be critical in designing with the EL materials and verifying them in a set of iterative cycles. Each cycle informed the next cycle and so forth. Three

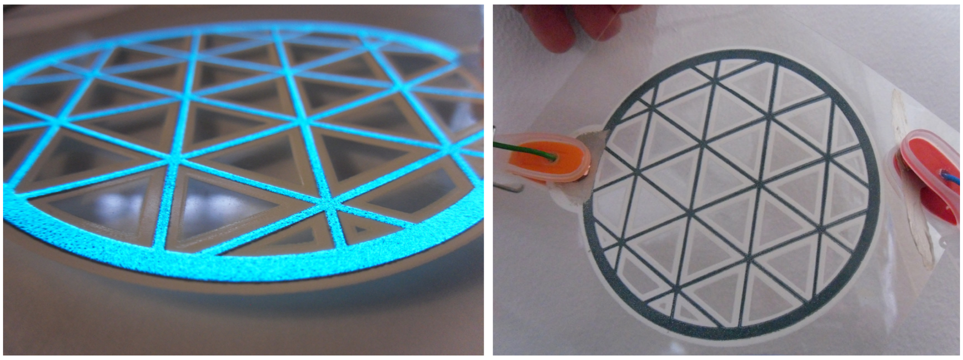


Figure 3.6 – Achieving transparency by creating hollow patterns: activated (left) and not-activated (right) modes.

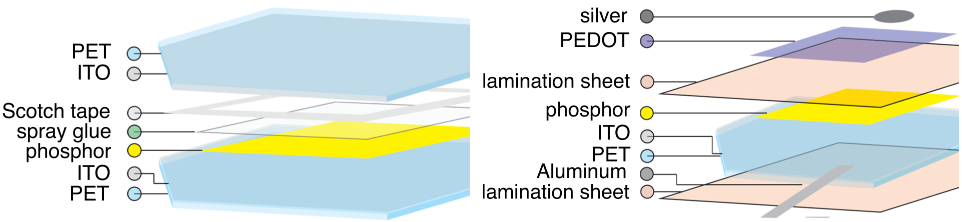


Figure 3.7 – The two layering sequences that were tried by the designer.

silk-screens with overall ten different pattern designs were prepared, and various materials (e.g., Art Aqua High Gloss Flip Flop as dielectric, see Fig. 3.5c) and layer thicknesses were tried (Fig. 3.5).

In the third tinkering session, the designer explored the 2D graphic designs that allows the samples to be partly transparent and partly opaque, as demonstrated in Fig. 3.6. The goal was to see how transparency can be achieved and influenced through meshed print patterns.

Besides playing with the 2D prints on a transparent ITO-coated PET sheet, the student tried various processes, such as lamination and dilution to substitute the white dielectric paste (barium-titanate) with a transparent alternative (e.g., scotch tape, spray glue) (Fig. 3.7). These explorations were a stepping stone towards a more deliberate investigation of the possibility to decouple the top and bottom electrodes (6th session). The ambition of creating transparent double-sided EL sample had motivated the earlier tinkering sessions. However, it was not the priority for the designer during the fifth and sixth tinkering session. In the last two tinkering sessions, it again shaped the designer's making activities.

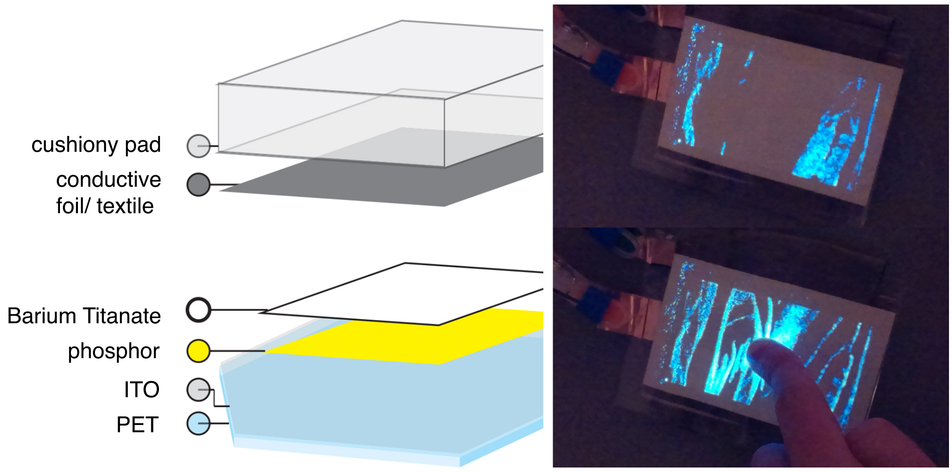


Figure 3.8 – Making an interactive EL sample using conductive textile in between the silver paste printed on a separate sheet and the phosphor printed on an ITO sheet: layering of the two separate pieces (left), the sample in action (right).

The next session of explorations focused on finding suitable connecting solutions for wiring an electroluminescent composite applied on a PET based ITO sheet. The need for this arose in earlier tinkering sessions, when many samples initially failed to work due to poor electrical connections. According to the designer, stable and durable connections were critical in prototyping a product demonstrator with the EL materials.

The realization that decoupling the two electrodes (i.e., printing them on separate substrates) could still result in functional samples opened up new ways of creating adaptive EL samples. In the sixth session of tinkering, the designer created couple of samples, in which the act of pressing the substrates against each other has replaced the need for an external switch. These samples co-located the pressing act (input) and light response (output) and featured dynamic light patterns even after the material was fabricated. The loose structure and the possibility of using a variety of conductive materials after fabrication (e.g., wrinkled conductive textile) allowed for registering bodily contacts and providing instant, dynamic, and customizable light feedback (Fig. 3.8).

Inspired by Franinović and Franzke (2015), the student experimented with water and other water-based gooey (Fig. 3.9) as a potential transparent conductor. He printed the silver paste on top of the dielectric layer but only covering a small patch. By adding some droplets of the conductive liquid on

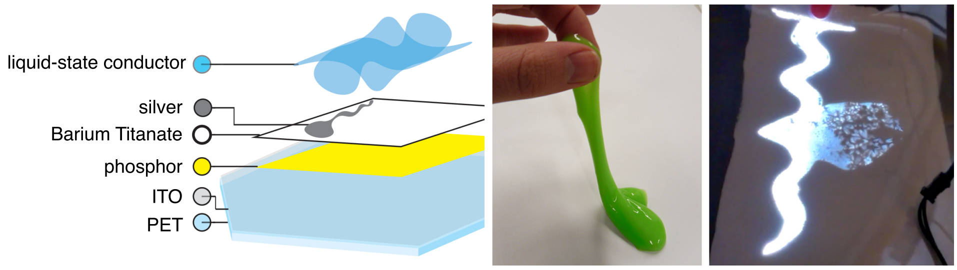


Figure 3.9 – The bottom-emitting water-activated EL sample: the layering sequence (left), the water-based gooey used in the designer's experiments (middle), the EL sample pressed against the gooey (right).

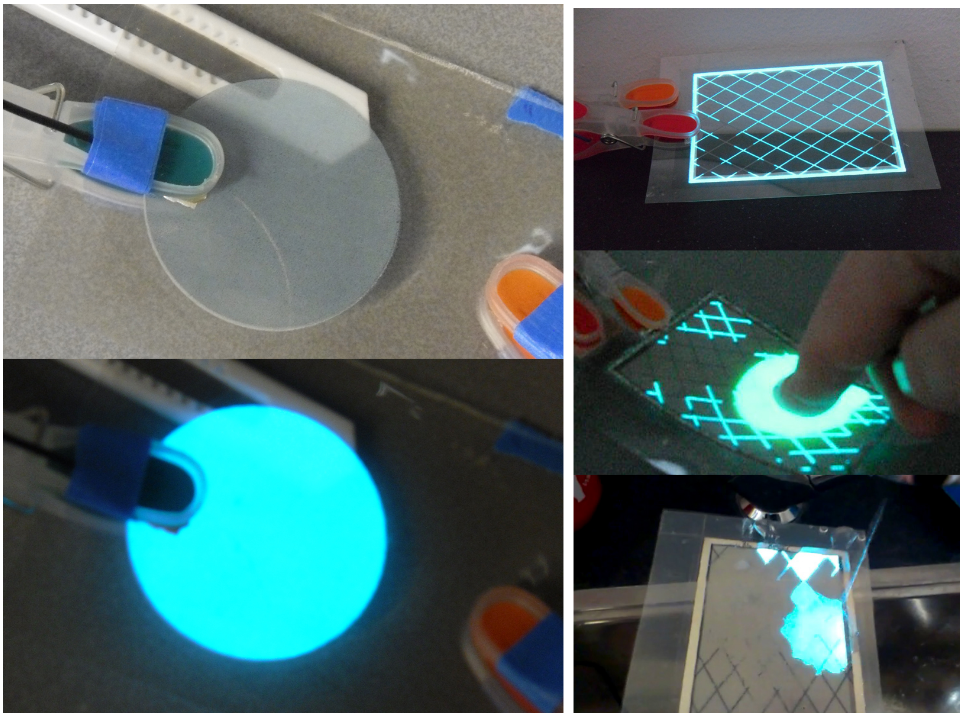


Figure 3.10 – The translucent EL samples: off and on states of the sample (left), the active grid pattern (right).

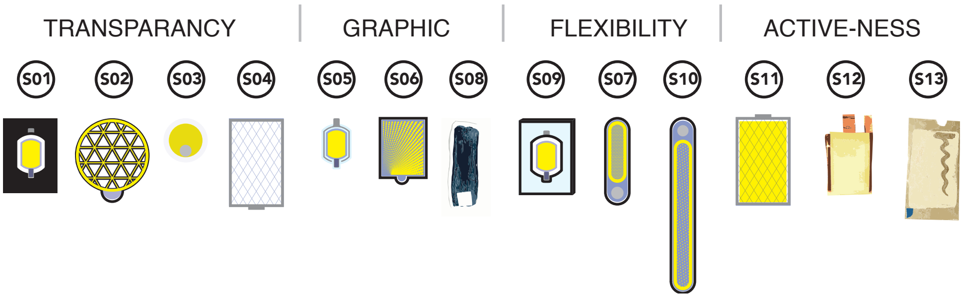


Figure 3.11 – The stimuli used in user studies for experiential characterization.

the table and placing the sample over them (the silver print is faced-down), the light patch could be expanded in dynamic patterns when the sample was pressed or slid (see Fig. 3.9, right).

In the final round of tinkering, the student tinkered with the dielectric component and used a UV-curable transparent dielectric ink. This resulted in translucent EL samples (S03, S04 in Fig. 3.11) that were quite lit (Fig. 3.10, left). Combining the two previously-explored strategies of using conductive liquid and patterned silver patterns, the designer made a translucent sample that could light up from both sides and change between grid and solid light patterns dynamically (Fig. 3.10, right).

Experiential characterization

Next to the eight tinkering sessions, the designer conducted multiple user studies followed by brief interview sessions to explore how people perceived the EL material samples. The MDD method instructs the designer to particularly take notes of the words, expressions and actions evoked when interacting with the samples. The idea behind the user study is to sample as much peculiar and interpersonal information as possible, so the designer can develop a sense of possible and plausible experience patterns. Not only this information inspires unique hedonic purposes to further develop the material, it also gives clue on what material characteristics to tweak and how so that the existing patterns can be improved/diminished (eventually towards a preferred experience pattern).

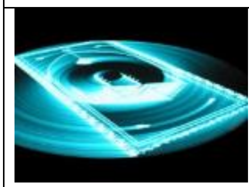
Six students participated in six individual user studies that each lasted 30-45 minutes. Due to the sensitivity of light visibility to the environment lightness, the sessions were held in a room where the light can be dimmed. During the sessions, the 13 EL samples (Fig. 3.11) were placed on a table in front of the participants. The sessions were video-recorded for further analysis. The participants could interact with the material sample in off-mode with bare hands. However, as a precaution, they were asked by the designer to wear insulating gloves when the samples were connected to the power source. Liquid conductors, such as water and Silly Putty were also provided to activate and interact with S11-13 (Fig. 3.11).

The EL samples elicited a broad range of associations and emotions influenced by their formal attributes including their graphic patterns, print qualities, light intensity, substrate materials. For instance, S06 was praised by all the participants for its intricate pattern design, whereas S08 was referred to as “hand-made“ and rather “sloppy”. Not every sample received equal attention and on average the participants spend more time on active category (S11-13). More than half the participants found the active samples “fun to play with”, mentioning that the “dynamic” light output kept them engaged.

The sensorial qualities of the light output (e.g., brightness) had a significant impact on how the participants carry out the additional performances. The bright samples evoked more enthusiasm and even for the less bright samples, the participants double checked the intensity knob of the EL driver to make sure that the brightness was maximized. The differences between the qualities of glow coming from the top and rear sides of the translucent samples also grabbed the participants’ attention. Participants also made comments about the audio aspect of the samples, generated by the DC/AC converter, and found the high-pitch sound “annoying”.

Even though the reactions to each sample varied for personal preferences, the designer recognize an emerging pattern: the EL samples that provided dynamic feedback were often interpreted as playful, imaginative and unusual, while the EL samples (S1-10) were in general regarded as decorative and ambient. As for the performative level, the static samples triggered bending, twisting, slapping, rolling, waving, stroking, scratching, and pressing. The actions dramatically changed in interaction with the active EL samples (S11-13) and included poking, pressing, rubbing, smearing on (with Silly Putty), splashing and finger painting on (with water). The visible textures (e.g., in S06) triggered additional stroking.

Table 3.1 – Examples of EL products collected by the designer for material benchmarking.

 Soft Rocker lounge chair by MIT	 EL snowboard - Light Tape UK	 Glow Headphones	 EL helmet kit by Lightmode
 EL Suits worn by Wrecking Crew Orchestra	 EL tape installation by Dan Corson	 EL tree by Hob	 Uzumaki concept watch by Firdaus Rohman
 EL dress by Kei Kagami	 El dream catcher (www.ch00ftech.com)	 EL Paper Sculptures by Marcus Tremonto	 butterfly nightlight by Soner Ozenc and John Wischhusen
 EL praying rug by Soner Ozenc	 Halo Mini (pet collar) by Vincent Pilot	 Luminous Lace sculpture by Loo. pH	 Disco Chair by Kiwi & Pom

EL materials Benchmarking

In addition to acquiring experiential and practical knowledge about the EL materials and their experiences, the designer conducted a desk research of the existing luminous technologies as well as EL applications. Addressed under material benchmarking in the MDD method, this sub-activity aims to get a richer view on the contexts and purposes of the material applications so far (Karana et al., 2015). The designer collected a number of existing products and concepts (see Table 3.1 for a snapshot of the collection) and elaborated on the motivations for using EL materials in them, as emphasized by their designers and producers.

Designer's investigations suggested that the active characteristics of EL materials when combined with other commonly exploited characteristics such as lightness, thin-ness, cool to the touch, flexibility, low consumption and form freedom had the potential to substantiate novel materials experiences. In Uzamaki concept watch and the praying rug concept by Soner Ozenc (Table 3.1), the designers offer dynamic features, respectively, two rotary luminous disks corresponding to hour and minute and a laced luminous pattern responsive to the correct direction (Mecca). However, these dynamic features are enabled by the motor and control unites, rather than the innate properties of the EL materials.

3.4.3 Conceptualizing and making of a demonstrative concept

In this section, the design acts of vision creation (Step 2), patterns distillation (Step 3) and conceptualization (Step 4) are further elaborated, to clarify how the understanding of the EL material system and its potentials mobilized the design process.

Vision creation, ideation, and concept choice

According to the designer, the EL materials offer active and responsive behavior that goes beyond a primary function of giving light. The experiential qualities elicited by the samples that foreground such behavior are distinct from the static samples and thus hint at less-explored and novel design opportunities. Accordingly, the materials experience vision is formulated as:

> to bring forward this dynamic behavior in combination with the

other prevalent characteristics (e.g., flexibility and intricate pattern design) in *a product that allures its users to look closer and engage, and to experience mundane aspects of everyday life with fascination and curiosity*

The third step in the MDD method is to identify the appropriate materials experience patterns (see Section 2.3) that get the designer one step closer to the qualities of the to-be-designed product. The designer assumes that translucent patterns that are hardly visible in the off-state and become luminous and bright can trigger a closer inspection. *Fascination* and *curiosity* would be then a consequence of a dynamic behavior that vary corresponding to the changes in the environment or/and human actions. With these patterns in mind and employing complementary idea association techniques (Lai, 2007) (e.g., brainstorming) more than 50 product ideas were generated (see Fig. 3.12 for a snapshot).

The ideas were then presented to the team and evaluated in terms of their capacity to manifest the materials experience vision. The idea of *a shelter that provides light in a gloomy rainy night* was found to be an appropriate and promising design direction. The final concept is an umbrella that brings forth the dynamic qualities of the EL materials so that creative and unprecedented performances (e.g., dancing in rain) are encouraged. From a practical point of view, the concept was a small-scale, portable product, which could be prototyped within our lab facilities.

Concept specification and fabrication

In order to accentuate the contrast between the off and on states, the designer decided to alter the structure. The idea first struck him when testing one of the translucent EL samples (Fig. 3.10b). Fig. 3.13 illustrates the modified structure, which stays completely dark in absence of water and lights up and fades away when water drops slide over the printed phosphor. The magical effect becomes possible by printing non-overlapping patterns of phosphor and silver electrode. The transparent dielectric layer encapsulates the ITO coating (bottom conductor) so when users touch the surface there will be no voltage difference, meaning no risk of electric shock. The print patterns to be used for screen-printing were then prepared and the three-step printing/curing process on ITO-coated A3 PET sheets was repeated eight times for making eight working EL samples. Fig. 3.14 captures the

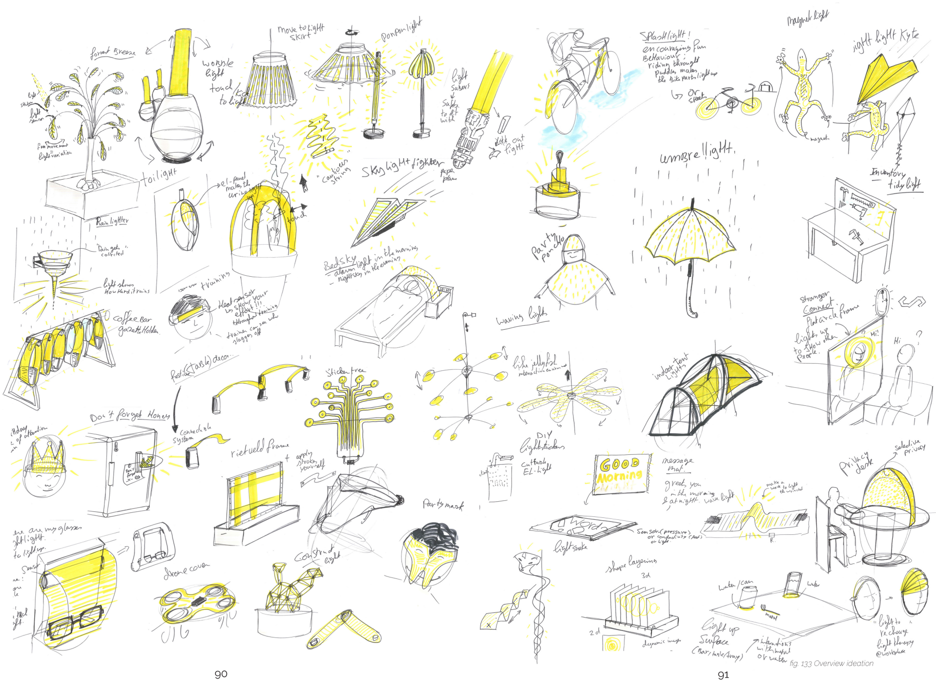


Figure 3.12 – A snap-shot of the sketched application ideas.

evolution of samples after each step. The processed EL samples were then integrated in an off-the-shelf umbrella (Fig. 3.15).

3.5 Discussion

The presented design case elaborates on the situated design activities that lead to conceptualizing and embodying a meaningful product application with the EL materials. It illustrates how designer's understanding of the EL potentials shaped during the material driven process and the space of

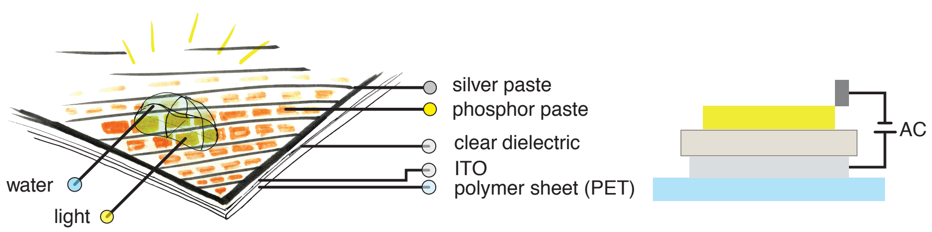


Figure 3.13 – Schematic of the working principle of the custom-made EL sheets for the Drop of Light concept.

