How Design Can Contribute to Materials Research

Explorative Prototyping As a Method for Collaboration Between Design and Materials Science

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Abstract

This thesis examines how design, particularly industrial design practice, can contribute to the research and development of materials and their applications in collaboration with materials science. The topic is approached through the notion of constructive design research, which refers to the utilization of concrete design outputs as a means for research.

The scientific community is struggling with increasing demands for the generation of impact through research, this being the case also in the field of materials science. The integration of design into materials research and development processes is seen as potentially beneficial for innovation. For such endeavours have yielded positive results in industry, but have still remained rare in academia. There is, however, no established view on how the collaboration between design and materials science should exactly function.

The theoretical research inspects these question through literature and interviews. It also examines how design and science relate, thus deriving abductive reasoning and practical knowledge as the core reasoning strategies of design. These are used to further inspect the approach and processes of design, by concluding with explorative prototyping as a method for design to contribute to materials research and development processes.

The practical research examines three case studies, in which explorative prototypes are used in different ways for different purposes. The first case describes the development and prototyping of a biomimetic structure, the second depicts a concept design process for nanomaterials, and the third a process, in which a material is tested and developed using physical prototyping.

The thesis concludes that design can, through explorative prototyping, create ideas for how materials could be applied and further developed. Explorative prototyping is thus utilized for understanding the context of use of materials, which requires a holistic perspective and the integration of knowledge from different fields. Thereby design uses and creates essentially contextual knowledge, which is vital for the generation of impact through research.

Foreword

As I originally set out to do my master's thesis on how design could be used in connection with scientific research, I did not know how challenging and long the process would become. At some point I understood that the topic was extremely broad, and condensing it into its current, still lengthy form took various iterations and changes of perspective. The whole process has however been a huge learning experience, and that is what I am most proud of.

I would first like to thank professor Olli Ikkala, as our collaboration originally inspired me to choose this topic for my thesis. Thanks go as well to his Molecular Materials group, and all of its researchers I have had the pleasure to work with. Cooperation with the group has initiated two processes that are examined in this thesis as case studies.

One of the cases depicts the development of a biomimetic structure inspired by nacre. The development of the structure was done in close collaboration with my friend Wycliffe Raduma. Other contributors in that process included also Jussi Mikkonen and Joona Manner from the Department of Design at Aalto, who aided with the 3D printed prototypes. Thanks go also to the Fluid Mechanics research group who have helped in the mathematical models of the structure.

After I had been working with Olli Ikkala and his group for a while, I got the chance to work also in the DWoC research project funded by Tekes, which aims for example at the development of product and business concepts around cellulose-based materials. I have now worked in that project as the design team's project coordinator since October 2013, and for this chance I want to thank the whole DWoC project organization, and especially Pirjo Kääriäinen from Textile Art and Design at Aalto, who originally suggested me for the post. One case study in this thesis is also derived from this project, and it deals with the prototyping of product concepts for foam formed pulp. In this case study I worked closely together with Tiina Härkäsalmi from the Sustainable Design research group at Aalto, and with scientists Jukka Ketoja and Jani Lehmonen from VTT. Huge thanks for a great collaboration go to all.

I also want to thank both of my thesis tutors, futurist Elina Hiltunen and professor Turkka Keinonen for giving me valuable guidance for my work. Also my colleagues from the design team in the DWoC project, Tiina Härkäsalmi and Marjaana Tanttu, have provided me with extremely good insights regarding my thesis. Naturally thanks go also to all the people who I have interviewed for this work, and who have aided me with their invaluable insights and expertise.