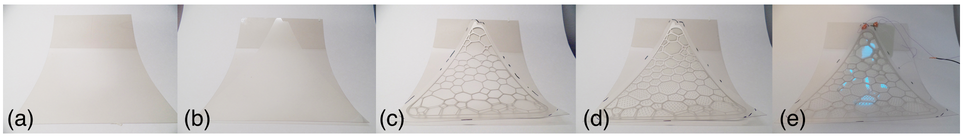


Figure 3.14 – Evolution of a single EL sheet to a functioning piece, (a) an A3 size ITO sheet, (b) clear dielectric, (c) silver honeycomb print, (d) phosphor flash icon print, (e) electrical connections and sample in action.

meaningful applications for the EL materials expanded.

The final concept, “a Drop of Light” (Fig. 3.16), is not only meaningful in its vision or intended experience, i.e., to bring joy and delight to people’s every day experiences of rain, and the means it provides to carry this vision through, i.e., a magical umbrella that transforms frisky rain droplets to light flashes, but also in how the vision and the means mutually reinforce one another. On one hand light is positively associated with energy, warmth, and direction, so it is a conceptually appropriate choice for changing a dull and gloomy experience into a joyful one. On the other hand, the responsive and magical quality of the water-activated EL materials could add drama and surprise to intensify the experience. The design owes its unique experiential qualities to the thin transparent plastic that can light up dynamically and responsively as well as the smart print pattern that not only enables the EL to be experienced as almost transparent but also conditions the dynamic appearances of light. Drawing on Karana’s definition of meaningful material application (Karana et al., 2015), the concept brings forward the unique technical and experiential qualities of the EL materials and bridges these qualities in appropriate and creative ways. It is hard to imagine that the designer could have come up with a similar design if he did not combine bottom-up and top-down approaches in supporting his understanding of the potentials.

3.5.1 Understanding of the material potentials

Encouraged by the MDD method, both bottom-up and top-down approaches were relied on in understanding the potentials of EL materials. It is evident that the potentials do not present themselves to the designer as “given”; they are rather constructed through situated actions and reflections (Schön, 1983). The sub-activities concerning technical characterization (e.g., tinkering), experiential characterization (e.g., user study) and benchmarking (e.g., collecting and clustering exiting applications) were

Figure 3.15 – Integration process of the EL sheets in the final prototype: eight water-activated EL sheets (top-left), preparing the connections (top-right), juxtaposing the EL sheets (bottom-left), wiring through the shank (bottom-right).

critical in shaping designer's understanding of the EL design potentials.

The eight tinkering sessions provided the designer with an understanding of the boundaries and affordances (i.e., action possibilities) in direct conversations with the EL materials. Additional iterations were dedicated to the stimuli-responsive behavior of the EL materials, specifically in relation to its electrical properties, and ranged from making 'working' samples to dealing with activation and interactivity. The designer allocated three tinkering sessions to improve his understanding of EL materials' performative qualities, enabled by the responsive behavior of the smart material and the foreseen benefits of coupling, co-locating, and coinciding action and light output. In interaction design literature, the importance of "coupling between action and function", as a direct approach to make electronic products that are intuitive to use, versus a semantic approach (e.g., using labels and icons), has been emphasized (e.g., Wensveen et al., 2004). Wensveen et al. (2004) argue that unlike most mechanical products,

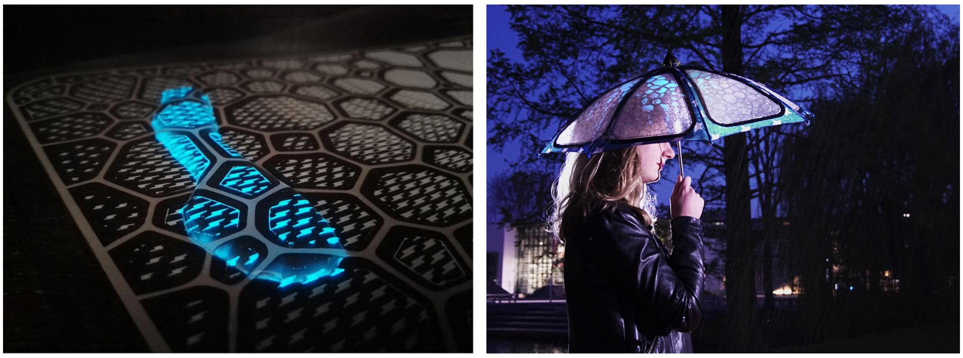


Figure 3.16 – Final prototype: close-up of the lit droplets (left), testing the final prototype in use context (right).

the coupling between action and response in electronic products is not confined to “the tight coupling laws of the physical world”, allowing for programming the relationships between the two. Similarly, with the EL materials the relationships between the action and the response were orchestrated, mainly through material structure, to unlock novel performances (e.g., pressing and brushing).

Complementing the tinkering activities, the potentials were also informed by the knowledge of how other people, as potential users, perceived and interacted with the EL samples. The user studies reinforced that even though the EL samples were made out of similar base ingredients and share *light-emitting* as their core function, they elicited a wide range of emotional responses and performances. Correspondingly, the designer characterized the EL materials in relation to the type and range of experiential qualities each sample supports or prevents (i.e., experiential characterization). Making and tinkering processes with the EL materials and reflection on the experiential qualities provided practical and experiential knowledge of the EL materials that substantiated designer’s theoretical understanding of the basic working principle.

Existing applications of the EL materials also influenced designer’s framing of the EL potentials and positioning and justifying the unique qualities of the to-be-design. Being around for a couple of decades, EL materials are used in variety of product applications (e.g., successful, dominant/niche), which work as a compass in navigating the design direction. More applications also mean that the bar is higher for the designer to make the design distinct. With new materials, there is less information of the existing applications, but at the same time, less competition.

3.5.2 Reflection on the MDD method

The MDD method provided a flexible structure to understanding of EL materials, their limitations and potentials, and ultimately envisioning and embodying meaningful product applications. By prioritizing material experiences in driving the development, rather than merely functional requirements and engineering performances, the method opens up novel development opportunities. To that aim, the method suggests, in essence, a set of activities in a certain sequence and a theoretical lens (i.e., Materials Experience Framework). Accordingly, we see tinkering and making activities scattered along the process. Having the ingredients of the EL as a starting point, the designer involved in processing the material right from an early stage. Even though in the first tinkering round, the designer's best hope was to fabricate a working EL device, in the follow-up tinkering sessions he pushed his understanding of the boundaries, using a variety of materials (e.g., to replace the ingredients) and processing tools and technologies (e.g., laminator machine). Essential to materials driven design, hereafter, we elaborate on the role of processing/fabricating and serendipities in discovering and mobilizing the material potentials.

Processing facilities (e.g., techniques and tools) are key in achieving the eventual qualities of materials. In the presented case, facilities used in the tinkering sessions played an important role in understanding what properties and qualities are (not) attainable. They allow the designer to not only test and reflect upon his assumptions about certain design potentials but also discover unprecedented ones. As a famous quote from Maslow (1966) wittily conveys “I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail.” Trying different processing tools and techniques is important if a variety of qualities is desired (e.g., appearance, dynamic character). The MDD method supports this by moving material fabrication to the early stage of the design process. Even though many modern design models advocate to bring consideration of manufacturing in early decision making (e.g., Andreasen & Hein, 1987; Ullman, 2003; Wynn & Clarkson, 2005), fabrication is often considered as “a state of being simply a production protocol”, rather than “a service station for the designer to gather knowledge” (Glynn & Sheil, 2011). This trend is, however, slowly shifting and significance of fabrication in early design stages is receiving more attention (Glynn & Sheil, 2011).

Accidental discoveries of certain material potentials also played an important role in conceptualizing and embodying the final design. For instance, the imprecision of phosphor and silver print (that were supposed to overlap) resulted in an unplanned observation during the material test and realizing the possibility to make non-overlapping print patterns that can dynamically lit as water droplets connect between them. The important role of accident in discovery and innovation has been signified in historical analyses of human achievement (e.g., Cannon, 1940; Roberts, 1989), and more specifically in the field of new product development (Eisenhardt & Tabrizi, 1995; Thomke, 2003). Studying 20 cases (ranging from metal sculptor, product development to service delivery team), R. D. Austin, Devin, and Sullivan (2012, p. 1517) reveal that “makers intentionally design their processes and surroundings to invite and exploit valuable accidents”. They argue that even though these processes are not “efficient” per se and are highly prone to “non-valuable” accidents, makers’ expertise helps them in managing the costs. The first step in the MDD method instructs designers to engage with the material through processing and tinkering. Such hands-on encounters potentially increase the chance of accidental discoveries. Simultaneously, the same step prepares the designers to be in the right mind-set to see value and relevance in those serendipitous accidents.

As expected, the theoretical framework of Materials Experience contributed to the framing and articulation of material potentials in eliciting certain experiences. In combination with the high-fidelity prototype of the final design, the MDD method allows for an effective communication of values that are otherwise very difficult to convey. For instance, while a Drop of Light can be described in terms of its function as an umbrella that lights up, such description entirely fails to capture the unique experiential qualities of the concept. In the absence of the prototypes, such a description cannot capture the subtle differences between a carnival umbrella and the proposed concept. However, in experience and use, the two elicit very different emotional response and performances. Designing with smart materials in between boundaries of form and function demands prototyping techniques that sufficiently portray these subtle differences and preferably allow the development team to experience them subjectively (Buchenau & Suri, 2000). Demonstrators that not only *work like*, but also *look like* and *behave like* the underdeveloped technology or its applications can be more effective in surfacing and addressing these subtleties (Barati et al., 2016).

But, what potentials are less likely to be discovered in a material driven design process? The MDD method is mainly concerned with applications that are producible *now* and with the existing facilities, so more speculative applications that are not bounded to the facilities of a specific lab or existing technological advancement are unlikely to emerge. Further, in material driven design assignments, materials understanding is expected to accumulate through conversations with the material and its properties, including trial and error processes, user studies and reflective thinking. However in case of the EL materials, the designer confronted material and technology-specific issues that were hardly resolvable in the absence of necessary expertise and facilities. The MDD method does not anticipate for the technical difficulties that require the designer to interact with materials experts/scientists and have access to advanced facilities. To smoothly execute the method and maintain designers' autonomy in understanding the material potentials, it is beneficial to explicitly mention these conditions and strategize the interactions and exchanges with the materials experts/scientists. Specifically with smart and programmable materials, the MDD method falls short of providing necessary support in dealing with computation and the cross-overs of smart material structure and computation. Without such strategies there is a chance that this extended design space with smart materials remains unexplored or at best under-explored.

3.5.3 Contributions to collaborative material/product development

The EL design case provides empirical evidence on how potentials of an underdeveloped smart material might be explored and framed, if the departure point is the ingredients and the focal objective is to design for materials experience. Towards conceptualizing design tools that can assist designers in better understanding of the potentials in early development, a number of explorations have been conducted and published (Barati, Karana, & Foole, 2017; Barati et al., 2015). Focusing on the situation where the underdeveloped smart material is mediated through information and representations, these studies suggest that value-creation is mainly attempted through rational mappings between the given characteristics and products' desired function and/or form, leading to an early definition and fixation of the application domains (e.g., injury rehabilitation) and application concepts (Barati et al., 2015). Although to approximate the *expected* functionalities and experiences, designers combined conventional materials (e.g., polymer sheet) and electronic components, such "bricolage" strategies (Vallgårda, Grönvall, & Fritsch, 2017) alone hardly led to a new understanding of the smart material potentials. Even after presenting to the materials scientists, those compositions failed to stimulate discussions about material potentials beyond the formal and functional limits of already-specified concepts. The presented material driven design case supplements those explorations by hinting at a design space that is less likely to be revealed when relying merely on top-down design approaches.

The comparison between the top-down approach and the material driven approach reinforces the assumption that how the material is introduced (e.g., through abstract representations, processed samples, or raw ingredient) affects the type and variety of activities and the envisioned affordances. For instance, manipulating the composite structure and trying alternative ingredients might not be readily supported in creative processes with off-the-shelf or ready-made EL samples. In line with the merits of the MDD method, we argue for a fusion of top-down and bottom-up strategies in exploring the potentials, with aspirations for exposing and debating the technological frames and cross-fertilizing the development process towards more creative outcomes. This requires collaborative projects to step beyond multidisciplinary workshops in which designers receive theoretical information about underdeveloped smart materials and embrace their active participation in (re)framing the potentials and boundaries, through tinkering and “making” (e.g., DIY, Rognoli, Bianchini, Maffei, & Karana, 2015; Tanenbaum, Williams, Desjardins, & Tanenbaum, 2013).

3.6 Conclusion

In this paper, we delved into the creative contributions of designers in connection to their understanding of the EL materials and their potentials. Accordingly, we sketched answers to the two questions of what designer’s creative contribution is and how it is unfolded during the design process. The insights, we argued, will be of great importance in strategizing upstream collaborative material/product developments to benefit from designers’ different framing of the potentials in relation to unique material experiences. The paper first explains how such materials understanding is supported by the MDD method. Relying on a theoretical framework, the MDD method combines experiential characterization, early material experimentations, and product benchmarking tools to enable a personal and inclusive understanding of the material potentials. Designer’s understanding is then complemented with an experience-focused vision creation, product ideation and demonstration. In the discussion, we elaborated on the role of the MDD method in unlocking and realizing unique material potentials as well as its limitation in dealing with the technical complexity and interactive qualities of smart materials. Leveraging on the process and outcome of the presented material driven design case, the paper urges for an equal partnership of designers in discovering and defining material potentials and boundaries, enabled by direct (yet technically supported) processes of the underdeveloped material.

4 Making of Performativity

As the material becomes active in disclosing the fullness of its capabilities, the boundaries between human and nonhuman performances are destabilized in productive practices that take their departure from materials. This paper illuminates the embodied crafting of action possibilities in material driven design (MDD) practices with electroluminescent materials. The paper describes and discusses aspects of the making process of electroluminescent materials in which matter, structure, form, and computation are manipulated to deliberately *disrupt* the affordance of the material, with the goal to explore unanticipated action possibilities and materialize the performative qualities of the sample. In light of this account, the paper concludes by urging the HCI community to performatively *rupture* the material, so to be able to act upon it as if it was always unfinished or underdeveloped. This, it is shown, can help open up the design space of smart material composites and reveal their latent affordances.

Chapter 4 is based on: Barati, B., Giaccardi, E., & Karana, E. (2018). The making of performativity in designing [with] smart material composites. *In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI'18)* (pp.5:1–5:11). ACM.

4.1 Introduction

Discussions about the unrealized capabilities of materials in the design of computational artifacts, and the experiences, performances and practices they contribute to generate, has steadily gained attention in the HCI community (Bergström et al., 2010; Vallgårda & Redström, 2007; Wiberg et al., 2013). Giaccardi and Karana (2015) have recently highlighted the importance for designers to consider the performative qualities elicited in embodied interaction with materials, in order to capitalize on the material's active role in the shaping of performances and practices.

Because of their dynamic properties, smart materials push the envelope of embodied and performative approaches to materials. In this space, the HCI community has explored their potential for giving physical expression to computational artifacts (Vallgårda & Redström, 2007) and for diffusing computation into the fabric of everyday artifacts (Buechley & Coelho, 2011). This work has contributed design strategies that take physical materials' properties as an entry point to harness computational expressiveness (Vallgårda et al., 2017). To account for the material's active role in the unfolding of action possibilities, hands-on approaches are privileged over representational approaches (Coelho, 2007; Vallgårda, 2014). Representational design approaches, such as geometry-based CAD modeling and visual collage, focus predominantly on what has to be produced rather than on how human and nonhuman formations are enacted or performed. These approaches that favor thinking over making or at best "making through thinking" (Ingold, 2013) has led to a "kink" between the world and the designer's idea of it (Brand, 1994; Ingold, 2013), and are being increasingly questioned in HCI design practice.

The active involvement of designers at the material level becomes particularly critical when investigating new materials that are developed by scientists (Schröpfer et al., 2011). Thermochromic dyes, shape-memory alloy, piezoelectric films, electroactive polymers and electroluminescent materials are only a few examples of an emerging group of materials, called smart materials. While some of these (highly) engineered materials are available on the market, many are still in early stages of development. What gathers these various types of materials under a same group is their dynamic qualities in response to specific external stimuli (e.g., changes in temperature). These materials are often developed to stretch the notion of technical performance to the nano- and micro-scale of materials and surfaces.

A growing number of HCI researchers have begun to work with smart materials (Coelho, 2007; Franinović & Franzke, 2015; Olberding et al., 2014), mostly to get a better sense of the blending design space at the convergence of physical and digital materials. In these cases, the focus is on the 'making' of smart material composites, rather than adopting them adhoc in the late stages of concept development. The importance of 'making' in supporting designerly processes of understanding is greatly emphasized in the design literature (Ingold, 2013; Nimkulrat, 2012; Tholander, Normark, & Rossitto, 2012; Vallgårda, 2014). Practitioners like Coelho (2007) often rely on craft techniques to explore and harness the potentials of smart materials. Löwgren (2015) goes further by describing his relationship with the material during the design process as “palpating” the material, a process in which he brings forth the corporeal component of what Schön characterizes as “reflective conversation” (Schön, 1992).

However, the advantage (but also the challenge) of working directly with smart materials is that the entanglement of physical and computational properties is not engineered upfront and can be purposefully made by the designer (e.g., Schröpfer et al., 2011). Their various 'becoming' (Bergström et al., 2010) hints at the importance of understanding their underdeveloped capabilities, and how these can be revealed over time and in response to their context of use: that is, their performative qualities (Giaccardi & Karana, 2015).

In the pursue of acquiring practical understandings of the (micro-scale) variables at play in the performative characterization of smart materials, present theorizations of performativity remain confined to either the designer's body (i.e., how the designer engages bodily with the material) or the artifact (i.e., how human performances unfolds at use time, once the artifact is made). This work instead aims to shed light on how designers may reveal unanticipated action possibilities in smart material composites, which we refer here to as 'the making of performativity.' To this end, we present a series of material driven design (MDD) explorations with electroluminescent materials aimed to create electroluminescent material samples with novel action possibilities. The described explorations concern aspects of the making process of electroluminescent materials in which matter, structure, form, and computation are manipulated to deliberately disrupt the affordance of the material, in order to explore action possibilities and materialize the performative qualities of the sample. By examining these explorations, the paper introduces the idea of *disruption of affordance* as a design strategy for working with smart material composites, considered as always unfinished or underdeveloped. The paper concludes by promoting a *performative rupturing* of smart material composites, which may open up a broader design space and reveal latent affordances.

4.2 Related work

4.2.1 Smart Material Composites

Smart materials refer to a wide range of materials that share a common feature: their one or more properties might be significantly altered in response to specific stimulus. Smart materials have been approached from different stances in HCI research, including their role in realizing ‘organic user interfaces’ (Coelho et al., 2009) and ‘computational composites’ (Vallgårda & Redström, 2007). Organic user interfaces specifically focus on smart materials and their intrinsic capability to respond. Based on this intrinsic capability, researchers of organic user interfaces explore how smart materials could transform the common-place flat shape of display devices, and, more generally, allow granularity between computational devices and physical material elements (Coelho et al., 2009). Other HCI researchers have adopted instead the broader definition of computational composites (Vallgårda & Redström, 2007). These are made of different physical and digital materials that are necessary for the final ‘composition’ to perform the way it does. Accordingly, they can exist in a number of states (e.g., colors, shapes, or positions), with the transition between different states being controlled or computed.

The notions of organic user interfaces and computational composites emphasize, respectively, a specific application context of these material composites (i.e., as user interfaces) and specific aspects of them (i.e., to reveal the properties of computation). With ‘smart material composites’ (SMC), we de-emphasize such frames of reference and instead refer to the underdeveloped state of smart material compositions which enables and drives creative processes with them. Seeing the composite as under-developed implies that there is a range of technical and experiential qualities that designers need to keep an open mind about. Like all becoming materials (Bergström et al., 2010), composites of smart materials have dynamic qualities that unfold over time and in response to the context of use. This type of plasticity renders the performativity of SMC's particularly interesting as an entry point for designing (with) them.

Featuring inherently dynamic qualities, SMC's enable seamless diffusion of computation into formable, flexible, and stretchable material substrates (Coelho et al., 2009; Vallgårda & Redström, 2007). Dealing with them, thus, requires a departure from established methods of encasing hard electronics in material membranes (most of our surrounded interactive artifacts). The dynamic and adaptive behavior of smart materials challenges prevalent assumptions about material conditions in design of artifacts (Addington & Schodek, 2005). For many materials, making and manufacturing processes have been greatly protocolized, and designers hardly question the early commitments informed by representational access to the material and its design space. However, this trend is slowly changing towards viewing making and manufacturing as "a service station for the designer to gather knowledge" (Glynn & Sheil, 2011). In order to realize what is truly possible with SMC's, researchers have emphasized the need to "move away from an outcome or result driven design process" towards an interest in understanding those technologies, through 'experimental engineering' (Vallgårda et al., 2017, p. 197). This is at odds with having "a specific purpose in mind", implying a prioritization of intention and/or vision (i.e. top-down approach) when making such composites (Vallgårda & Redström, 2007).

Among the approaches suggested for expanding ways of working with SMC's are improvised making, tinkering, and bricolage with existing technologies (Vallgårda et al., 2017). The need for hands-on experiences with the technology has been acknowledged in understanding, exploring, and sharing the expressive potential and the dynamic qualities of digital and hybrid technologies (Sundström et al., 2011; Vallgårda, 2014). Coelho's experimentation with conductive yarns and shape memory alloy wires follows a similar line of work, amplifying the suitability of craft techniques in realizing new technical and aesthetic possibilities at the intersection of smart materials and computation (Coelho, 2007). Franinović and Franzke (2015) has also shown in their work on ephemeral paper interfaces that manual fabrication becomes a critical part of exploring novel and unprecedented aesthetic qualities and expressions. The crafted SMC's in both works blur the boundaries between 'soft' and 'hard' materials in a different processes than just form-giving. These and similar attempts to use materials as an entry point for design practice represent a radical shift in HCI from application design (driven by task completion) to open-ended engagement with the materiality of present technologies (Jung, Wiltse, Wiberg, & Stolterman, 2017).

4.2.2 Material Driven Design Practices

As discussed, materials and their inherent properties can be a fundamental point of departure for discovering and exploring new functional possibilities as well as for designing distinct experiences or shaping desired practices. Over the last decades, the field of interactive arts has creatively stretched the use of technological components and materials (e.g., the work of Loop.ph with electroluminescent wires). A design project that takes the material as an entry point can be motivated by personal curiosity or fascination for a specific material, or commissioned by scientists or an external firm (Lindberg, Hartzén, Wodke, & Lindström, 2013).

However, as design projects with a large variety of emerging materials from smart materials (Ritter, 2007) to bio-based materials (Granberg et al., 2015; Karana & Nijkamp, 2014) are becoming widespread in the field, design scholars have emphasized the need for a deliberate approach to the exploration and capitalization of materials' potential. Referred to as MDD (Karana et al., 2015), the approach pushes beyond the materials' current states of development, whether already developed and marketed, or still underdeveloped. The MDD practices challenge the assumption that design is to re-render "what has already come to pass in the past" (Ingold, 2012), i.e., materials as given, finished and to-be-applied, and instead take materials as open, unfinished and to-be-designed.

What is distinct and deliberate about MDD practices is that they consider design variables that extend beyond product features such as texture and shape, to include, for example, micro-scale structure or direction of yarns or fibers in a composite, so that the material becomes something that needs to be designed (or redesigned) as well. It is this very rupturing of 'materials as finished' and a sensitivity to "flows and transformations of materials as against state of matter" (Ingold, 2011, p. 210) that opens up a space for both the designer and the material to re-relate in combinations other than what has so far been thought possible.

By shifting designers' attention to what materials offer in direct experimentation (Ingold, 2009), MDD practices approach 'making' as a way to unfold the material's capabilities in very-fine grained fashion. The capabilities are not characterized only in engineering and technical terms but also in relation to material experiences, i.e., "experiential characterization" (Karana et al., 2015). The sensitivity for the qualities and actions elicited by the material in interaction (Giaccardi & Karana, 2015) equips the designer with broad understanding of the capabilities.

The MDD practices foreground processual and performative understanding of the material in terms of what they do when you work with them and practically experience them (Ingold, 2012). This paper leverages on such understanding of smart material composites, facilitated through MDD practices, and explores the finer-grained entry points in creating experiential qualities, at performative level. It specifies certain phenomena and strategies that surfaced in navigating the performative possibilities, i.e., the design space in relation to performative characterization of these composites.

4.2.3 Notions of Performativity in HCI Design Practice

Performativity is a multivalent concept used within diverse fields. The idea of performativity initially was conceptualized as linguistic in nature, referring to "the power of language to effect change in the world" as opposed to "describe the world" (J. L. Austin, 1962). It later expanded to consider the embodied and expressive character of human and nonhuman actions and engagements (or performances), always "located at the creative, improvisatory edge of practice in the moment it is carried out" (Schieffelin, 1998, p. 199), and as such always specific and different from each and every other performance (Schechner, 2003).

In the broad field of design, attention to performativity contributes to understandings of the ways in which artifacts are imagined, made and experienced, emphasizing that how the artifact looks like matters as much as how the material performs technically and experientially–that is, how it affects our perceptions and experiences (Kolarevic & Klinger, 2008).

In designing buildings, for example, attention to performativity calls for approaches that "predates the post occupancy design considerations" and equips the building with "the potential to adjust itself to foreseen and unforeseen external contingencies" (Kanaani, 2015; Leatherbarrow, 2005).

In the design of textiles, it may concern elasticity of the material construct of the garment, beyond its pure geometry, so that it can be open to change and alteration by the human body (Schillig, 2010). In product design, attention to performativity has spurred objects designed to disrupt a product expected experience or function, so to require unique performances and counteract prescribed behaviors and dominant routines (Niedderer, 2007).

In HCI,Spence (2016) identifies four applications of the concept of performativity. These are in relation to: (a) the capability of things (e.g., words or artifacts) to act on the world; (b) an emphasis on processes and events (rather than the single object or result); (c) a focus on people's active engagement with the world; and (d) theatrical performance.

Contributions in HCI to understanding and applying performativity in relation to people's bodily engagements and theatrical performance is vast and substantial. It goes from foundational work on technology as situated (Dourish, 2001) and as 'lived and felt' (McCarthy & Wright, 2004), to work that more specifically considers the interaction with a computer as a theatrical performance to be orchestrated Benford and Giannachi (2011), to projects that use performativity to emphasize the physically embodied nature of human interactions and what that means for designers (Jacucci et al., 2009; Jacucci & Wagner, 2007; Lian & Toni, 2010), in particular their "free-flow, non-directed conversation" with design materials (Iacucci et al., 2002). Embodied ideation methods, including role-playing and body-storming, have paid special attention to the corporeal aspects of imagining yourself in the minds and bodies of people carrying out practices (Giaccardi, Paredes, Díaz, & Alvarado, 2012; Kuijer, Jong, & Eijk, 2013; Wilde, Vallgårda, & Tomico, 2017), on the premise that "by acting before understanding, we approach the possibility of learning in our bones" (Schleicher, Jones, & Kachur, 2010, p. 51). It is the line of HCI work concerned with bodily conversations with the design material (e.g., Iacucci et al., 2002) and how design can shape human and nonhuman performances (or capability to perform, more specifically in our case), which this paper contributes to.

More specifically, the paper relates to craft-oriented works in HCI that emphasize the role of pragmatic skillful engagement in supporting forms of knowing through an immersive sensory experience of the material at hand (Dewey, 1934; Nimkulrat, 2012). HCI papers describing craft-oriented practices with traditional materials include leather (Tsaknaki, Fernaeus, &

Schaub, 2014), hand-blown glass (Schmid, Rümelin, & Richter, 2013), and paper (e.g., Buechley, Hendrix, & Eisenberg, 2009).

Similar to these studies, Karana, Giaccardi, Stamhuis, and Goossensen (2016) illustrate a designer's journey in foregrounding the performative qualities of a range of materials. The design process is focused on the familiar practice of 'tuning the radio' to explore alternative and possibly more expressive performances for tuning (e.g., *kneading*). Here different materials and their unique qualities were considered in their performative character rather than as form-giving substances. However, in these early explorations of the performative qualities of materials, the bodily aspect of the performance is addressed from the perspective of the user only. In this paper instead, we are interested in teasing out the perspective of the designer in her making practice, and the strategies that have been put in place 'before understanding' and developing a vision for how the material should be infused in products. In doing so, the paper shifts the focus from selecting materials for their known performative qualities to an investigation of what the material may offer in response to the designer's skillful, bodily engagement in an open-ended design situation, in which the material is approached as 'underdeveloped.'

4.3 Design explorations of electroluminescent materials

Electroluminescent materials are smart materials that emit light in response to changes in a strong electric field. They have been recently used for prototyping customized thin-film displays, because of the rapid and inexpensive fabrication techniques such as screen printing and conducive inkjet printing made available to non-experts (Olberding et al., 2014). These fabrication techniques enable luminescent materials to be easily crafted through tinkering with the layered structure of electroluminescent composites and their main constituting elements. These components include two electrodes (at least one of which must be transparent to let the light escape), phosphor, dielectric insulator, and substrate. The choice of electroluminescent materials as a case for our research is motivated by the EU project, Light.Touch.Matters. The project proposed collaborative development of smart material composites, by involving designers in the early processes of developing composites of thin-film luminescent materials and piezoelectric polymers. These underdeveloped pressure and deformation sensing luminescent composites could, as proposed, unlock novel experiences and applications, particularly in relation to their unique performative qualities. To identify the design space with these underdeveloped composites, we initiated several MDD projects, e.g., departing from unprocessed electroluminescent materials.

In this paper, we present four explorations from different MDD projects carried out by industrial/product design students at Delft University of Technology. These explorations are selected from five material driven design projects. Three of these explorations were group projects conducted for the Materials for Design elective course; two were part of master's graduation projects. The elective course was approximately nine weeks, and graduation projects lasted from five to six months. All students were given the same design assignment to create product applications with the electroluminescent materials. They were instructed to follow the step-wise method of Material Driven Design (Karana et al., 2015) which prioritizes materials understanding through tinkering and making, and promotes designing for materials experience.

Wondering 'how designers explore the performative qualities of electroluminescent materials departing from an underdeveloped state', our investigations focus specifically on the material making of the design students. The designers were initially acquainted with the 'materials experience framework' (Giaccardi & Karana, 2015) and were offered an introductory workshop on the basics of electroluminescent material printing. The first author closely observed and made notes of their processes on a daily basis through direct supervision. The designers also were asked to document their process through written explanation, photographs and videos of their experiments and samples. By triangulating data from the first author's notes that were taken during these processes and data from the designers' own diaries (textual annotations, pictures, and physical materials samples), we reconstructed how each final electroluminescent sample has come into being. These served as input for the analysis of the design variables/phenomena at stake and their relations to the actions and qualities evoked by the created samples.

The reconstructed explorations were, accordingly, clustered in relation to the four variables/phenomena of 'matter', 'structure', 'form' and 'computation'. These concepts not only are largely used in materials science and design models (Ashby & Johnson, 2002; van Kesteren, 2008) and material driven

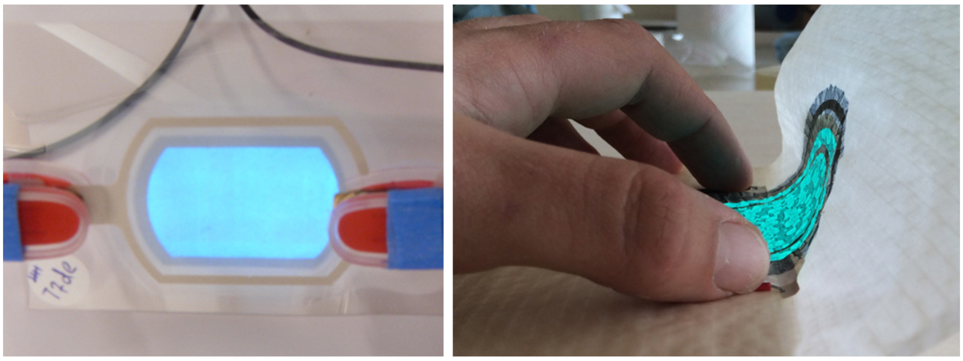


Figure 4.1 – Two different layering sequences were used: bottom-emitting electroluminescent sample (left), top-emitting electroluminescent sample (right).

HCI research (Döring, Sylvester, & Schmidt, 2013; Jung & Stolterman, 2012; Vallgårda & Redström, 2007), but also were referred to (implicitly or explicitly) by the students. Anchoring the analysis and discussion to these concepts we were able to reach beyond the limits of our specific material case (electroluminescent materials) and to draw inferences that are relevant to a wider range of smart material composites. Interestingly, a converging strategy was identified in their making of performativity that is elaborated in the following section.

4.3.1 Making Electroluminescent Material Samples

In order to make an operational electroluminescent sample, the designers were instructed to print and cure (in the oven) three layers of materials on an indium tin oxide (ITO) coated polymer sheet in sequence. First, the phosphor paste was screen printed and cured in the oven and then the same procedure was repeated for the dielectric paste and, finally, for the silver paste. The electroluminescent sample made through this process is referred to as *bottom-emitting* sample, since light exits from the rear side of the substrate sheet (Figure 4.1, left). Several *top-emitting* samples were also made, using variety of non-conductive substrates, such as paper and textiles (Figure 4.1, right). For fabricating those samples, the printing sequence had to be altered (silver, dielectric and phosphor) and a fourth ingredient, the transparent organic conductor ink (PEDOT), had to be added on top. The samples were then connected to a powered DC-AC converter through dedicated connection points and, in case of no defect, lit up.

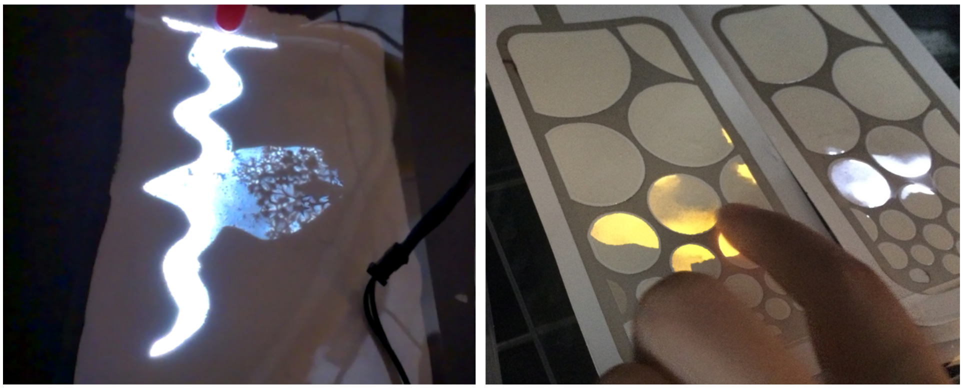


Figure 4.2 – Using water as a replacement for the printed conductor: the bottom-emitting sample (left), top-emitting sample (right).

Besides the knowledge of the layering sequence and the ingredients and know-how of screen printing in making operational electroluminescent samples, all the designers were equipped with a higher level understanding of the electroluminescent basic working principles. For instance, in either top or bottom emitting sample, the phosphor paste must be enclosed between two electrodes or at least one electrode must be transparent. The underdeveloped state of the electroluminescent materials, when accompanied by the conceptual and practical support, enabled them to explore the relationship of matter, structure, form, and computation for creating an expanded set of (performative) qualities.

Design exploration #1: Matter

In an exploration series, the designers followed the layering sequence presented in the work of Franinović and Franzke (2015) to create samples that require water to illuminate. The realization that the solid electrodes can be partially replaced with liquid conductors motivated new ways of interacting with electroluminescent materials. As shown by Franinović and Franzke (2015), water can be *sprayed* (e.g., using a syringe) or *splashed* using hands. In addition to water, the designer experimented with a water-based gooey substance (i.e., Silly Putty) on both bottom- and top-emitting electroluminescent samples and explored the action possibilities of incorporating different matters. Since electroluminescent requires relatively high voltage, it is not safe to simultaneously touch the top and bottom electrodes. Isolating the bottom conductor from skin contact, the designer created safe-to-touch samples that elicited playful interactions

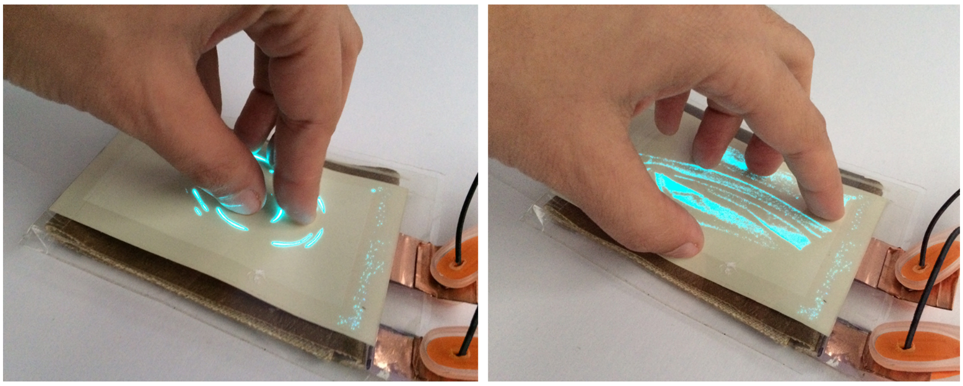


Figure 4.3 – Using different conductive materials in between the separated structure: conductive rubber band (left) and conductive textile (right).

such as *sweeping* and *brushing* with fingers (Figure 4.2, right). In another trial of this exploration series, the designer made a bottom-emitting sample that was placed over a smear of Silly Putty and water (Figure 4.2, left). This sample elicited very different range of actions, including *pressing*, *stroking*, and *poking*. Viscosity of the Silly Putty and its sticky and bouncy qualities were key in encouraging those actions.

Design exploration #2: Structure

In another exploration series to make active samples, the designer separated the two electrodes. The possibility was accidentally discovered by Franinović and Franzke (2015), when they used an ITO coated polymer on an unfinished electroluminescent sample (which was basically missing one electrode). The structural intervention resulted in two separate sheets that do not emit light unless assembled and pressed against each. The two separate sheet allowed the light output to be varied in pattern, corresponding to the conductivity and contact area of the conductive materials placed in between them (Figure 4.3). The designer harnessed the qualities of conductive materials, including textiles (e.g., to wrinkle) and rubber (e.g., to bounce back) to stimulate variety of actions such as *rubbing* and *pressing with the palm*. In the interplay between structure and the interactive/experiential qualities, the sample is both operational and flexible/adaptable, inviting the designer to further explore the relationship of material, body, and light.

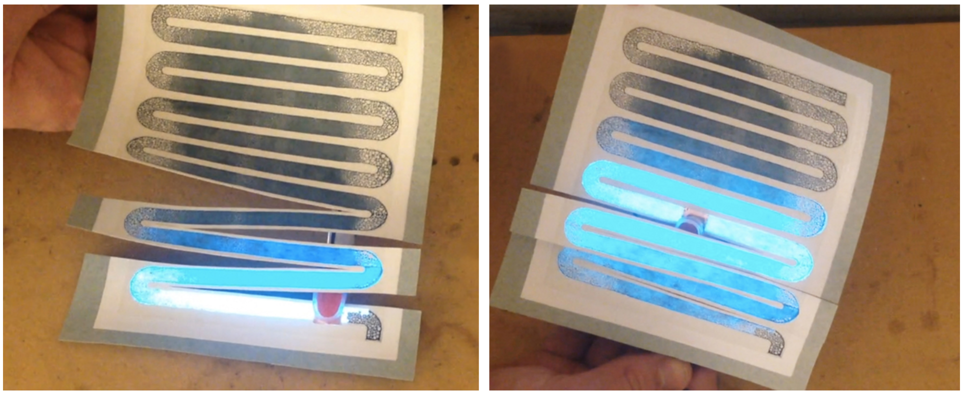


Figure 4.4 – The gradient effect achieved by altering the form of the printed top-conductor.

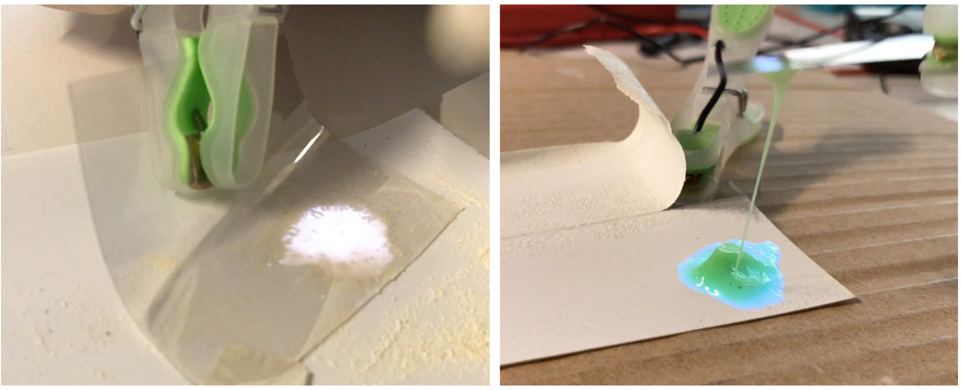


Figure 4.5 – Tinkering process with the phosphor powder (left) and Silly-Putty (right).