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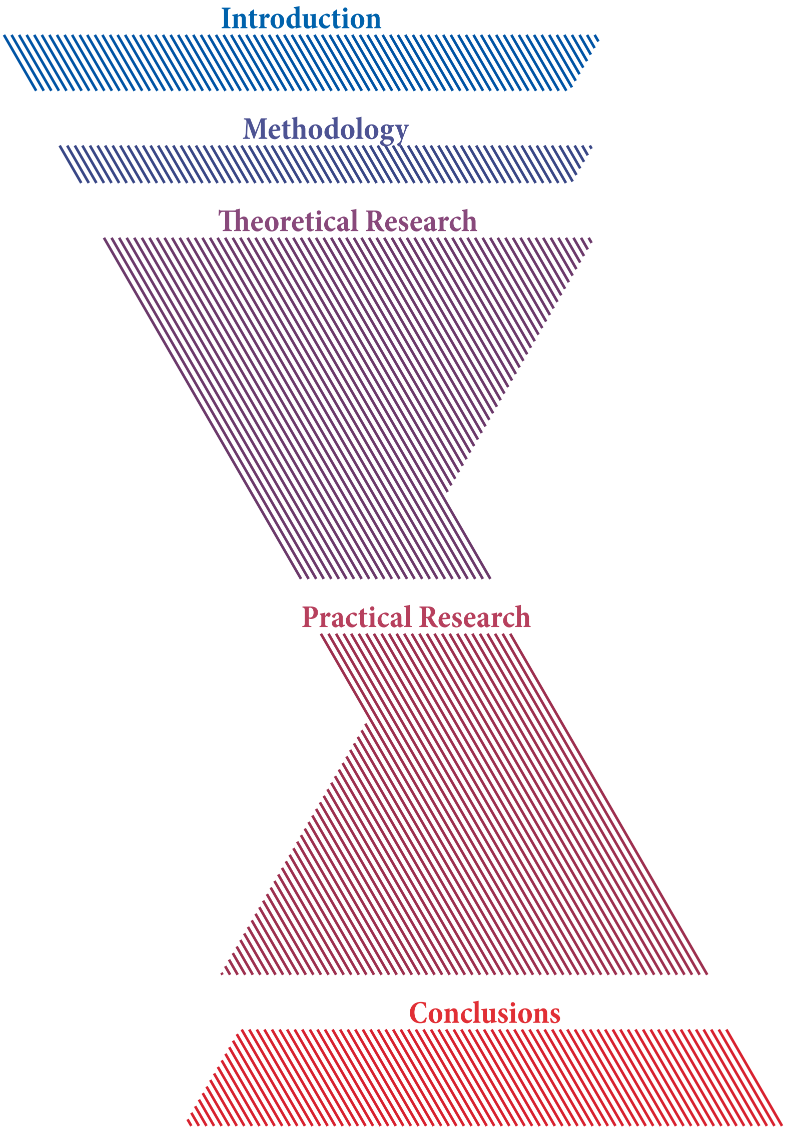
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Introduction

1 How Could Design Contribute to Materials Science?

The objective of this thesis is to explore ways, in which design practice could contribute to scientific research in the field of materials science. The goal is to not only scrutinize possible practical approaches for this, but also some basic reasons why this collaboration could be meaningful, and, in which ways it could be valuable for materials research and design processes. Hence the aim is to investigate collaborative efforts, which would function in a reciprocal way between design and materials science, situating them equally in dialogue with each other. Thereby the goal is to avoid the traditional industrial approach, where design is mainly used as a tool for commercializing technological inventions at the end of the process. Instead, the starting point for this investigation is to look into some of the benefits of using design at the very beginning of technology development: at the stage of scientific research. Thereby this thesis is not only targeting specifically applied or basic research, but instead it tries to connect them through the integration of design.

This thesis studies these questions through theoretical and practical research performed at the intersections of design and materials science. The theoretical investigation is drawn from related literature, as well as from interviews and discussions performed with experts from various fields working in academia and industry respectively. The practical research, on the other hand, explores three case studies related to two distinct research projects, in which the utilization and development of novel materials is approached also from a design perspective.

This thesis approaches the matter through a steeply tapering funnel. First, the theoretical investigation starts by depicting some of the current challenges related to (materials) science, in order to set up justifications for why design could be explored as a potential contributor for scientific research. Next, the relation between design and science is scrutinized, for extracting some fundamental characteristics of the design approach that could benefit materials science. Thereafter some of design’s core reasoning strategies are explained, in order to determine certain practical objectives, and hence also some concrete outcomes that could support collaborations between design and materials science.