Design exploration #3: Form

The next exploration began with a discovery that length of the top electrode can be a variable in designing with electroluminescent materials. The ratio of length to area determines electrical resistance of each point along the printed line, and, by playing with the resistance, a gradient effect can be created. The designer, accordingly, prepared a serpentine pattern for printing the top electrode (i.e., PEDOT) on a thick paper substrate. Using multiple connection points, the light gradient could be moved along the printed trace, as illustrated in Figure 4.4. To access the middle parts with the connection clips, the substrate was cut, leading to an accordion form, which also allowed for *stretching* and *contracting* actions. Inspired by such stretchable form, the idea to incorporate additional contact points at the edges of the cuts was also envisaged. With such modification, possibly, the

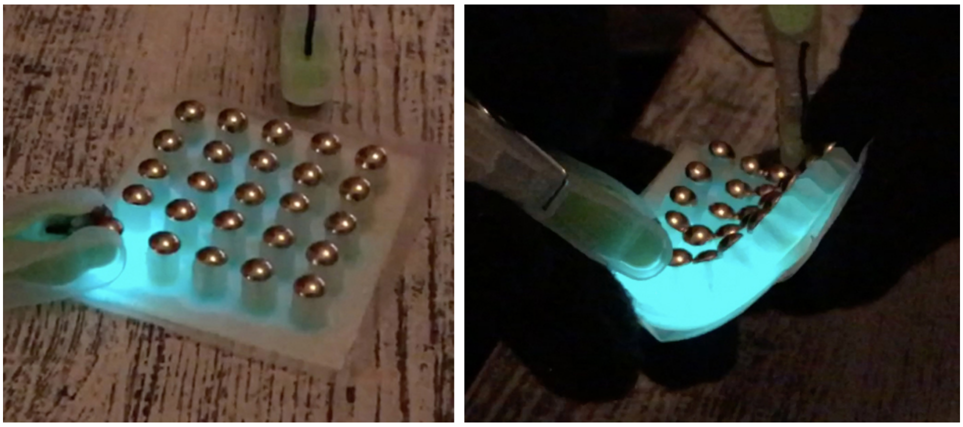


Figure 4.6 – The electroluminescent sample with multiple bulgy contact points.

gradient light could grow and shrink corresponding to the action.

In another project, the designers take the idea of corresponding the light spatial movement with people's action to a new level. They began with a series of experimentation with (cured) phosphor powder, to see if it can light up in between two ITO sheets (one insulated with layer of dielectric). However, except for hardly visible sparks not much of light could be produced by this recipe. They continued the experimentation by sprinkling water on the powder and the uncured phosphor paste, which in both cases resulted in visible light output (Figure 4.5, left). Seeing that liquid-form phosphor performs better, the idea of using powder phosphor was abandoned. Similar to the exploration #1, the designers printed the phosphor layer on the insulated ITO sheet and explored with Silly Putty. The possibility of having the connection point distant from the unfinished printed sheet was experienced during their tinkering with Silly Putty (Figure 4.5, right). Having multiple Silly Putty lumps on a single sheet (that basically leveled the connection points) let the designers light the phosphor underneath individually or collectively. Understanding how the height of the lumps unlocked new action possibilities, they created a sample that combined the idea of multiple connections and the structural separation (exploration #2). By making an array of small bumps with metal caps on a sheet of silicon (Figure 4.6), the designers conditioned activation of the phosphor in each bump to making contact with the adjacent ones. The design requires people to *bend*, *squeeze*, and *knead* the silicon sample to spread the light.

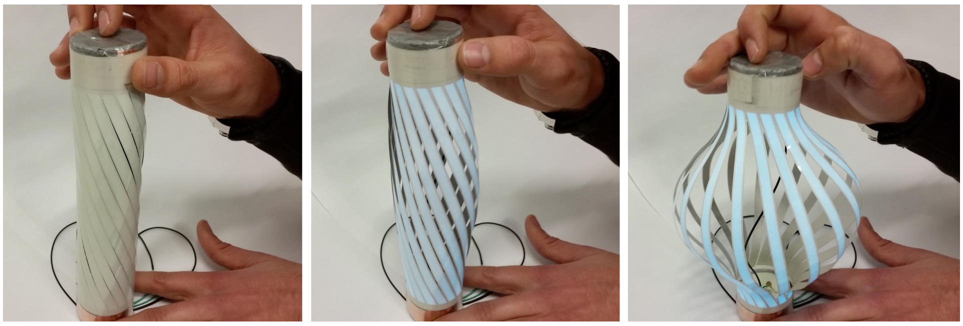


Figure 4.7 – Computationally corresponding action with electroluminescent light intensity.

Design exploration #4: Computation

Besides inspecting how matter, structure, and form of the electroluminescent materials contribute to creating novel performances, the designers also re-examined the possibilities of manipulating the electrical connections and control unit. Creating a range of cuts (inspired by Japanese art of Kirigami), that allow the 2D surface to become 3D objects, the designers followed a more classic approach to exploring the action possibilities. The performable structures, however, did not provide any response unless an external sensing component was incorporated. With no structural alteration and relying merely on a cutting technique (form), an intermediate object (not sample, nor a product) (Barati et al., 2016) was created. As illustrated in Figure 4.7, the object could deform between a closed cylindrical and an open vase-like shape. The designers realized that such deformation can control entry of the surrounding light into the cylinder. Thus, the electroluminescent light output could be conditioned by people's action (e.g., *twisting with a gentle inward press*) by means of incorporating a light sensor inside the cylinder and modifying the electroluminescent driver electronics.

4.4 The Making of Performativity in Material Driven Design Practices

Skillful engagement with electroluminescent materials enabled designers to get a feel for action possibilities of the material that were unknown and unrealized in the early stages of the process. Designers' performances were key in perceiving and materializing the affordances of electroluminescent materials. Studying this making process enables to

Figure 4.8 – Functional disruption in the product series designed by Katherina Kamprani: (a) Thick Cutlery Set and (b) Chained Fork (source: https://www.theuncomfortable.com/).

explain how such performative potential was actualized. The cases used to illustrate the process pinpoint and identify variations of what we believe is an overarching *disruption* strategy in characterizing and mobilizing performativity.

Approaching electroluminescent materials through a rupture of their components destabilizes conventional boundaries between human and nonhuman performances, and displaces the common designer-technology relations. *It is through this material driven displacement that a space opens up for the designer and the electroluminescent material to perform and relate in combinations other than what has been initially thought possible*. This departure from common designer-technology relations relies on a performative understanding of the composite as underdeveloped.

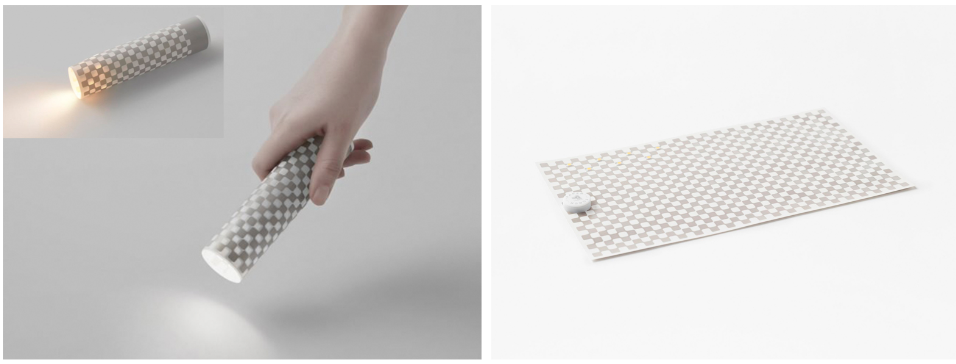


Figure 4.9 – Paper Torch by Nendo (http://www.nendo.jp/en/works/paper-torch/).

4.4.1 Disruption of Affordance as Design Strategy

The term disruption has been increasingly used over the last years mainly in relation to design thinking in business innovation (Christensen, 2006; DeFillippi, Rieple, & Wikström, 2016). Often, disruption of the known and existing is needed for change to take place. Design is a practice particularly apt to make change happen. Disruption in this case refers to the problematizing attitude of the designer along the process of making and conceptualizing, in the urge to push boundaries.

At the product level, pushing boundaries by means of disruption is often the result of a disruption of the function conventionally attributed to well-known objects (e.g., dishware). For example, Niedderer (2007) has designed a series of "performative objects" meant to be forcefully social. By breaking the "plan for action" embodied in the product, the designer fundamentally disrupts patterns of perception and preconception. From this series, 'Social Cups' are designed to shape people's interaction with each other by means of a deliberate functional disruption. Five round-bottom cups are connected by a mechanism that allows them to stand upright. When at least three cups are connected, they form a stable unit. As the function of standing is disrupted if more cups are detached, people are encouraged to socially interact with each other in a mindful way. As a consequence of this functional disruption and the actions put in place by people to compensate for the disruption, people perform with the cups in an unconventional way, which in Niedderer's work is meant to promote sociability. Other examples of functional disruption can be found in the product series called 'The Uncomfortable' (see Figure 4.8), designed by Athens-based designer Katherina Kamprani. Being deformed (e.g., a watering can), too thick (e.g., thick cutlery), not sturdy enough (e.g., chain fork), these products incorporate various strategies to break the affordances necessary to perform the conventional function of *watering the plant* or *eating*. In this series function is disrupted without offering a clear means of compensation or an alternative plan for action (Niedderer, 2007). They are intentionally dis-functional. However, in both Niedderer's and Kamprani's work, the expectation to perform and the norm of efficient functionality are equally challenged. While both sets of objects maintain visual and semiotic references to the original product categories (champagne glasses, cutlery), at the pragmatic level they disrupt the *expected affordances* of those categories. A similar approach in HCI design practice is found for example in the work of Pierce and Paulos (2015).

When it comes to the material level, disruption is rather a more fine-grained rupture aimed to actualize *unexpected affordances*. Imagine that we have a rigid composite sheet developed originally for certain structural performance. The heterogeneity of the composite, in making, allows for a range of samples that are fully rigid, fully flexible, or both qualities at once (e.g., rigid from one direction, flexible from another). After being fabricated, however, the flexible sample and the patterned sample enable new action possibilities that were not afforded readily by the rigid composite. In MDD practices, materials are often processed and treated to prompt new and unanticipated qualities, beyond established boundaries (e.g., Thompson & Ng Yan Ling, 2013). These boundaries can be our expectations for materials to perform in certain ways and/or a norm of efficient functionality (Niedderer, 2007). An example that gets close to challenging those boundaries is 'Paper Torch' by Nendo (Figure 4.9). The flat surface may not maintain visual and semiotic references to a torch, but it affords rolling so that it can be gripped in hand the way a typical torch is handled. By varying the path length of each LED, corresponded to how tight the paper is rolled, brighter or dimmer lighting can be achieved. Moreover, due to the characteristic of the LEDs, the light color can switch between warm orange and white color, as the paper is rolled inside out. Here, perhaps, the *ambiguity of affordances* and an intentional resourcefulness of Paper Torch are accounted for its adaptation in different use situations and the unfolding of new performances.

In the electroluminescent cases described in this paper, we noticed similar diversions from existing recipes that can be framed as various manifestations of affordace creation through disruption. Borrowing Niedderer's logic, we may say that changes in matter, structure, form, and computation disrupt the light-giving 'function' of the electroluminescent materials that was initially afforded by the switch. Performativity is thus achieved through deliberate disruptions of this obvious plan for action and by introducing other means to compensate for it. Anchoring to design variables of matter, structure, form, and computation, designers managed to variously disrupt the efficacy of switching On/Off action and materialized new action possibilities involving people's corporeal interaction with the luminescent material.

In exploration #1 and #3 the state of the conductor is variously altered (liquid, solid, gel) to diversify action possibilities. By taking the state of matter as an entry point (Döring et al., 2013) and replacing the solid conductor with liquid or gel conductors, the designer breaks the static interaction pattern and enables creative patterns of action to unfold. In exploration #2, the loose structure enables a wide range of actions from adding different conductive materials in between the substrates to modulate the contact area, by stroking and pressing the modified composite to reveal the patterned light. In both explorations, the electroluminescent driver as well as the connection points stay intact and unchanged.

On the contrary, in exploration #3, the designers increase the control states between solid-surface illumination and dynamic patterns by increasing the connection points, facilitated by the specific form of the sample. These connection points, basically, intervene into how the electroluminescent driver and the composite structure interface. By channeling stimuli (electric current) through more connection points, an originally single-contact electroluminescent composite is transformed into a multi-contact sample. In other words, the designers made a matrix of electroluminescent patches that were individually controlled through physical engagement with the substrate. Finally in exploration #4, the designers did not change the material structure, as both the layer sequence and the components stayed the same. Instead they hacked the electroluminescent driver and controlled the electrical stimuli based on the input from an ambient light sensor. The particular form of the object and the programmed behavior together could then influence the light output in relation to one's action.

The material samples created by the designers do not have a specific function, like a cup or a fork might have. Rather, the expected light-giving quality of electroluminescent materials is disrupted through structural and non-structural interventions, with deliberation to open up new action possibilities. In this way, the samples can give light in ways that move past the conventional switching of an On/Off button. Because the novel performances, afforded by the new action possibilities, unfolded in the making process cannot be easily 'restored' in the context of use, designers will need to think of how to invite people to splash water or move the gradient light. In all the described cases, after creating the material sample, the designers were asked to explore which conditions and situations might help facilitate the performances encountered by the designer in the making process. For instance, inspired by the gradient quality of light output and the possibility of spatially moving it across the printed pattern, the designers came up with the idea of a 'discovery' book for children. As shown in Figure 4.10, the solid print of the top electrode conceals the hidden visual pattern that can be revealed by means of moving the torch (electrical connection) over the page. The torch provides a symbolic cue to hint how

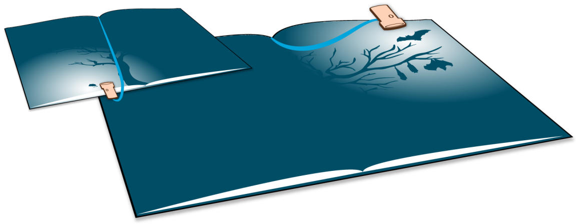


Figure 4.10 – The children book concept, inspired by the gradient sample.

the content of the book might be accessed. Without active browsing using the torch, the content of the page remains invisible. In this example, the deliberate disruption of the book function (i.e., providing visual content) and resulting curiosity to see the content of the page encourage desired performances in a specific context of use.

4.4.2 Understanding the Material as Underdeveloped

When designing (with) smart material composites, being able to bodily engage and collaborate with the material to elicit unexpected performances is key to encounter new capabilities and demonstrate *different faces of a material* (cf. Granberg et al., 2015). The Material Driven Design approach grafts onto existing creative practices (e.g., interactive arts) and materials but it also moves past practice-based material exploration and customization to create new opportunities for a broader spectrum of designers. This performative understanding of the material echoes theoretical positions that regard matter as an active participant, denying that there are representations on the one hand and, somehow, separate entities awaiting representation on the other hand (cf. Barad, 2003). The conceptual articulation of smart materials as underdeveloped composites is critical to unpack the ways in which designers might methodologically bring about the performative potential of a smart material by means of variations, hacks or disruptions of the electroluminescent material's matter, structure, form, and mechanisms of computation. In this perspective, materials are understood and acted upon as unfinished or underdeveloped entities, which we have referred to in this paper as 'the making of performativity'.

To explain how the designers enacted the performativity of electroluminescent materials, both *properties* and *function* seem to be insufficient concepts. The former qualifies an existing material sample (answering what it is), while the latter concerns its contextual purpose (answering what it is for). The relational concept of *affordance* (Gibson,

1979) perhaps can provide designers with a more inclusive and useful approach–as in Gibson's original definition, an affordance is just "a material disposition" (Harré, 2002) where both properties and function are underspecified.

While the making of affordance (e.g., portability) in design can be driven by having a clear function in mind (e.g., serving food), MDD practices take a rather *bottom-up* understanding of affordance that is anchored to the material. In tinkering with an underdeveloped material whose affordances can still be manipulated, the way in which the designers act upon the material may become the medium for materializing affordances (cf. Dokumaci, 2017). For instance, as discussed in exploration #3, the electroluminescent cardboard unfolded new possibilities for action and expression once practically cut to reach to the middle part of the cardboard.

Initial hypotheses in the making of composite might be useful when designers have sufficient understanding of the range of technical and experiential qualities of the composition, in relation to the envisioned context of use. For instance, in the explorations with electroluminescent materials, designers were able to make assumptions based on prior knowledge of physics law (e.g., the possibility of gradient light due to the inverse relation between resistance and current). Even in that case, later in the process of making the children book, the whole page lit up and the actual prototype did not work as envisioned (see Figure 4.10). While a technical explanation is that the large printed area has comparably small resistance to create the gradient effect, additional experimentation and making iterations were necessary. As Ingold points out,

> Thinking does have the habit of running ahead of making and it does. There is to which we are not just feeling our way forward but in which our actions are being pulled in front. Our imagination runs a head of what we do. And yet when we are working with materials there is a limit to how fast we can move. Materials have their own way. they held us back momentarily in check with slow movement of working with materials (Ingold, 2012).

Compared to amateurish tinkering, the skillful making informed by both technical and practical knowledge is a clear advantage of MDD practices that promote a performative understanding and engagement with the material as always 'unfinished.' In such practices, the rupturing of the material to new capabilities can be considered as a form of *affordance-making*: *a making process in which both the designer and the material perform in response to the skillful exploration of not-yet actualized affordances*.

4.5 Conclusion

In this paper, we have presented and discussed a number of material driven design (MDD) explorations which take their departure from an underdeveloped smart material composite, specifically an electroluminescent material composite. These explorations are focused on the creation of electroluminescent material samples with novel action possibilities and are facilitated by the designer's skillful engagement with the electroluminescent material. In describing the making processes, we have articulated how bodily manipulations of matter, structure, form, and computation can facilitate the emergence of certain performances. Examining the explorations from the perspective of what we refer to as the 'making of performativity' in MDD practices, the paper introduces the idea of *disruption of affordance* as a design strategy for working with smart material composites. We conclude by promoting how such conceptual articulation of smart materials as underdeveloped composites may unpack new ways of bringing about the performative potential of a smart material and revealing its latent affordances. In the MDD approach, as proposed, materials are understood and acted upon as always unfinished or underdeveloped. This offers HCI design practice with smart material composites a better leveraging of the dynamic properties of such materials, and potentially more dynamic responses and performances by the products in which these materials may be infused.

5 Materials Potential Framework

Given the growing interest in 'upstream' collaborative projects between designers and materials scientists, it is crucial to scrutinize designers' creative contribution to materials development beyond coming up with application ideas. Overcoming this outdated preconception requires a shift away from the dominant perspective of cognitive psychology that understands creativity as in designer's mind to an understanding of it as distributed between the designer and the material world. Creativity as such requires designers' active participation in 'discovering' the novel potentials of material rather than merely translating the 'given' materials information to product applications. In this paper we propose the 'Materials Potential Framework' to liberate materials from the stigma of a solutionist approach only (e.g. materials selection and application potential), and open up the possibility to approach materials, generatively, for all they have to offer (i.e. materials potential). To that aim, our paper explores the existing notions in the discussions of *material potentials*, namely form, function, and experience as materials potential, and provides a conceptualization beyond the evident merits of the eventual product applications. The conceptualization of *affordances as material potentials* shifts the focus to designers' skillful act of making and fabricating as a way of 'perceiving', 'inventing', and 'exploiting' novel affordances of conventional and emerging materials.

Chapter 5 is in the review process of *International Journal of Design*: Barati, B. & Karana, E. Affordances as materials potential: What design can do for materials development.

5.1 Introduction

Parallel to the growing interest in 'upstream' collaborative projects between designers and materials scientists (e.g., EU Projects like LTM, BioX, Damadei, Trash2Cash), researchers have pondered on what designers could do for materials development (e.g., Nathan et al., 2012). Referred to as 'creativity/design-driven' materials development, these projects make an explicit reference to the creativity contributions expected from designers, for example, by assisting in the development of prototypes to illustrate possible application areas, or by bringing the perspective of consumers to material research. But how can 'designers' contribute to such projects if the materials development state is still far from being 'commercialized'? Is their creative contribution about 'generating product ideas' for these new, yet 'underdeveloped', materials? Or, does it go beyond?

Many researchers and practitioners have argued that designers can bring to light a different, possibly more encompassing, understanding of the potentials of a new material (e.g., Colette, 2017; Lefteri, 2012; Miodownik, 2007; Montalti, 2017; Nathan et al., 2012; Nimkulrat, 2009). Traditionally in materials and design, materials potential is framed as the application potential of materials, following the triad of 'fabrication' (i.e., preparation of materials for initial use), 'application' (i.e., transformation of materials into products), and 'appreciation' (i.e., reception of materials by the entire community of users) (Doordan, 2003). This conceptualization falls short of specifying the creative contributions of many designers who are involved in material(driven) design practices, e.g., DIY-materials (Rognoli et al., 2015). These emerging design practices at the intersection of design, materials science, biology, arts, and crafts, radically changed the role of the designer from a 'passive recipient' to an 'active maker' of materials (Myers & Antonelli, 2012; Ribul, 2013; Rognoli et al., 2015). In these practices, the material 'elicits and actualizes' (designers') intentionality. The 'mediational potential' of the material (Malafouris, 2008), identified by the 'situational affordances' (Gibson, 1979; Knappett, 2004) and discovered through skilled action (Ingold, 2013), shapes the nature of designer's intentions (Malafouris, 2008) and creative action (Glăveanu, 2014); so as the creative contribution of designers to materials development. Studying these skillful material practices has contributed to more recent theories of creativity, namely embodied creativity (Stanciu, 2015) and distributed creativity (Glăveanu, 2014), looking into the intimate interplay between the mind, the body, and the environment in the unfoldment of human creativity (Rietveld and Kiverstein, 2014). However, these relatively recent scientific endeavors are still in their infancy (Stanciu, 2015); therefore, far from being embedded in design research and in the organization of collaborative projects where designers are expected to make a creative contribution.

As we turn our attention to how ‘creative contribution, or creativity’ is understood in design, we notice that most cognitive theories responsible for idea and concept generation (e.g., divergent, analogical and associative thinking), hardly scratch the complexity of such creative practices (Glăveanu, 2014; Malafouris, 2008). They have explained how *problem framing* (Schön, 1983), coevolution of problem and solution pairs (Dorst & Cross, 2001) and interpreting and bridging the information, in a brief, for example, are important in supporting a ‘creative event’ (Dorst & Cross, 2001). Viewing design as a ‘problem-solving’ activity has led to assess design creativity based on generated outcomes that are novel and efficient (or appropriate) in resolving ‘problems’. But perhaps, the concept of problem-solving ‘leaves too much out that are of real significance’ (Malafouris, 2008, p. 32) in understanding of how material potentials are discovered and exploited in material (driven) design practices. Embracing those theories of problem-solving that consider the phenomenological compound of brain, body and resource (see Hutchins, 1995; Kirsh, 1996), many design researchers elaborated on how the social context of designing and external (visual and informational) stimuli (e.g., Howard, Culley, & Dekoninck, 2010) may influence designers’ creative performance. These embodied and distributed views, however, have not challenged the established position of ‘idea-generation’ as the main focus of creativity studies in the field of design research (e.g. Chulvi, González-Cruz, Mulet, & Aguilar-Zambrano, 2013; Sarkar & Chakrabarti, 2011).

The disconnection between the emerging material practices and prevalent understanding of creativity in design can have consequences for the proposed methodologies or organizational structures’ of such collaborative projects, and the achieved outcomes. For instance, designers might be expected to understand new (and possibly yet-underdeveloped) materials and their potentials and conceptualize applications, while their access to the new material is kept indirect and mediated (e.g., through information and schematics, Barati, Karana, & Hekkert, in review). Or, the project might be organized in a way that designers end up framing and rendering with their *imaginative minds* what others (e.g., material scientists, engineers) have already assumed to be the material potentials (cf. Ingold, 2012). There is no problem with such a one-way dialogue, as long as the 'guest' designers are clearly briefed and commissioned, rather than referring to the project as creativity-driven materials development.

We strongly believe that designers should be equal partners in projects where 'creativity-driven materials development' is considered as the core merit. This requires designers' active participation in 'discovering' the novel potentials of material rather than merely translating the 'given' materials information to product applications. To that aim, we need to revise our understanding of the design practice as an evolving interdisciplinary material practice, corresponding to the recent developments in the field, and work with creativity theories that embrace and reflect such embodied and distributed accounts of design creativity. To take a theoretical step towards supporting such equity in upstream collaborative projects, our paper explores the existing notions in the discussions of material potentials and provides a conceptualization beyond the evident merits of the (proposed) product applications. Drawing on the recent work in the emerging fields of embodied and distributed creativity (e.g., Glăveanu, 2014; Malafouris, 2014; Rietveld & Kiverstein, 2014), we introduce and elaborate on 'affordances as material potentials'.

A framework of 'Materials Potential' is presented to provide an expanded vocabulary in specifying and discussing designers' creative contribution to materials development. To that aim, the paper revises the prominent concepts in material-related design literature (i.e., form, function, experience) in the understanding of materials potential to date. It expands on this conceptualization by shifting the focus to designer's skillful act in materials engagement and discuss how novel affordances, as materials potential, are 'perceived', 'invented', and 'exploited' through the act of making (Glăveanu, 2012). We present a number of design cases from our and the others' creative material driven design practices to illustrate how these theoretical concepts may apply.

5.2 Materials and Creativity Crossovers in Design

The aim of this background section is to provide an overview of the developments in the field of design research at the crossing of materials and creativity, ever since the Bauhaus.

The Bauhaus (1919-1933) has a profound influence in the development of the design fields, particularly, in establishing a pedagogical and pragmatic approach to materials understanding and creativity (Vernon & Sullivan, 2007). The masters and students at the Bauhaus were first to combine the know-how of traditional craftsmanship with contemporary machine processes, and to create a unified style that brought together art, craft and technology. Bauhaus masters were keen advocates of learning about/with materials through sensory encounters and hands-on exploration (Bayer, 1975). Their educational approach reflected the intimate connection between direct experiences of materials and learning about their essential and diverse characteristics. The hands-on approach was indispensable to the central principle of 'truth to materials', which favored forms and expressions that were 'honest' to the 'nature' of the material. The Bauhaus promoted the use of unorthodox materials (e.g., tubular steel) and leveraged on their design potentials in constructing furniture pieces that are now considered design classics (e.g., cantilever chair by Marcel Breuer).

The first-year workshops with different materials (*vorkurs*) at the Bauhaus was a means to liberate the pupil "from the dead weight of the conventions" (Mindrup, 2014). Here, creativity is in transgressing such norms and is directly linked to the visual and tactile experience and practical application of materials and forms that emerge from a process of manufacture (Franciscono, 1971; Mindrup, 2014). The 'Bauhaus idea', as argued by Moholy-Nagy, was to delve into a given medium in order to extract the key properties of its structure and translate them as 'productive principles' (Mindrup, 2014). He remarked, for instance, how the processes of cutting and sawing made a rigid board 'rubber-like', irrespective of whether the board was made of cardboard, plywood or metal (Mindrup, 2014).

Many designers in the history of design followed a similar approach and constructed products by direct exploration and manipulation of materials and their diverse shape, texture and finishing possibilities. Contemporary examples include Paulo Ulian (marble), Tokujin Yoshioka (paper, glass), and Piet Hein Eek (scrap wood). However, as complexity of the design projects and problems escalated, materials knowledge and expertise became increasingly distributed among designers, engineers, material suppliers, and manufacturers, given rise to a need for efficiently exchanging the 'key' materials information.

Designers as 'problem solvers' and 'visionaries' needed efficient ways of realizing their solutions by selecting the 'right' material from a large pool of commercial materials, that were largely developed by scientists and engineers. The elaboration of 'materials selection' models and tools in design literature mirrors this established need of design practice, closely linked to functional design. The scientific understanding of materials, made possible through probing and measuring their structure and properties, allow designers to handle materials as bundles of properties (Ashby, 1999). As Ashby (1999) explains, it is not a material, per se, that the designer seeks; it is a specific combination of process and material attributes. This scientific/engineering perspective to materials provided solution to the complexity of finding an optimum match to predefined design intention and requirements. So, instead of trying each and every material directly, digital databases and property profiles enabled designers to compare the technical performance of the materials and reduce their choices to a handful. Today there are numerous tools, specifically developed to assist product designers and engineers in their material decisions (for a review of the digital tools for materials selection see Ramalhete, Senos, & Aguiar, 2010), including general databases (e.g., Cambridge Engineering Selector (CES) by Granta) and manufacturer databases (e.g., Sensotact® by Renault in Allione, Buiatti, De Giorgi, & Lerma, 2012). Cambridge Engineering Selector (CES), for instance, provides a vast database for materials and their properties, allowing designers to find, plot, and compare materials data.

Besides their functional roles in embodying products, physical materials inspire and enable designers to explore and navigate the solution space (Halskov, Christensen, & Wiberg, 2018). Furthermore, they are instrumental in creating tangible manifestations and representations of the intended design (e.g., Brandt & Grunnet, 2000; Buchenau & Suri, 2000; Ehn & Kyng, 1992). Field observations and interviews with product designers affirm that they largely rely on their personal and professional experiences with materials (Karana, 2009; Pedgley, 2014; Petreca, 2016; van Kesteren, 2008). They visit material fairs (e.g. Material Xperience Fair by Materia, or materials library of Materials Connexion), collect material samples and product parts to expand their repertoire of new materials and trends as well as to touch and feel new materials. It has been argued that such hands on experience with new material samples compensates for the limitation of property-profiles and data sheets in capturing and transferring aesthetic experience and meanings of materials (Akin & Pedgley, 2016). Yet, over the past decade, design researchers have developed tools and approaches for materials selection, to deliberate over experience-related aspects of materials and and include them more systematically in the design process beyond individual experiences of designers (e.g., Karana, 2009; Rognoli, 2010; van Kesteren, 2008; Zuo, 2010) (see Pedgley, 2014 for an overview). To incorporate a phenomenological understanding, most initiatives rely on user-centered approaches, such as interview and focus-group studies, and propose novel approaches to include stakeholders in material decisions (Pedgley, 2014).

A more recent development in materials and design concerns a growing number of 'experimentalists' and 'makers' among artists, designers, architects, and engineers with a focal interest in (materials) fabrication (see, Karana et al., 2015; Kolarevic & Klinger, 2008; Kretzer, 2017). Technological developments, namely advanced and smart materials and new means of digitally enabled material production, as well as concerns regarding sustainability (Ferris, 2013) and democratization of technologiesand empowerment of societies (Tanenbaum et al., 2013) are closely linked to this persistent design movement. As a consequence of such technological and social developments, the largely linear and standardized interface of design and materials in the twentieth century is giving way to the collaboration of diverse interests and a rigorous exploration of alternative, non-linear, non-standard design and material practices (Kolarevic & Klinger, 2008).

In the multitude of the contemporary creative making practices, we may recognize the resurgence or return of craft (Ferris, 2013) and small-scale, localized manufacturing initiatives emerging around the more technologically-inclined maker movement (see Landwehr Sydow, 2017). Starting off as non-specialist sidesteps of the more professionalized studio crafts and hobbyist individualistic projects (Landwehr Sydow, 2017), the craft activism and maker movement have reached considerable public interest. Despite significant differences in their materials and techniques, they both share "a spirit of independent making and creative problem-solving outside of mainstream commodity culture" and operate at (small) scales to retain an intimate relationship with media and materials (Ferris, 2013). The movements emphasize learning-through-doing (active learning) and transcend traditionally separate domains and ways of working, while typically being connected to wider 'open source' communities that support informal, networked, peer-led, and shared learning (e.g., through Facebook interest groups and YouTube).

Fundamental to these ongoing developments is a new attitude towards achieving design intent through interrogating materiality (e.g., Karana et al., 2015; Kolarevic & Klinger, 2008), a return to 'making'; a shift of paradigm towards material driven design approaches (Karana et al., 2015; N. Oxman, 2010). As evident by the DIY materials practices (Rognoli et al., 2015), and experimental architecture (Kolarevic & Klinger, 2008), the new generation of designers are willing to learn from free-wheeling, open-ended, but doggedly focused forms of design research and experimentation (Steele, 2008). Their practice pushes beyond the existing formulas and design guidelines of the existing materials, as evident by the growing number of commercial materials and machines developed by designers (e.g., Precious plastic machines by Dave Hakkens), such as the conductive paint by Bare Conductive and plastic flossing machine by Poly-floss Factory. As such, we are witnessing that design practice is moving beyond selecting materials and exploring the *application potential* of materials. Even when these practices end up with product applications, as Karana, Blauwhoff, Hultink, and Camere (2018) emphasize in case of growing design1, these applications are often hypothetical (i.e., not feasible to produce as a consumer product in its current state of development), archetypical (i.e., having typical forms/simple functions, utilities), and/or they use the grown material as a surrogate for a conventional materia.

5.3 The Materials Potential Framework

As the creative contribution of designers to materials development is shifting from finding application potentials to an expanded definition of discovering materials potential in the blend of fabrication, application, and appreciation (i.e., user experiences), a new conceptualization is required to discuss what those potentials are.

When we talk about potential, we typically refer to "latent qualities or abilities that may be developed and lead to future success or usefulness." (Oxford Dictionary). So, it is about qualities and abilities that are not actualized yet. In the context of creative practices with materials, researchers and practitioners commonly talk about form possibilities (e.g., complex, organic, etc.), expression potential (e.g., for textiles, Nimkulrat, 2009), performative potential (e.g., for EL materials, Barati, Karana, Jansen, & Claus, submitted), and application potential in relation to the function the material might serve. In engineering design, the potentials might be further quantified in terms of cutting down cost and enhancing technical performances, such as 'impact resistance', relative to the existing measures.

In order to investigate how materials potential has been conceptualized in design to date, we revised some established and recent conceptual frameworks within the materials and design domain. In a glance, materials potential might refer to the abilities of materials to shape the product (i.e., *form as materials potential*), to serve functionality in use (i.e. *function as materials potential*), and to elicit experiences from people in their situated interactions with products, including a range of emotions and meanings (i.e., *experience as materials potential*).

5.3.1 Form as Materials Potential

The relationship between material and form is a critical and controversial one in the history of art and design (Lloyd Thomas, 2007). For long in Western philosophy, the material was designated as subsidiary to form; merely its manifestation (Jeska, 2008). Later this view was contradicted by scholars who believed that every material should take on its appropriate form (e.g., Gottfried Semper in Jeska, 2008). The phrase of form follows materials (Ashby & Johnson, 2003; Jeska, 2008) emphasizes material as a characterizing element of the design. This implies that "every material possesses its own language of forms", which have come into being with and through materials (Loos, 1982).

In design, form concerns product's sensual qualities, particularly its visual appearance (e.g., shape, volume, composition). Imagining materials as forms that are yet-to-become is possible only by a conceptual separation between form, structure and material. Moholy-Nagy instead refers to a shape "arrived at" or "valid in" a material. In other words, it is only in retrospective that we can reflect on how the material might have enabled certain shapes. However, geometric-driven form generation, carried into the development and design logic of CAD has largely institutionalized the separation and largely a prioritization of form over material (Pantazis, 2013). As a consequence of such developments, but also informed by the precedent examples and their prior experiences with materials, designers often speak about the form freedom, and form possibilities of the material.

The close and inseparable interaction between shape, material and manufacturing process has been emphasized in most materials selection models (e.g., Ashby, Shercliff, & Cebon, 2007). The manufacturing process has a two-way relationship with material and shape. It is obviously influenced by the material (e.g., sewing may not be a suitable process for

Figure 5.1 – Static and Kinetic novel forms made with natural wood, respectively in a bench by Matthias Pliessnig (left) and lighting by Steven Léprizé (right).

joining metals) and at the same time, it determines the shape, the size, and, to a large extent, the cost of a component (Ashby et al., 2007). The ability of materials to be shaped and finished in a certain way indicates their mighty potential to embody certain forms and possibly render creating other forms difficult (or invalid). Fig. 5.1 shows two examples of novel forms made with natural wood. The bench by Matthias Pliessnig benefits from steam-bending techniques to unlock the potential of wood to shape complex double curvature forms (Fig. 5.1a). Steven Léprizé's lighting pushes the form and expression possibilities of wooden veneer, by skilfully processing and combining wood with another material (i.e., rubber). In both examples, materials potential might be understood and described in relation to creating novel forms.

With the advancement of smart and computational materials, the temporal dimension of form has gained prominent attention, i.e., temporal form (Vallgårda et al., 2015). The temporal form in so-called computational composites is enabled by the computational structure (Vallgårda et al., 2015) and materials enable the "material manifestations of temporal forms that enable our interactions with computational things". The temporal dimension of physical form, however, does not have a casual relation to computation, meaning that materials do not always need computation to reveal the temporal dimension of their physical forms. In fact, there are many non-computational designs that invest in the natural changes of material properties and forms, over time (e.g., graceful aging, Bridgens, Lilley, Smalley, & Balasundaram, 2015) and in relation to the environment

Figure 5.2 – The passive (left) and active (right) role of wood in conceptualizing kinetic forms, left: shape changing wooden veneer by Menges and Reichert (2012) and right: Explosion Cabinet by Sebastian Errazuriz.

and use. Recent works on growing materials (Karana et al., 2018) and 4D structures (MIT) also take interest in material as a 'physical event' that unfolds over time.

Fig. 5.2 presents two wooden kinetic 'skin' designs. In the work of Menges and Reichert (2012) on the left, the wooden veneer changes shape when absorbing moisture from the air, pushing for a novel kinetic form by exploiting its unique hygroscopic characteristics. The role of wood in the kinetic shape of Explosion Cabinet by Sebastian Errazuriz is however more symbolic, reinforcing the image of a conventional material used in a conventional box-like cabinet. The expressive envelope of the kinetic form (i.e., from 'intact' to 'exploded' and vice versa) is pushed by the designer's reinterpretation of the sliding dovetail joint commonly used in cabinet making.

Drawing on DiSalvo's distinction between form and expression, the latter refers to "how the materiality of the product is rendered by design" (DiSalvo, 2006, p. 40). To explain how expression reflects designers' world view, DiSalvo compares the works of Dieter Rams and Etorre Sottsass, and argues that while both designers shared a common belief that designers can influence the experience of use, one approached this by minimizing the expressiveness of the product (i.e., the product becomes a tool), and the other by perturbing the environment. In her practice-led research, Nimkulrat (2009) explores the relationship between paper string and artistic expression and elaborates on how the material (i.e., paper string) was important in her creative practice: "I recognised the expressive potential of the chosen type of paper string when making the artworks in this series and imaging them being in a particular exhibition space." (p. 57)

The interplay of designer's act of *making* and *imagining* brings to the world of actual, "a deep dimension of the world that exists in a hidden and unexpressed form, waiting to happen" (Merleau-Ponty, 1968, p. 267). Her research emphasizes the active quality or expressivity of the material in informing the artist about how to proceed with the creative processes.

5.3.2 Function as Materials Potential

Function refers to the utility goals of a product or more generally "the work a product is designed to do" (DiSalvo, 2006). For instance, a chair's first and foremost function is to provide sitting. Function is a key concept in producing descriptions of artefacts (Roozenburg & Eekels, 1995; Suh, 1990), that explicitly addresses how users derive benefits from their use. Even though in design (engineering) research the concept of function is often being used in relation to the physical goals of artefacts (e.g., Galle, 2009; Vermaas & Dorst, 2007), some design theorists argue that it is difficult to separate product functionality, i.e., how effectively a product allows for its prescribed function to be achieved, from its aesthetic qualities that do it so (e.g., Crilly, 2009; Papanek, 1972). Drawing on Papanek's notion of 'function complex', a set of functions that includes 'association' and 'aesthetics', and work of Searle (1995) and Parsons and Carlson (2008) among others, Crilly (2009) elaborates on a broader range of non-technical function classes such as 'aesthetic functions' and 'social (or status) functions'. He argues that these classes of function might be further qualified as 'proper', 'latent/manifested', anchoring both to design intentionality and actual use. According to DiSalvo (2006) the how of the relation between 'operational' (both technical and social) and 'aesthetic' functions of a product is dialogical to design expression (i.e., style; see previous subsection), and to the overall experience of a product (discussed in the next section).