The practical research explores these issues through three case studies, each portraying different aspects of the preceding theoretical outline. The case studies highlight processes from two distinct research projects, of which one is a smaller and more informal undertaking, and the other a larger strategic opening. Both projects deal with the application, research, and development of biomaterials and nanomaterials, such as cellulose-based materials and nacre (mother-of-pearl). The insights gathered through the case studies are contrasted with the preceding theoretical framework. The thesis ends with some general conclusions of the practical and theoretical research, and with suggestions of further studies.

1.1 The Scope, Goals, and Terminology of the Thesis

If the inclusion of design practice into materials research can generate contributions to materials science, and vice versa, it simultaneously means that design is also used as a form of research activity. It is rather difficult to pin down one single definition of design, or design research respectively, but research related to design is mostly exploratory, and usually entails ways for inquiry and for the production of new knowledge (Cross, 2007a).

Christopher Frayling (1993) outlines three categories of design research: research into design (sometimes also "research about design"), research for design, and research through design. Frayling describes "research into design" as the most straightforward form of research, which aims to study design itself, its history, and, for example, its social, economical, cultural aspects. "Research for design", on the other hand, includes research activity that seeks to collect reference material that serves and supports the design process, in which the final outcome is some sort of product or artefact. Thus research is used for enhancing the design of an end result. Finally, “research through design” refers to activity, in which new knowledge is created through design work. Frayling lists for example materials research, where the characteristics of materials are studied by creating designs out of them, and also developmental work, where technologies are used in novel ways not thought of before. Thus, although designers often research other fields for their design process, the resulting design itself can likewise be a source of new knowledge (Stappers, 2006, 2007).

Koskinen et al. (2011) take Frayling’s notion of “research through design” and build on it, introducing the concept of “constructive design research”, which they describe as “…design research in which construction – be it product, system, space, or media – takes center place and becomes they key means in constructing knowledge” (p. 5). In their book Koskinen et al. however do not review design research that builds on natural sciences, as they note that such research efforts have traditionally mainly belonged to the fields of ceramics and glass design and conservation.

This thesis however applies processes and methods from industrial design practice into the context of natural sciences, more specifically to the field of materials science. Because the topic is very broad, it could be examined more thoroughly on just a theoretical basis, but the goal of this thesis is to involve also a strong practical perspective. Thereby it takes the approach of constructive design research and implements it into the realm of materials science. As the case studies deal with bio- and nanomaterials, aspects from chemistry and physics are also strongly linked to the process.

Introducing industrial design practice to materials science is rather natural in the sense that industrial design is traditionally strongly involved with the development of products and applications, which relate to our material world. Therefore, although some themes are examined through a more general scrutiny of “design” and “science”, it is done specifically through the perspectives of industrial design and materials science.

Due to the topic’s broadness does this thesis not seek this to unveil absolute truths or precise procedural descriptions about the collaboration between design and material science. Instead, it tries to investigate this relatively unexplored territory in a meaningful way for finding interesting insights about such initiatives. The goal is thus to highlight some aspects of the process and its outcomes that could be interesting for further study, especially as the portrayed case studies describe processes from early phases of the projects. Nevertheless, as design has rarely been set in parallel with materials science in academic materials research, it is possible to find interesting aspects also through a broader and more general exploration of such collaborative endeavours. After all, an important aspect of the design approach is to retain a clear view on the big picture.

1.2 The Motivation Behind the Work

"We would definitely need a designer here," states academy professor Olli Ikkala during a visit to Aalto University's Nanotalo, in early 2013. The Aalto Nanotalo, located at the heart of the university's Otaniemi campus area, is an epitome of scientific culture. It is a cutting-edge research facility housing for example the Molecular Materials research group led by professor Ikkala. The building includes also the Nanomicroscopy Center, which incorporates one of the most advanced laboratory settings of its kind, offering a number of high-resolution microscopy equipment for soft, hard and biomaterial characterization (Aalto University, 2013a). The facility is equipped for example with Finland's only sub-ångström (one ångstrom = 10^{-10} meters) transmission electron microscope, and various other high-tech equipment for advanced materials research (Aalto University, 2013b). For the average person this kind of working environment would probably first emit a sense of abstraction and theory, making professor Ikkala's need for a practice-based designer in this "home of science" sound first unexpected. However, precisely this separating preconception seems to be the reason inducing this need.