Materials, due to their structural and other functional roles (e.g. heat conductivity) in products, contribute to a product's utility/use, or "functional justification" (Moholy-Nagy, 1947). Linking materials and their properties to the well-justified functions of existing artefacts provides an effective way to articulate the potential value and benefits of those materials. The potential of the material thus can be framed in allowing for the function(s) to be achieved more efficiently. Fig. 5.3 illustrates novel functions of mycelium and electroluminescent materials, respectively. The first example is a chair by Officina Corpuscoli. The foam-like mycelium-based material, which is

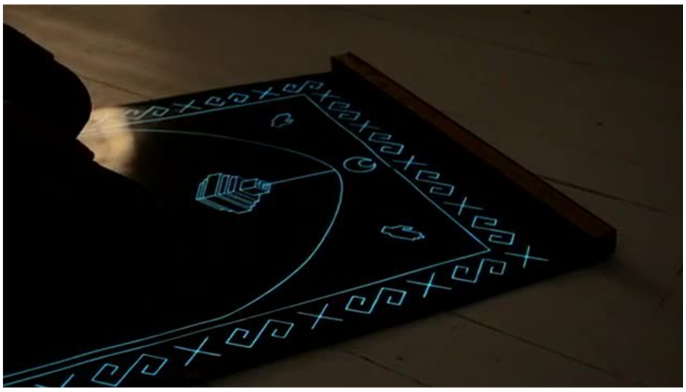


Figure 5.3 – Materials potential can be articulated in relation to their structural and functional role in the eventual product application, left: novel functionality of mycelium in joining the seat to the wooden legs and right: unlocking a novel function for a praying mat, using integrated EL wires.

fabricated by inoculating an individual strain of fungi in a substrate of organic substances, not only shapes the seat but also joins the seat to the wooden legs. Arguably, it is not the application (i.e., chair) that is novel per se but novelty arises in the functionality of mycelium to join the two different materials without the need for additional materials and components. The chair demonstrates a novel potential of mycelium: its 'function' as a natural joint.

The second example is the EL Sajjadah by Soner Ozenc. The EL wires woven into the material of the praying mat contribute to its novel function: guiding prayers to the right direction (Muslims pray facing Mecca). Note that in contrast to the previous example, using EL materials for signaling is not novel, it is the novel functionality of the prayer mat and using the embedded digital compass to control the EL wires that manifest a novel exploitation of the EL materials. The two examples put forward that the functional potential of materials might be discussed without an explicit reference to the product form or the making process.

The compatibility of function and language (in producing analytical descriptions of non-existing artefacts) gives function additional power and privilege (over form) in the discussion of materials potential. Ashby's model for materials selection in mechanical design (1999) makes materials selection operational by such translation of artifacts into (technical) functions (i.e., what the product or the product component does), and materials into attribute profiles. The materials potential to serve functionalities in products becomes a matter of mapping between predefined functions and certain material attributes. For instance, certain textiles might be considered to be proper for upholstery (i.e., providing furniture with padding and fabric cover) because of their specific set of attributes, including their weave structure and durability. This does not necessarily mean that designers could/would not consider them for designing a wearable piece. The functional justification for using them is affected by the extent to which the property profile of those material matches the functional design requirements.

5.3.3 Experience as Materials Potential

Moving beyond usability measures of (interactive) products (Norman, 2004) and placing emphasis on the 'affective' qualities in experiencing them (P. M. A. Desmet & Hekkert, 2007), experience design (Hassenzahl, 2010) or design for experience (Schifferstein & Hekkert, 2008) has become a meta school of thought/ movement in product and interaction design with myriads of heuristics, methods and tools (see Hassenzahl, 2010).

Materials as the building blocks of products, charged with (socio-cultural) meanings (Karana, 2009; Wilkes et al., 2016), play an important role in shaping our experiences of products (Karana, Hekkert, & Kandachar, 2008; Karana, Pedgley, & Rognoli, 2014). Ashby and Johnson (2002) acknowledge that the mechanical design model misses out the user-product interaction aspects and elaborate on the role of materials and fabrication process not only "to convey information and respond to user actions", but to influence "the aesthetics, associations, and perceptions of the product" (p. 35). Understanding how materials are experienced by people and identifying the patterns of materials experience (Giaccardi & Karana, 2015), has thus become an important focus for materials selection in designing for 'meaningful' experiences. User-centered inquiries (e.g., interviews, focus group) and ethnographic studies in particular contexts of use (Wilkes et al., 2016) are among methods to collect relevant data about material experiences (e.g., Fisher, 2004). In material driven design, instead of choosing the material for the benefit of the experiences, the *experience vision* is deliberated to reveal novel potentials of the material (Karana et al., 2015).

Karana et al. (2015) propose that characterizing materials in terms of their 'sensorial', 'affective', and 'interpretive' qualities, as well as their

Figure 5.4 – The experiential potential of materials, left: the umbrella provides a novel experience of rain, through the custom-made water-activated EL print and right: mycelium-based packaging design offers a distinct unboxing experience.

‘performative’ qualities can help with the identification of their experiential potential, i.e., potential to elicit experiences. The identification/conceptualization of these four levels of materials experience (Giaccardi & Karana, 2015) were aimed at structuring and articulating the experiences of materials in human encounters and practices. The attention to the *performative qualities* of materials and the possible links between material properties and the performed actions observed in user-material interactions has resulted in material driven projects with an explicit intention to push the ‘normative’ action repertoire (e.g., Barati et al., 2018). Fig. 5.4 illustrates two examples of such (material driven) designs with mycelium and electroluminescent materials. ‘Second Skin’, by Davine Blauwhoff, is a packaging solution that exploits crumble-ability and biodegradability of the mycelium-based material in creating a distinct unboxing experience (Karana et al., 2018). The second example is ‘a Drop of Light’ by Stan Claus, which is an umbrella that showcases the potential of electroluminescent (EL) materials in pushing for new experiences of and performances in rain. The prototype provides a semi-transparent window for its user to see the lit raindrops as they slide off the convex surface, using custom-made water-activated EL parts (Barati et al., submitted).

5.3.4 Summary of Accounts

So far, we have shown how materials potential can be conceptualized in relation to aspects of form, function, and (materials) experience. Even though these aspects are conceptually separated, in reality they are rather intertwined, affect and result from each other. For example, a material might simultaneously enable surprisingly (i.e., experience potential) thin yet strong shapes (i.e., form potential) to sit on (i.e., function potential). However, such understandings of a material's potential do not reflect how novel materials potentials actually come about in creative practices. This may suggest that material potentials are ever-existing effects, awaiting the creative mind to recognize them, independent of the fluxes of creation process, the designer's skills, the properties of the medium used to communicate the material (e.g., technical information, video of the making process, the processed material, or the ingredients), and the social context (who the designer interacts with), time, and place (what equipment the designer has access to).

So if these concepts are anchored to the final result of the design process rather than the act/action of creation itself, is there any other concept that could shed light on the emergence of material potentials? Drawing on Jame's distinction between the two modes of acquiring knowledge (James, 1895, 1981), "concepts" and "percepts", so far, we have treated material potentials as *concepts*, being uncovered through analyses of the material and its possible relations to product function, form, and the levels of materials experience (e.g., performative level). Concepts are crucial in (1) steering us practically by providing "an immense map of relations among the elements of things", (2) bringing new values, insights, points of emphasis into our perceptual life, and (3) making a frame out of things, an independent existence, even in the absence of sense, i.e., the phenomena of immediate (unmediated) experience James (1996, p. 73-74).

On the other hand, understanding materials potential as *percepts* means that knowing about a material's potentials requires immediate (i.e., unmediated) experience and awareness of its qualities. Immediate experience consists of objects and their relations, as well as a suggestion of what possibilities may follow, while still unrealized; what Heft (2003) refers to as *feeling of tendency*. In our everyday creativities, we are perceiving and exploiting the potentials of materials without deliberately reflecting on those relationships. The early stages of materials development imply that there may not have been any (or many) design precedents. Thus, designers lack the necessary body of knowledge and experience to rely on in analysis of the materials potential. This put forwards a need for yet another concept in understanding material potentials rather as *percepts*.

5.3.5 Affordance as Materials Potential

Design researchers have found the concept of affordance, introduced by Gibson (1979), relevant to design because it cuts across traditional subject-object dualities (e.g., Gaver, 1996; Norman, 1999). Despite the debates on the nature and scope of the notion (Lanamäki, Thapa, & Stendal, 2016; Rietveld & Kiverstein, 2014), there is widespread agreement that affordances are possibilities for action offered to an animal by the environment, by the substances, surfaces, objects, and other living creatures that surround the animal (Chemero, 2003, 2009; Heft, 2001; E. S. Reed, 1996). There have been debates among scholars whether affordances are dispositional properties of the environment (e.g., E. S. Reed, 1996), or rather relations between features of the environment and the abilities of organisms (e.g., Chemero, 2003). Others such as Rietveld and Kiverstein (2014) have found a way for affordances to be both relations and a resource.

An immediate benefit of the affordance concept for capturing a materials' potential, as argued by Gaver (1996), is that it enables descriptions of the material in terms of process-abilities. As such a potential of leather might be that it can be embossed and even tattooed as being shown in the leather iPad case by Inko (Fig. 5.5). What the designer demonstrates with the iPad case is a way and know-how to fabricate robust printed circuits, revealed through working skillfully with the affordances of the conductive ink, the leather, and the tattoo machine. The convenient and useful definition of affordances as possibilities for action, however, can obscure the richness of the concept in explaining how novel affordances are being discovered (e.g., Glăveanu, 2012; Rietveld & Kiverstein, 2014).

Lanamäki et al. (2016) identified four stances of affordances, as discussed in the literature, the first being "canonical affordances", which are universal action-possibilities bound with specific ways of living, for instance, chairs –in general– provide sitting. We may notice overlaps between canonical affordances and the concept of function in design literature (e.g., Niedderer, 2007). The second stance is "affordance as completed action", which conceptualizes affordances as inseparable from the situated actions of the individual. This seems to overlap with the performative level in analyzing

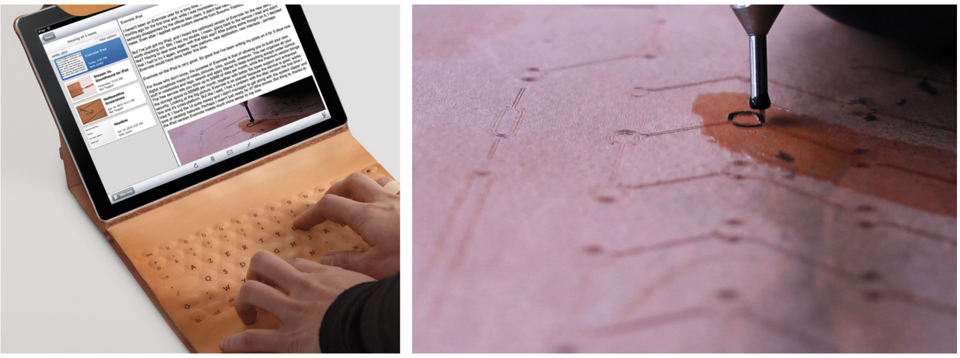


Figure 5.5 – A novel potential of the leather has been unlocked in relation and through the skillful act of tattooing the conductive ink.

material experiences (see previous section), as it concerns how particular people in particular ‘situational wholes’ perform as they do. The third stance considers affordances as qualities and resources that can be designed into artefacts, for instance that the (physical) design (i.e., form) of a door handle can be modified in ways that it affords pulling/pushing. The fourth and final stance views affordances as opportunities for action (Stoffregen, 2003, p. 124) that may or may not have been intended, but are emerging through action. Lanamäki et al. (2016) made distinctions between the third and fourth stances, referring to them respectively as “design affordances” and “potential affordances”. Drawing on the fourth stance, affordances as potential of a material are explored through interaction with them and cannot simply be “built into” or “read out of” artifacts (Fisher, 2004). This conceptualization of affordances emphasizes the generative role of immediate experience and material engagement in discovering novel affordances. As Carr (1986) explains:

> In the midst of an action the future is not something expected or prefigured in the present, not something which is simply to come; it is something to be brought about by the action in which I am engaged (Carr, 1986, p. 36).

Affordance as Materials Potential is what a specific material has to ‘offer’ in the collaborative act of people, materials, making (processes), and the surrounding environment. It is “to consider the action potentials embedded within the environment and available to creators for use or change, and thus, ultimately, to re-conceptualize agency and intentionality” (Glăveanu, 2014, p. 61). In the theoretical discussion of how novel affordances emerge, the relation between affordance and intentionality, and the (conditions for) emergence of affordances over time become central. The latter brings to light developmental (micro-scale) and historical (macro-scale) discourses on the co-evolution of affordances (Glăveanu, 2014), which we briefly touch upon.

Design practitioners and researchers have reflected on the relations between affordances and (design) intentionality in various creative practices. Franinović (2013) describes her (material driven) design activity as being governed by following what the materials afford, instead of "trying to impose ideas on matter by controlling their physical properties". In her making practice with paper strings, Nimkulrat (2009) considers both scenarios of letting the material "speak" freely for itself, and seeing the material speak under her control (i.e., prior manipulation). Intentionality, as a component of extended cognition (Malafouris, 2008), is "an orientation towards the world, shaped, at each moment, by both person and the environment" (Glăveanu, 2014, p. 88). It seems that various kinds of 'know-how', including a set of skills, stances, assumptions and habits, arise in a state of "prior-intention", i.e., the intention to act precedes the action itself (Searle, 1983). In material practices such as pottery, the line between human intentionality and material affordance becomes more difficult to draw, to the extent that the former may identify with the latter (Malafouris, 2008).

According to the relational conceptualization of affordances (e.g., Chemero, 2003), the individual's ability and skills make affordances available to them. (Franinović, 2013) argues that in creative processes that involve hands-on experiments with the materials, "hidden" affordances begin to emerge. Their emergence cannot be explained unless both the developing skills of the designer and the resourcefulness of those materials co-play. More generally, we can say that skilled agents are (or else become) able to "collaborate" (Ingold, 2013, p. 128) with the socio-material surroundings, through "learning how to deal with these very specific material settings" (Rietveld & Kiverstein, 2014, p. 333). Going beyond the individual and her situated actions, Rietveld and Kiverstein (2014) propose that affordances are as much relations between aspects of environment and skills available to a "form of life". Borrowing the notion of "form of life" from Wittgenstein (1993), they consider affordances relative to the accumulated skills available to a community, who share a relatively stable and regular ways of doing things.

By locating affordances in the context of a form of life, affordances can be given a reality independent from any individual's actual engagement with them here and now, or percepts (E. S. Reed, 1996; Rietveld & Kiverstein, 2014). They become resources the environment offers (E. S. Reed, 1996) or potentials for action available to the form of life to pick them up, even before someone actually did so. Such a conceptualization of affordances makes it possible to describe and prescribe the discovery of novel affordances, namely, “by stimulating the application of an existing skill to different aspects of the environment” (Rietveld & Kiverstein, 2014, p. 339). The earlier example of the tattooed leather circuit (Fig. 5.5) is a clear example of how an existing skill/technique/tool unlocked the perception of novel affordances of leather and conductive paint.

5.4 Unlocking Novel Affordances in Material Driven Design

Creativity in the crossovers of materials and design seems to go beyond a ‘general’ problem-solving activity. There is no doubt that past experiences/engagements with existing materials, and visual comparison tools between property profiles enable designers to make hypotheses about new materials and predictions about how they might be processed and experienced. However, for those thoughts and imaginations to be realized in the world, affordances of the environment (i.e. the material, existing skills, techniques and tools) become the conditions. Conceptualizing affordances as materials potential brings to attention the limitations of precedent-based reasoning (R. E. Oxman & Oxman, 1992). As long as creativity is assumed inside a designer’s mind, “the extended intentionality” (Malafouris, 2008) that is intimately linked to the novel affordances remains largely unexplored. A recent interview with designers involved in a collaborative material development project suggests that designers settle with obvious material potentials if the conditions for discovering novel affordances do not present themselves (Barati et al., in review).

According to Glaveanu’s framework of creativity (2012), novel affordances fall in three spaces of possibilities marginal to what is usually done, as the material, personal (i.e., intentional) and socio-cultural constraints interact with one another: “unperceived affordances”, “uninvented affordances”, and “unexploited affordances”. Unperceived affordances are action potentials that are materially achievable and do not violate any particular cultural norms, but designers are unaware of their existence and thus have no explicit intention of making ‘use’ of them. Tinkering and experimenting with the material out of curiosity, accidents and even mistakes may contribute to bringing those unnoticed action potentials to designer's attention (e.g., Franinović & Franzke, 2015). The history of inventions provides great examples of how materials engagement and experimentation can lead to spontaneous discoveries (e.g., Teflon). Uninvented affordances are those possibilities of action that are favorable by the designer and the society but are not-yet-available. An invention of new tools and techniques, or repurposing existing ones (Rognoli et al., 2015) can unlock such novel affordances, enabling the designer to combine or transform the basic capacities of the material. Unexploited affordances are action potentials that remain unexploited due to a certain normativity embodied in the socially accepted ways of thinking about or interacting with the material world. Such novel affordances might be unveiled through transgressions of (cultural/professional) norms (see Glaveanu's analysis of Romanian 'egg decoration' craft practice for more details, 2012).

Many material driven design practices have contributed to the unlocking of novel affordances through the following mechanisms: spontaneous discovery, invention of techniques and transgression of norms or rather a combination of them.

5.4.1 Spontaneous Discovery in Material Driven Design

Materials experimentation is often pregnant with accidents, not all of them of course turn into a discovery that can be creatively explored further. Many remain a trial and error exercise. An example of a serendipitous accident has been reported in the work of Franinović and Franzke (2015) with electroluminescent (EL) materials. Franinović and Franzke (2015) note how their curiosity-driven experimentations with the unfinished (half-way processed) sample opened up new action potentials to explore the materials responsive behavior. The new affordances of the EL materials, such as to print the layers on separate sheets and to place liquid/textile conductive materials in between, have allowed for diversification of EL's performative qualities (e.g., Barati et al., 2018), and as shown in the example of 'Drop of Light' (Fig. 5.4) permitted material expressions and experiences, different from conventional EL applications.

Understanding materials and technologies as reconfigurable, dynamic, and emergent composites/assemblies (see De Landa, 2011) that can be directly fabricated, orchestrated and manipulated by designers has significantly enlarged the area of materials unperceived affordances. An example of composite fabrication in pursuit of the unity of skin, structure, and effect (Kolarevic & Klinger, 2008) is BioLogic fabric by MIT Media Lab & Royal College of Art, incorporating bacteria on fabric substrate to create a variety of bending behavior in response to sweat and humidity. Perceiving the behavior (e.g., to expand and contract in reaction to moisture) and affordances of Bacillus Subtilis microorganism (e.g., to be assembled on thin fabric), was key to the novel deployment of these bacteria, which had been used, for centuries, to ferment foods in Japan. Out-of-the-box thinking in such experimental endeavors results from a much more informed knowledge base of the reciprocities between materials, their behavioral characteristics and the systemic behavior of their assembly/composition (e.g., Kolarevic & Klinger, 2008; Menges & Reichert, 2012).

5.4.2 Transgression of Norms in Material Driven Design

As the previous example suggests another significant source of creativity in material driven design practices comes from transgressing certain norms (e.g., concerning how materials are being processed and used). The design activity might lead to an exploitation of the known affordances of materials that were usually considered to be 'undesired' (e.g., swelling wood). The work of Menges and Reichert (2012) and Wójcik (2015) with wood exemplifies novel exploitation of a traditionally undesired 'swelling' characteristic of the material for creating moisture-responsive kinetic forms. Wojcik's 2015 experimentation with wood exploits the phenomena of 'parquet buckling', caused by increased moisture content in wood to create self-bending shapes. The architectural practice of Menges and Reichert (2012) further transgresses a norm of relying on technological equipment (e.g., external sensors) "superimposed on material constructs", by "instrumentalising hygroscopic material behavior". This demanded an in-depth understanding of the veneer composites (e.g., their response range and behavior) in relation to the identified design variables, ranging from anatomy and direction of fibers, to geometry of the sample, to humidity control during the fabrication phase (Menges & Reichert, 2012). The role of (performance-driven) digital simulation in estimating the emergent (kinetic) form, as a factor of dynamic interaction between the material, the composition/assembly and the environment, has been emphasized (see also De Landa, 2011).

Recently, designers have pushed the known affordances of recycled plastics through transgressing the norm of plastic recycling, i.e., separating different types of plastics, and rather universally mixing them. In both works of Shahar Livne (Fig. 5.6, left) and Henry Louis Miller, we see that discarded plastics, regardless of their types, are grinded and combined with soil/cement to create new materials. Livne's approach to plastics is the imitation of a natural geological process known as metamorphism that she assumes will in a far future transform the discarded plastics to a new material. The transformation revealed affordances that were initially unperceived, namely to hand-pressing the plastic compound into the final shape, resembling working with clay. Miller 'uses' affordances of grinded waste plastics to aggregate cement and makes 'plastic concrete', a new material as strong as conventional concrete. Unlike Miller's material solution for an existing need (to replace a mined ingredient with waste materials), Livne's approach to material making is not concerned with serving needs as they are presently understood, instead seeks to envision a future where plastic, as a nostalgic and valuable material is being mined from ancient land-fields (see speculative design, Dunne & Raby, 2013).