Discussions with professor Ikkala shed light into why the intersection between design and materials science could contain a lot of potential, and why there seems to be a rising need for the collaboration between these traditionally distinct disciplines. International competition is getting harsher in industry and academia respectively. A relatively small nation like Finland needs to take its assets and resources and make the best out of them. Scientific research, technology development, and design have traditionally been major strengths in the Finnish innovation culture, and bridging these can be of great importance for sustaining the national innovation potential. On top of this, innovation is not only a national question, but also entails increasingly complex systemic challenges, which affect societies on a global scale. Big challenges relate to questions such as sustainability, exploitation of resources, and economic equality, which all require more holistic solutions to be resolved. Bridging diverse perspectives through a highly interdisciplinary approach can provide extra momentum for innovation, which could help us tackle some of these complex issues facing us today.

Design has been moving upstream in innovation processes during the last decades, targeting increasingly fundamental topics. Initiatives such as the former Helsinki Design Lab, working under the Finnish Innovation Fund, Sitra, have pushed design's boundaries further by exploring commendably new practices such as "strategic design", through which design has been taken even to the realms of governance and public decision making (Helsinki Design Lab, 2010). After all, what would not be designed, and what could not be improved through good design? In regards of technology and product development, the next step for design is to set itself in connection with scientific research, the birthplace of new technology. Perhaps this way we could approach the development of future products and applications through a more holistic lens, thus working towards a better and more sustainable material world.

Figure 1.1 Chunks of nanocellulose in a design laboratory.

Methodology

2 The Methods of Research

This thesis explores the contributive role of design in the collaboration between design and materials science through three distinct approaches. Firstly, the investigation is addressed through a theoretical framework that is built using literature related to the characteristics of scientific research, to the differences and relation between design and science, as well as to the processes and methods of the design approach.

Secondly, the theory is supported by discussions and interviews conducted with experts from various fields, who currently work in both academia and industry. These interviews are used for bringing forth also more personal perspectives to the practices of scientific research, as well as to the processes and methods of interdisciplinary collaboration from the perspective of design. Additionally, some of the interviews relate only to the case studies, and to "research for design", as they are used for example to advance the development of structures, for acquainting with topics related to concept design, or for learning about the properties of the materials dealt with in the case studies. However, some of the interviews relate to both, the case-specific research and the broader topic concerning the collaboration between design and science. The reason for this is that some of the interviews concerning the case studies were also used for informing the general discussion of this thesis. Many issues related to the collaborations depicted in the case studies were naturally also linked to the overall relation between design and science, and to their respective objectives and ways of working.

The third method of research is the practical investigation carried out through the three case studies, and their processes and outcomes. The goal is to contrast the theoretical framework with the observations done through the practical investigations in the case studies. The three case studies relate to two distinct research projects situated in the intersection of design and materials science. Each case study reflects on distinct perspectives and processes for utilizing design in the context of scientific materials research. However, all case studies relate to the research and development of bio- and nanomaterials, including cellulose-based materials such as nanocellulose, as well as nacre, also know as mother-of-pearl, and its synthetic derivative. They are all also approached through the perspective of constructive design research.

2.1 The Documentation of Research

The research and development work depicted in the case studies was mainly documented by keeping a daily project diary from each process. The diaries included notes about daily occurrences, developments, and thoughts related to the processes. New ideas, possible problems, aspects related to the cooperation with scientists, as well as potential design solutions were documented through written notes and drawings. The goal was to document the processes as diversely as possible. Further on in the process, documentation was done also through CAD models and their iterations, as well as through photographs portraying specific parts of the processes, such as mould and model building. In two cases out of three also physical prototypes were produced, tested, and documented.