While critical design theory has less to say directly about how to make things that transgress (Bardzell, Bardzell, & Stolterman, 2014), material driven design practices have shown ways to do that by searching and discovering unorthodox material sources, such as waste animal blood by Basse Stittgen, and urban smog (e.g., Smog Free Ring by Studio Roosegaarde, serVies by Annemarie Piscaer and Iris de Kievith). These creative practices with and through materials challenge the norms and conventions inscribed in materials, including their socio-cultural meaning, and their use. For instance, a realization of animal blood, discarded in large quantities by slaughterhouses, as a material source triggers Stittgen to further explore its 'material-ability'. The designer exploits the known affordances of blood (e.g., to dry) to process a powder that can then be heated and pressed into a black and solid material, shown in Fig. 5.6, right. The process uncovers and exploits novel affordances of blood, or more specifically albumin protein to act as a binding agent, in creating a protein-based biopolymer that is 100 per cent processed blood. While the ideas in the speculative and critical design projects are meant to reach beyond the objects (Dunne, 2008), the act of making/creating is bound to the affordances of the medium, contributing (in a positive or negative way) to the projection of those ideas.

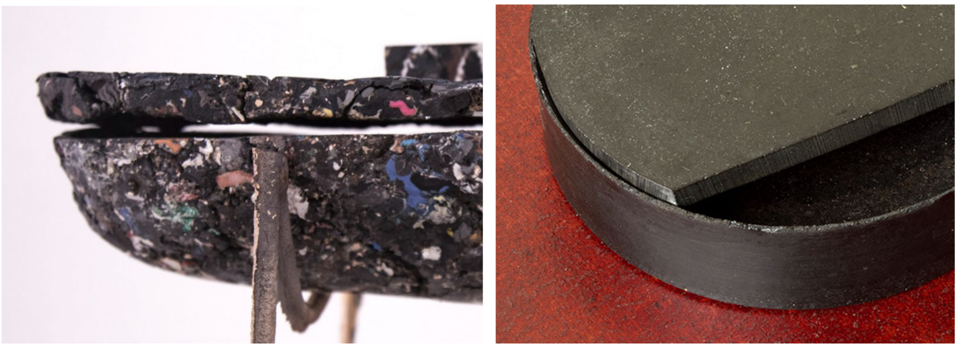


Figure 5.6 – Mixing plastics universally (left) and drying and pressing blood (right): transgressing the norms in materials design.

5.4.3 Invention of Techniques in Material Driven Design

Invention of new tools/machines, repurposing, modifying, and combining existing production tools and techniques have been key to expanding novel affordances (see for an overview, Rognoli et al., 2015). The development of new machines such as multi-material 3D printers have enabled high-resolution control over dot deposition of soft, rigid, and transparent plastics in a single printed material. MIT Self-Assembly Lab recently showcased the possibilities of creating multi-material prints that can change shape 'directly off the print bed' and termed this new way of production, '4D printing' (Skylar, 2014). The new way of production, in this case 4D printing, has further opened up unprecedented form and experience design opportunities, see for instance shape-shifting noodles by MIT, enabled by 3D printing strips of edible cellulose over the top gelatin layer. Existing machinery can be as much relevant when it comes to pushing for novel affordances. The Poly-floss machine (Fig. 5.7, left) is a clear example of how repurposing an existing machine has contributed to the invention (i.e., 'floss-ability') and exploitation of novel affordances of plastics (e.g., in making multi-structured forms) and enabled new ways of recycling plastic parts. Evident by FiDU, a metal-inflating method (Fig. 5.7, right) invented by Oskar Zieta, combining different machines has capitalized the known affordances of metal sheets (e.g., to be spot-welded, to apply hydro-forming techniques) and exploits newly perceived ones (i.e., to be blown up uniquely by playing with the pressure and thickness of the sheets).

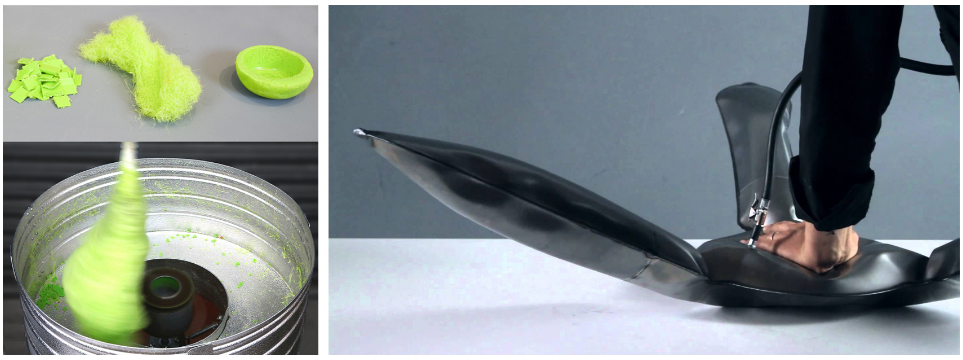


Figure 5.7 – Repurposing and inventing tools and techniques may unlock novel material affordances, left: plastic flossing by Polyfloss Factory and right: metal inflating by Oskar Zieta.

5.5 Discussion

In this paper, we elaborated on the notion of materials potential in design to promote a stand that design's highest contribution to materials development is not merely the final product application. Designers can actively contribute to discovering novel affordances, through their skillful, embodied, distributed act of tinkering, experimenting and making. In this creative process they not only expand the materials' potentials, but simultaneously push the boundaries of the material at hand and inspire material scientists to explore new territories in their development. This reciprocity is at the core of the these emergent material practices.

The concept of affordances has offered a lens to understand and analyze how concrete material (driven design) practices might be linked to designers' intentionality, through their 'skilled' action (Ingold, 2013) and 'skilled' cognition, responsible for their selective engagement with the rich landscape of affordances (Rietveld & Kiverstein, 2014). Our creative practices with smart materials (Barati et al., 2018, submitted) and growing materials (Karana et al., 2018) suggest that novel affordances are a moment-to-moment collaboration of the material and the social, even when the action is initially pulled by the intention of the designer. Bound to material engagement, affordances as materials potential take a step forward in understanding "the synergistic process by which, out of brains, bodies and things, mind emerges" (Malafouris, 2008, p. 58). The fruits of such experimental material research may focus on materials samples as much as on making recipes (see Ribul, 2013), industrial processes and production.

Understanding *affordances as materials potential* offer further implications for collaborative material development, which we will shortly address below.

5.5.1 Curiosity Driven Approach in Collaborative Material Development

The affordances of a material are understood in and through material engagement, and do not require a reference to the final outcome (e.g., an experience vision; a desired form or function). This conceptualization legitimizes curiosity-driven and experimental approaches in search of novel material potentials. De Landa (2004) argues that new materials offer not only the potential for an increased performance of a design but also can lead to design proposals "changed by something that comes from within the materials." While collaboration might reward the approaches that generate most valuable output (in terms of market value), solutionist approaches do not always turn out to be the most effective ones. There are evidences from medicine studies that 'shovel-ready' approaches do not necessarily result in most valuable output (in this case medicine), compared to fundamental research and curiosity-driven approaches (Spector, Harrison, & Fishman, 2018). This means that even if the motivation of collaboration is solely for creative/profitable outcomes, setting out an application-design oriented methodology might not be ultimately as productive, compared to encouraging more curiosity-driven and non-direct experimental approaches. According to Olma (2016), in such collaborative projects, creative and innovative results are achieved through the autonomy of art and design disciplines, which is "the foundation on which the creative industries approach built" (p. 37), rather than enthusiasm for the 'surface' design of consumer goods.

For the collaboration to work out, the expected contributions from designers need to be in agreement with designers' motivation to participate in such collaborative projects (see Lindberg et al., 2013). Mainstream product designers might not be willing to spend too much time to master a new material (the way craftsmen or material scientists do) or exploring novel affordances, when they already have a product concept with promising market prospect. It is important to find an optimum trade-off between too much and too little time dedicated to finding the affordances relevant to designers' concerns. This can be achieved by involving designers (and artists) who are more inclined to material design and experimentation and see reward and value in blurring the boundaries between product design and material making. Not only these growing population of designers are willing to spend time and effort in materials understanding but also they can also function as proxies between material scientists and other product designers in collaborative materials development. Their proxy function may involve activities including, but not limited to, simplifying the making/fabrication processes (e.g., screen printing EL materials; recycled plastic) and demystifying the science behind technologies and materials behavior, demonstrating/visualizing basic working principles, boundaries, and potentials, and assisting with performance-driven computational model and simulation tools (N. Oxman, 2010).

Promoting research-based experimental material practices does not mean that novel affordances cannot be uncovered in materials exploration that is part of a solutionist approach, i.e., to inspire new solutions for a predefined concept. In fact, in a solutionist approach narrower aspects of the material (e.g., focusing on its surface finishing) might be subject to more focused investigation (e.g., hygienic design requirements). However, many researchers agree that conventional design methods, where a conceptual sketch through iterations becomes a working prototype, can hardly scratch the surface of materials novel affordances (e.g., Bergström et al., 2010; Karana et al., 2015). The representations of the final forms and qualities might not only be difficult or impossible to produce with the specific material, but also neglect, the otherwise, unique affordances of that material. The desire to work with a specific material, i.e., material driven design, leads designers to apply design strategies that are driven by material properties and behavior, to ensure that their imagination bears “sufficient causative relation to actual existing material possibilities, so as to render it plausible, and therefore (at least potentially) attainable” (Borges, 2013). To keep an open mind about the unique material potentials, Karana et al. (2015) encourage designers to invest in an early “material understanding” step, in which the material is (systematically) tinkered with, experientially characterized, and compared against other materials.

5.5.2 Communicating Material Potentials in Collaborative Material Development

The challenge of communication between materials scientists and designers in collaborative materials development and the need for an effective dialogue between the two communities have been discussed in the literature (e.g., Wilkes et al., 2016). To mitigate this multidisciplinary challenge, researchers have proposed isomorphic material samples (Wilkes et al., 2016) and material liaisons who are familiar with both worlds (Hornbuckle, 2018). These tools and strategies tap into the mediating role of physical samples, as ‘boundary objects’ (Star & Griesemer, 1989) and ‘liminality’ of individuals who understand both designers’ and materials scientists’ languages (e.g., Lindsay, 2010). To explore and communicate the material and its potentials, designers rather aim for intermediate objects, such as material demonstrators (Barati et al., 2016). In experimental architecture, pavilions function in similar ways as “an experimental laboratory and a case study to introduce new ideas and techniques” (Bohnenberger, 2013). Such facilitations may be good for promoting some kinds of exchange and understanding by overcoming the language barriers (e.g., Sundström et al., 2011), but are not deliberated to promote material making abilities or to change social dynamics arising from the knowledge (and thus power) gap between designers and material scientists. Those require strategic and targeted interventions and purposeful project organizations that change the relationships between people and resources, for instance, through pedagogies (cf. Loi & Dillon, 2006) and participatory learning (e.g., Clapp, 2016; Mose Biskjaer, Dalsgaard, & Halskov, 2014). Such interventions not only promote and foster cross-disciplinary abilities which can lead to new perspectives (Glaveanu, 2015) and possibilities for action (Rietveld & Kiverstein, 2014) and, by extension, equity (cf. Davidson, 2017), but also stimulate creative improvisation (cf. Dillon, Wang, Vesisenaho, Valtonen, & Havu-Nuutinen, 2013; Olma, 2016; Vesisenaho et al., 2017).

5.6 conclusion

The proposed framework of materials potential emphasizes the possibilities for action offered by a specific material beyond a means for achieving intended qualities in an eventual product application. To that aim, the paper elaborates on the notion of affordances as materials potential in the context of material driven design practices. Accordingly, we argued that even though designers’ creative contribution in collaborative material development is considered largely product-oriented, enabling them to interrogate materials for intended form, function, and experience, it is only through making that affordances are perceived, invented, and exploited.

With concrete examples we instantiated how novel affordances have been surfaced in material driven design processes with conventional and new/emerging materials. We argue that understanding affordances as materials potential in collaborative material development projects requires (the support of) designers' active participation in making/fabricating and the promotion of curiosity-driven approach purposefully coupled with a solutionist approach in search of novel material potentials.

6 Discussion & Conclusions

Our research journey was driven by an exploratory study into the design processes that departed from the LTM materials, which are underdeveloped smart material composites (USMC) that can emit light when pressed and deformed. At the early stages of their development these composite materials were communicated to product designers through descriptions of their physical and functional characteristics. The designers, who had joined material scientists in the co-development of these composites, were asked to come up with meaningful product application concepts, which demonstrate the unique potentials of these underdeveloped materials. Our findings from the interview studies with design professionals and observations through a number of design cases showed that understanding the experiential qualities of these materials, in particular their dynamic (e.g., changes of light intensity over time) and performative (e.g., actions for activating the light) qualities, necessary for unlocking their design potentials, was challenging. We concluded that this difficulty rose mainly due to a lack of direct experience with the underdeveloped composite or otherwise tangible representations of it, which could let the development team directly experience the dynamic and performative qualities.

In **Chapter 2**, we discussed that material samples to complement the abstract descriptions were in themselves insufficient in communicating the LTM materials' dynamic and performative qualities. Through a number of student design projects that departed from the same introduction to the LTM material and the same design brief professional designers had been provided with, we investigated the range of tools and techniques used to capture and communicate the dynamic and performative qualities of the LTM materials. Students used a variety of tools and techniques, ranging from animated and interactive on-screen graphics to off-the-shelf force sensors and LED lamps connected to an Arduino board. We showed the importance of “experience prototyping” in the early stages of the co-development of the USMCs to understand and communicate their performative qualities. A smart material demonstrator was created using electroluminescent (EL) materials to support a direct experience, showing a performable structure that gradually dimmed/ illuminated in response to the user’s action of twisting.

With the aim of supporting an early exploration and discussion of the LTM materials’ dynamic and performative qualities, two versions of a hybrid sketching tool, a foot-operated station and an iPad app, were designed and implemented. The idea behind the sketching tool was to let the development team subjectively experience dynamic surface lighting of a performable structure unfolding over time and in response to their actions. The Chroma key technique was used to over-impose the dynamic light patterns in live-stream videos of the interaction with the physical samples and mockups. The interviews with the LTM designers who had tried the first version of the tool indicated that such a sketching tool could have considerably improved the interdisciplinary communication of the dynamic qualities of the LTM materials. Three stages of the development process were considered of special importance: (1) when introducing these materials to the designers, (2) when representing the early application ideas to the material scientists, and (3) when further developing the concepts within the design team.

In parallel, we initiated material driven design cases to investigate how materiality of a USMC and tinkering with it, a mode of materials understanding where the designer directly works with the material (Karana et al., 2015), influence the creative process, particularly the discovery of novel potentials. The unprocessed electroluminescent (EL) materials, which were used for creating the demonstrator, provided a relevant starting point for the material driven design process. Not only the EL materials resembled the thin-film OLED component of the LTM materials, but we were also able to provide the design students with in-house equipment and expertise needed for fabricating EL material samples. **Chapter 3** reported on a designer’s journey that departed from the unprocessed EL materials. The activities and decisions made throughout the material driven design process were recorded. Unlike the design processes with the LTM materials, in which the designers had indirect access to the USMC through material information and physical representations, the design student was instructed to actively participate in material making and processing. The case study showed that a designer's hands-on approach together with his interest in the experiential aspects of the EL materials, concerning the aesthetic experience and performative character of the material samples, unfolded new action possibilities and development trajectories. The designer's contribution to materials development in this material driven design case clearly reached beyond finding meaningful product offerings. Throughout the process, the designer discovered new ways to alter the performative character of the EL material samples, which were not "given" or known prior to the design process.

Chapter 4 reported on a number of material driven design explorations with the EL materials. It identified a design strategy that stretched the performative qualities of EL material samples by deliberately disrupting their function, to give light when switched on. The ingredients used in fabricating the EL samples, the structure of layers, the printed pattern and the form of connection points, and the components of computation all served as parameters in the making of the performative qualities. The material driven design processes helped us to elaborate on a creative contribution of designers to materials development, a contribution that was largely unspecified to date.

In answering what the designer's contribution is, **Chapter 5** provided a theoretical foundation that emphasizes *novel affordances* unlocked in materials engagement as materials potential. We argued that such an action-oriented understanding complements the existing product-oriented accounts that conceptualize materials potential with reference to form, function, and experience of the eventual product. Designers' creative contribution to the development of materials can thus be broadly defined in relation to novel affordances *perceived*, *invented* and *exploited* through making and processing [with] the material (cf. Glăveanu, 2012).

Based on our research, we will next discuss three main issues that demand further investigation: representation tools and techniques, material driven design processes, and designers' creative role in materials development.

6.1 Generative Design Tools for Materials Development

In the thesis, we focused on the challenge of representing the USMC's dynamic and performative qualities. Our proposed two-fold solution incorporated (1) a material demonstrator that clearly communicates a gap in experience prototyping at the intersection of performable structure and responsive surface lighting; and (2) a hybrid sketching tool that digitally augments the surface of physical objects with computer-generated dynamic behaviors. Using the sketching tool, the development team could produce quick and direct representations of the USMC and/or the application ideas in a way that other members can experience them first-hand. The resulting prototypes, as verified by our interview results presented in **Chapter 2**, are deliberately "incomplete" (Lim et al., 2008), and do not provide information on the limitations of the actual composites and other boundaries of the collaboration (e.g., time and resource constraints). The representation tool allows designers to transcend these boundaries so the opportunities and constraints can be explored and defined through two-way discussions with material scientists.

As design and development processes evolve, more accurate simulation tools and/or application-specific prototyping tools and techniques might be necessary or desired. This presents an opportunity for developing design tools in future work. Researchers have already shown the usefulness of the generative parametric design tools that make use of performance-driven data, including the structural and environmental performance underlying a specific application design (Bohnenberger, 2013; Neri, 2010). Such computational tools assume an inherent relation between geometry and performance in devising advanced analytical functions (Neri, 2010), supporting the generation of multiple development trajectories and providing immediate evaluation of them (Malé-Alemany & Sousa, 2008). In the material driven design processes, we took note of the instances that the designers could benefit from such generative tools in further exploring the experiential design space. For instance, the initially observed behavior of the EL sample in response to water could potentially unlock new material experiences that could have been further explored, prior to specifying and prototyping the umbrella. We discussed in **Chapter 3** that the image editing tools used by the design student were not suitable for exploring the experiential design space opened up by altering the specified design parameters and relations. We think that the designer could have greatly benefited from a parametric design tool that let him generate computational simulations of the EL sample as a function of the design parameters, such as the shape and size of the printed pattern, the thickness and flexibility of the substrate material, and the contextual parameters, e.g. the exposure of the material to water, and the brightness of the environment (influencing how visible the light is). The relevance and the effectiveness of such generative, parametric tools in the context of material driven design processes and collaborative materials development requires further research.

6.2 Understanding “Scientific Phenomena” Behind Materials

Our observations of the design processes with the EL materials indicated the need for a conceptual understanding of these materials and the scientific phenomenon underlying their light-emitting function (i.e., electroluminescence). Explaining the smart materials’ working principles has been emphasized when introducing them to designers, both in an educational context and in design and development processes (Addington & Schodek, 2005). In our design case studies, we observed that the existing theoretical knowledge of EL’s basic working principle helped our design students in making assumptions about how the composite might behave if certain structural changes and alterations were carried out. In **Chapter 4**, we also emphasized a conceptual understanding of the smart materials as ‘underdeveloped’ composites to bring forth the design space corresponding to their “becoming”, rather than being. We believe that departing the design process from unprocessed EL materials, instead of ready-made EL devices, put the designers in the right mindset for playing with the finer-grained design variables (e.g., composites’ layering structure) and processing new material samples. Further investigation would be necessary to verify the productive role of such conceptual understandings of materials in material driven processes, especially with regard to the perception of novel material affordances.

The design processes with smart materials as argued by Brownell (2010) require new modes of collaboration among material scientists, engineers and designers. The MDD method leaves the decisions regarding when to involve material scientists and engineers in the process to the designer. Specifically, in case of the EL materials, the making process brought additional complexity concerning their electrical properties and responsive behavior. The designers were uncertain whether the manipulated EL samples would light up when connected to the powered driver, and behave according to their predictions. The only way to know was to actually make the samples and wire them. The technical support provided by the materials scientist in explaining the behavior of (faulty) samples and proposing alternative ingredients and processing techniques was essential to eliminate unnecessary trial and error. We think that the MDD method can benefit from more deliberation on both the need and modes of collaboration, for instance by reflecting and elaborating on the expertise needed in the material driven design processes. Nevertheless, as stated by the interviewed designers in **Chapter 2** and observed in the EL case study **[Chapter 3]**, designers seem to somehow find ways to reach out to material scientists and engineers when needed, implying that the technical contributions of those experts is rather clear to them.

6.3 Transferring "Designerly" Materials Understanding

This thesis did not investigate how the new understandings from a material driven design process can be transferred to other designers. In craft, apprenticeship provides an effective way of transferring experiential and tacit knowledge from masters to novices. Material recipes and making tutorials are particularly useful when working with a material for the first time (Rognoli et al., 2015). In our material driven design projects, we relied on transferring necessary material and processing knowledge through a period of apprenticeship. In addition, we looked into possible ways that we could speed up and optimize the process of learning the basics of the EL materials, fabricating them, and troubleshooting. One example is the process chart, developed by our graduation student that summarized his personal approach to troubleshooting what went wrong with the EL samples that seemed not to be working as expected (see, Claus, 2016). Other examples are the map of material design variables influencing the ultimate qualities of the fabricated EL composite (see Fig. 3.2) and the semantic graphs used to relate and differentiate the EL samples according to the data gathered during the user study (see, Claus, 2016). It seems that a combination of various methods, ranging from step-by-step making recipes, material processing videos, and fabricated material samples (including the faulty ones), to graphical and semantic charts helped with transferring a designerly understanding of the EL materials. While further research is necessary to argue for their effectiveness and generalizability to other smart material cases, these design approaches could each inspire new research directions.

6.4 Materials Potential in Continuity of Material and Symbol

In the EL cases, we emphasized the role of tinkering and making in the discovery of novel material affordances, which are at risk when designers rely too much on top-down design approaches, starting with a product vision or/and user needs. This, of course, does not mean that material driven design limits the designers' pallet to the physical affordances and the here-and-now of perception. In fact, as argued in **Chapter 5** affordances that were perceived in material driven design processes are not only action potentials unlocked mechanically through material engagement, but can be as much unlocked by symbolic constructions. Similar to any manmade object, underdeveloped smart material composites are concomitantly "material" and "symbolic". The latter implies that their being becomes "meaningful" to human designer/user in mediating their relation to the world and to other people (Vygotsky, 1978). The symbolic meaning of materials is, however, largely constructed rather than simply "predetermined". For instance, the symbolic construction of the tattoo culture and a particular relationship of it to ink and (animal) skin and the physical properties of the materials (including the Bare Conductive ink) may equally contribute to unlocking the action of tattooing the conductive ink into the leather (see Fig. 5.5). Relying merely on top-down approaches that prioritize designers' application design vision over direct engagement and exploration of the new material may reinforce a tendency to rely on "known" affordances, deduced from the "given" information and/or previous experiences with other materials. The Material Understanding Step of the MDD method aims to marry between bottom-up experimentation and tinkering with the martial and top-down approaches in exploring novel material affordances. Among top-down approaches, experiential characterization capitalizes on the experiential and interpersonal qualities that the material might elicit (in relation to other people), while benchmarking investigates the world of the past, situating the material within a cultural and historical context (e.g., cultural meanings, proven solutions, unsuccessful attempts). Our conceptualization of 'affordances as materials potential' considers the convolutions of direct affordance and indirect associations (cf. Costall, 1995) in the discovery of novel material potentials.

6.5 Towards Equal Partnership in Collaborative Materials Development

The thesis urges for equal partnerships of designers and materials scientists in collaborative materials development projects, enabling designers' active participation in discovering and defining material potentials and boundaries. Reducing designers' creative role in collaborative materials development to 'coming up' with application ideas is a logical consequence of creativity being understood as "in the designer's mind". The EL design case presented in **Chapter 3** shed light on the dynamic interactions of the designer with the materials, user-study participants, and the materials scientist in exploring novel affordances. Those and many similar cases contradict the expected role of designers to be material/technology "appliers" and rather promote them as active makers of the new material. Researchers have previously touched upon the limitation of relying merely on user-centered approaches in understanding digital materials, arguing that these approaches should not distract the multidisciplinary development team from collaboratively exploring their potentials and boundaries (cf. Sundström et al., 2011). The social dimension of creativity (Glăveanu, 2015) asks to look into the interrelation between designers and material scientists in collaborative projects, not only in terms of multidisciplinary communication and transferring knowledge, but also with respect to their expected roles, autonomy and authority (e.g., the ownership of the project), and the impacts these may have on collectively exploring the novel material affordances.

With this thesis, we hope to start a discussion that could eventually contribute to the discourse of product design and materials development, and particularly initiate a design influence on materials development. Through material demonstrators and scientific papers presented at international conferences, such as the ACM conferences (CHI and TEI), design and engineering conferences (DesForM, EKSIG) and publications in peer-reviewed journals (International Journal of Design and International Journal of Design Engineering) we have reached out to a diverse range of audiences.

6.6 Last Words

Shifting the focus from exploring application possibilities of a USMC, that can only be accessed through information provided by the material scientists, to working directly on processing the material was a key turning point in my PhD research. It opened my eyes to the opportunities and promising development trajectories that simply remain unexplored when a designers' role is constrained to thinking creatively about the product applications of a new and yet-underdeveloped material. I shared the frustration of not fully understanding the material's behavior and not knowing how to compensate for this lack of understanding with the students who participated in my observational studies early on. The interview results of designers from the LTM project showed that the students and I were not alone in experiencing a feeling of frustration and desperation. The shift to material driven design projects, which allowed for materials making and manipulations of the properties, shed light on how these creative processes support designer's understanding of a material and perception of its (novel) affordances. It further surfaced the issues related to the ownership and organization of collaborative materials development projects, touching upon the designer's and material scientist's expected roles and contributions. The identification and articulation of a designer's creative contribution that reaches beyond application design is a small step forward in closing the gap in the discourse between materials science and design. My hope is that the thesis will stimulate future project organizers to reflect on these issues so that the two communities can have a more equal share in defining the material development trajectories.

Appendix

Semi-structured Interview Guide

Table 1 – Questions used in the interviews with the designers.

Number	Focus	5-scale Questions & Semi-Structured Interview Guide
1	General impression of the LTM project and their contribution	How different the design circumstances in the LTM project was from your everyday practice? (1) Not different - (5) Very different
2		To what extent you think your concept showcase the unique potential of the LTM materials? (1) Not at all - (5) Exceptionally
3		How do you rate the influence of design in material development in the LTM project? (1) Not influential - (5) Very influential
4	Understanding of the LTM materials	In the first concept design round, how certain you were about the design boundaries, the LTM's unique potential, and the degree of freedom designers had in designing with the LTM materials?
5		What caused your uncertainty?
6		When did you feel that you have good understanding of the boundaries and the unique potential of the LTM materials? What factor or factors positively influenced your understanding?
7	Use of prototyping and other support tools	What tools, technologies and techniques have you used in understanding/ exploring/ communicating the experiential characteristics of the LTM materials and your design ideas? (Supplement with picture/video if possible)
8		Do you recall any difficulty in relation to the dynamic qualities of your designs?
9	Feedback on applicability of the demonstrators and the Chroma-key tool	How could the electroluminescent demonstrators benefit your understanding of the LTM materials?
10		How in the process of designing with the LTM materials you think the Chroma-key simulator could be useful?
11		What limitations do you anticipate in using the current version of the Chroma-key simulator?

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Summary

In the past decade, the interest in collaborative materials development projects with designers and materials scientists has gained momentum. Designers' involvement in early materials development is expected to inform the development process about the potentials of a new material, beyond the values of efficiency and convenience. This paper-based PhD thesis is an attempt to understand *what design can do* for materials development through studying and questioning current practice. The research has evolved in the specific context of the EU project, Light.Touch.Matters (LTM) that put into practice a proposed methodology for organizing such collaborative projects. The LTM project and its organization set the departure point for further investigations into the new design situation.

Being curious about designers' unique contribution to 'upstream' collaborative projects, we first explored how designers understand, explore, and communicate the LTM material (i.e., a composite proposal of flexible OLED and piezoelectric polymer) and its potentials when the design process departs from a description of its physical and functional properties. One final master project and three group projects were initiated with a generic design brief to design with the LTM materials, similar to the brief that professional designers had received in the LTM project. **Chapter 2** reports on observations, notes, and diaries of the activities performed by our students and the tools and techniques used and developed after receiving the brief and before presenting the final prototypes.

The analysis showed that the common response of design students to the brief was to explore seemingly relevant application domains (e.g., sports, rehabilitation) and use-contexts (e.g., kitchen, outdoor), and generate application ideas. Such a product-oriented approach did not take into account the specific behavior of piezo-polymers or OLEDs, or generate new knowledge of these, but largely tapped into either formal or functional resemblance between the LTM material (e.g., thin and flexible sheet,

pressure-sensitive) and the existing products. As a result, the experiential qualities of the LTM material were explored within the boundaries of the existing use practices and intended interaction scenarios, with little eye for new potentials offered by these USMCs. The material (dynamic) behavior, ‘envisioned’ by the product application concept, remained generic enough so that it can also be prototyped with existing, off-the-shelf pressure-sensing and light-emitting technologies. It was only later in the design process that higher fidelity prototypes were considered, incorporating these digital components into the passive physical mock-ups. The *toolkit* presented in Chapter 2 responds to the need for understanding and communicating the dynamic and performative qualities early on in the design process and collaboratively exploring, identifying, and negotiating the design boundaries. The proposed solution consists of a high-fidelity material demonstrator and a supplementary sketching tool. The former enables the development team members to subjectively experience a specific fusion of material deformation and computational-driven behavior, while the latter lets the designers assimilate the new material knowledge into product design ideas.

After this exploratory research, which involved a number of design case studies and interviews with the LTM designers, the specific research direction for the following studies was chosen, exploring the role of material tinkering and fabrication in understanding the potential of novel materials. This potential remains unexplored when the ‘underdeveloped smart material composite’ (USMC) is only conveniently represented through fixed physical and functional properties.

To comprehend this unexplored design space, the research took a shift towards ‘material driven design’, referring to a design situation where the actual material, rather than information, is the departure point of the design process. Thus, a range of exploratory studies was conducted to identify the benefits of having unmediated, direct access to a material, such as allowing for tinkering to understand the material potentials. **Chapter 3** presents a material driven design case focusing on electroluminescent (EL) materials that serve as an exemplar of how a material driven design approach can offer new action possibilities that are less likely to surface in mere top-down design approaches. For instance, manipulating the composite structure and trying alternative ingredients, as observed in the EL design case, might not be readily supported in concept design processes that depart from functional descriptions of EL materials or a ready-made EL device. To explore this unnoticed/unanticipated design space, designers need to step outside their described role and ‘comfort zone’ and bend the disciplinary limits (e.g., material sample making).

Further analysis of the material driven design explorations with the EL material hinted at a converging design strategy related to the performative character of the EL samples. While in the standard EL device, the light-giving function is activated by a switch, the explorations reveal a number of ways that this main function was deliberately disrupted, meaning that the switch alone could not activate the EL samples, and in addition to that the users were required to co-perform through touching, rubbing, and kneading actions. Reporting on those material explorations, **Chapter 4** elaborates on the design strategy, which deliberated over such a disruption at the levels of matter, structure, form, and computation. In **Chapter 5**, we turn back to the main research question of the thesis, concerning how designers explore novel material potentials and expand on the existing (product-oriented) conceptualizations of materials potential.

Material driven design processes provide us with evidence that the designer’s creativity reaches well beyond mapping the known and ‘given’ properties of existing product applications. It often involves discovering novel affordances that could not have been anticipated or intended prior to tinkering with and processing the material. **Chapter 5** elaborates on ‘why’ and ‘how’ material driven design processes require a new conceptualization of ‘materials potential’ that considers the process and product as a continuum rather than a means to an end. The notion of ‘affordances as materials potential’ is introduced and used to discuss the creative contribution of designers that goes beyond the merits of proposing product applications.

In conclusion, this thesis proposes a novel understanding of design creativity in the context of collaborative materials development. Our material driven design cases allowed for direct, yet technically supported processes of the USMC in a constructive understanding of its novel affordances. They helped us to identify and lay bare the limitation of product-oriented approaches that “black-box” the USMC, rather than investing in understanding the material and exploring its unique potentials. Contributing to the three main research topics of (1) representation techniques, (2) material driven design processes, and (3) design creativity, this research is a modest and crucial step towards what we believe to be a paradigm shift in how (product) design practice and education currently interface with materials and technology.

Samenvatting

In het afgelopen decennium hebben we een toename gezien van projecten waarin ontwerpers en materiaalwetenschappers samenwerken aan de ontwikkeling van nieuwe materialen. Van de vroege betrokkenheid van ontwerpers bij die ontwikkeling wordt verwacht dat daarmee mogelijkheden van het materiaal zichtbaar worden die voorbijgaan aan kwaliteiten als efficiëntie en gemak. Dit proefschrift, gebaseerd op papers, is een poging te begrijpen “what design can do” in de ontwikkeling van materialen door bestaande praktijken te bestuderen en bevragen. Het onderzoek is ontstaan in de context van het EU-project Light.Touch.Matters (LTM) waarin een methodologie is voorgesteld voor de organisatie van dergelijke samenwerkingsprojecten. Dat LTM-project en haar organisatie vormen het vertrekpunt voor verder onderzoek naar deze nieuwe ontwerppraktijk.

Vanuit een nieuwsgierigheid naar de unieke bijdrage van ontwerpers aan dergelijke samenwerkingsprojecten hebben we allereerst geëxploreerd hoe ontwerpers het LTM-materiaal (een composiet van een flexibele OLED en een piezoelektrische polymeer) en haar mogelijkheden begrijpen, onderzoeken, en communiceren wanneer het ontwerpproces begint met een beschrijving van de fysieke en functionele eigenschappen van het materiaal. Conform de opdracht die professionele ontwerpers hadden ontvangen in het LTM-project, zijn een afstudeerproject en drie groepsprojecten opgezet met de generieke ontwerpopdracht om een toepassing te ontwerpen voor de LTM-materialen. **Hoofdstuk 2** beschrijft de observaties, aantekeningen en dagboeken van de activiteiten van onze studenten en de tools en technieken die zijn gebruikt en ontwikkeld nadat de opdracht was ontvangen en voordat het uiteindelijke prototype werd gepresenteerd.

De resultaten lieten zien dat de gebruikelijke reactie van ontwerpstudenten is om schijnbaar relevante toepassingsdomeinen (b.v. sport, revalidatie) en gebruikerscontexten (b.v. de keuken, buitenshuis) te onderzoeken om zo tot ideeën voor een toepassing te komen. Een dergelijke product-georiënteerde benadering houdt geen rekening met of ontwikkeld nieuwe kennis over het specifieke gedrag van piezo-polymeren of OLEDs, maar kijkt vooral naar formele of functionele overeenkomsten tussen het LTM-materiaal (b.v. een dunne en flexibele laag, drukgevoelig) en bestaande producten. Het gevolg daarvan is dat de ervaringskwaliteiten van het LTM-materiaal enkel werden verkend binnen de grenzen van bestaande gebruikspraktijken en voorgenomen interactie scenario's, met weinig oog voor de nieuwe mogelijkheden die deze 'onderontwikkelde, slimme, materiaal composieten' (USMCs) bieden. Het (dynamische) gedrag van het materiaal zoals voorgesteld in de toepassing is zo algemeen dat het ook gemodelleerd kan worden met bestaande, drukgevoelige en lichtgevende technologieën die zo van de plank komen. Pas later in het ontwerpproces werden ook prototypes overwogen met een grotere precisie die deze digitale componenten opnemen in passieve, fysieke mock-ups. De *toolkit* uit hoofdstuk 2 komt tegemoet aan de wens om de dynamische en performatieve kwaliteiten al vroeg in het ontwerpproces te begrijpen en communiceren om zo samen de ontwerpgrenzen te verkennen, bediscussiëren, en vaststellen. De voorgestelde oplossing bestaat uit een natuurgetrouwe demonstratie van het materiaal en een bijbehorende schetstool. De eerste stelt de leden van het ontwikkelteam in staat om de specifieke samenhang tussen de deformatie van het materiaal en het computergestuurde gedrag subjectief te ervaren, terwijl laatstgenoemde tool de ontwerpers ondersteunt bij het toepassen van de nieuwe kennis over het materiaal in ontwerpideeën.

Na dit exploratieve onderzoek, dat gebruik maakte van een aantal design casestudies en interviews met de LTM ontwerpers, werd de specifieke onderzoeksrichting voor de daaropvolgende studies bepaald: het verkennen van de rol van 'tinkering' met materialen en hun fabricatie in het begrijpen van de mogelijkheid van nieuwe materialen. Deze mogelijkheid blijft onderbelicht wanneer de USMCs gemakshalve alleen gerepresenteerd worden door vastomlijnde fysieke en functionele eigenschappen.

Om dit deel van de ontwerpruimte te verkennen maakte het onderzoek een wending richting "material driven design", dat verwijst naar een ontwerpbenadering waarin het feitelijke materiaal, in plaats van een beschrijving, het uitgangspunt vormt van het ontwerpproces. Een serie exploratieve studies is uitgevoerd om de voordelen van onbemiddelde, directe toegang tot het materiaal vast te stellen, zoals het toestaan van tinkering om de materiaal mogelijkheden te begrijpen. **Hoofdstuk 3** behandelt een materiaal-gedreven ontwerpcase dat zich richt op elektro-luminescente (EL) materialen dat dient als een voorbeeld van hoe een materiaal-gedreven ontwerpproces nieuwe actiemogelijkheden kan bieden die waarschijnlijk niet aan het licht komen bij top-down benaderingen. Het manipuleren van de structuur van de composiet en het uitproberen van alternatieve ingrediënten, zoals waargenomen in de EL-ontwerpcase, worden bijvoorbeeld niet ondersteund in ontwerpprocessen die vertrekken vanuit functionele beschrijvingen van EL-materialen of een kant-en-klaar EL-apparaat. Het ziet ernaar uit dat ontwerpers uit hun voorgeschreven rol en 'comfort zone' moeten stappen om deze onbekende ontwerpruimte te verkennen en de disciplinaire grenzen op te rekken (b.v. door het maken van een materiaal sample).

Verdere analyses van de materiaal-gedreven ontwerp verkenningen met het EL-materiaal wijzen op een ontwerpstrategie die samenhangt met het performatieve karakter van de EL-samples. Terwijl in een standaard EL-apparaat de lichtgevende functie wordt geactiveerd door een schakelaar, lieten de verkenningen een aantal manieren zien waarop deze hoofdfunctie bewust was onderbroken. Dit toont aan dat de schakelaar alleen niet de EL-samples kan activeren, en dat in aansluiting daarop gebruikers mee moesten werken door aanraken, wrijven en kneden. **Hoofdstuk 4** gaat verder in op deze ontwerpstrategie waarin verschillende manieren om de lichtgevende functie van het EL-materiaal te onderbreken op het niveau van materie, structuur, vorm, en berekening worden overwogen. In **hoofdstuk 5** keren we terug naar de primaire onderzoeksvraag van dit proefschrift: hoe kunnen ontwerpers nieuwe materiaal mogelijkheden verkennen en de bestaande (product-georiënteerde) ideevorming rond de mogelijkheid van een materiaal uitbreiden?

Materiaal-gedreven ontwerpprocessen geven ons het bewijs dat de creativiteit van ontwerpers verder gaat dan het in kaart brengen van de bekende en 'gegeven' eigenschappen van product toepassingen. Vaak gaat het om het ontdekken van nieuwe 'affordances' die niet voorzien of voorgenomen waren voorafgaand aan de tinkering met en verwerking van het materiaal. **Hoofdstuk 5** staat verder stil bij 'waarom' en 'hoe' materiaal-gedreven processen nieuwe ideevorming rond de 'materiaal mogelijkheden' vereisen die het proces en het product zien als een continuüm in plaats van een middel tot een doel. Het begrip 'affordances als een materiaal mogelijkheid' is geïntroduceerd en gebruikt om de creatieve bijdrage van ontwerpers te bespreken die verdergaat dan het voorstellen van product toepassingen.

Tot slot, in dit proefschrift wordt een nieuw begrip van ontwerp creativiteit gelanceerd in de context van het gezamenlijk ontwikkelen van materialen. Onze materiaal-gedreven ontwerp cases geven ruimte aan directe en door techniek ondersteunde verwerking van de USMC door middel van een constructief begrip van haar affordances. Zij hebben ons geholpen om de beperking van product-georiënteerde benaderingen –die de USMC zien als een 'black box'– bloot te leggen door te investeren in het begrijpen van het materiaal en haar unieke mogelijkheden. Door bij te dragen aan de drie belangrijkste onderzoeksthema's, (1) technieken van representatie, (2) materiaal-gedreven ontwerpprocessen, en (3) ontwerp creativiteit, is dit onderzoek een bescheiden maar cruciale stap naar –wat wij denken– een paradigma verandering in hoe de ontwerppraktijk en ontwerponderwijs dient om te gaan met materialen en technologie.

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