Notes of the collaborative design work carried out in the case studies, which also aided in understanding the bigger picture of this thesis, were mainly documented through diary entries, drawings, and photographs. The interviews used as basis for the theoretical research and for the case studies were mainly documented through written notes, as well as through voice recordings. The entire list of the interviews that were carried out as part of the theoretical and/or practical research can be found in the appendix of this thesis.

Theoretical Research

3 New Challenges for Scientific Research

The scientific field in general, and hereby also materials science, is today facing a growing amount of demands and challenges. Science's successes have made it a central part of the generation of wealth and well-being, which has entwined it tightly with the rest of society. This has, however, rendered the world, and the questions for science, also more complicated. (Nowotny, Scott, & Gibbons, 2001) The drive towards effect and impact has thus become increasingly pronounced also for scientific research, and hence the need for impact generation has turned into a serious question for the scientific community. As these new objectives and requirements have increasingly become emphasized next to more conventional ones, such as the advancement of self-supporting fundamental knowledge, science has had to approach research from new perspectives.

Research should, for one, have societal impact, aiding in tackling current and forthcoming challenges through the development of purposeful applications. Applications enabled through scientific research should for example also support business and enhance sustainability. (T. Härkäsalmi, personal communication, February 21, 2014) Research results should thus have value also outside of the scientific community, and present wider contributions to academia, industry and the public sector respectively.

These requirements are articulate, not only at later stages of research, when results are applied for technology development, but at earlier stages of research as well. In fact, the case is apparently very similar for applied and more fundamental investigations. This trend manifests itself for example in today's scientific publications, which increasingly emphasize that published articles should also scrutinize the potential applicability of the conducted research. This is seen to bring relevance to the research. It also puts pressure on the scientists to address the potential utilizations of their research in their scientific papers. This situation is particularly true for more prestigious scientific publications, where most scientists aspire to publish their papers in. (A. Gröschel, personal communication, February 3, 2013; O. Ikkala, personal communication, June 11, 2013)

This progression holds true also for evaluations regarding research funding. For example the requirements for EU-funded scientific research programs are increasingly stressing the impact potential of projects (H. Toivonen, personal communication, August 15, 2013). The EU functions as one of the most significant public funding agencies for scientific research globally, which gives their policies influence not only in Europe, but internationally as well. The policies are clearly impact-driven, and aim mainly at improving European competitiveness through its industry and public system. Funding in the EU is distributed through research programs, to which multinational research consortiums apply by competing against each other. A pool of experts, drawn from academia, industry and from public administration, evaluates the applications, in contrast to the traditional peer-review model present in sciences. The goal is thus to get the most competent experts to review the applications according to the criteria set by the EU, of which only one third counts for the proposals scientific quality. The other two main criteria concern the quality of the consortium to perform the project, and the potential impact of the project. (Kuutti, 2007)

Additionally, this does not seem to be the case only in the EU. The National Science Foundation (NSF) in the U.S. is heading in a similar kind of direction. The NSF has for example established a new program titled "Design of Engineering Materials Systems" (DEMS), which puts emphasis also on the design perspective's integral part in the systemic development of engineering materials. This new program "supports fundamental research intended to lead to new paradigms of design, development, and insertion of advanced engineering material systems" (National Science Foundation, 2013). Thus the program strives to bridge theory with principles from engineering and design, thereby highlighting the creation of fundamental knowledge in unison with investigations regarding the use and applications of this knowledge. The integration of additional values, next to more traditional science-based criteria in research, thus appears apparent also in the NSF. The synopsis of the DEMS program even clearly articulates how proposals "without an intellectual emphasis on design are not appropriate for this program", thereby distinctly stressing also the importance of the design perspective within the process.

As with the DEMS program, the need for impact has affected also materials science in general. In order to answer to more complex societal and industrial requirements related to aspects such as sustainability, resource efficiency, and enhanced performance, materials scientists have for example reached to nature for clues that could aid in material development. For example biomaterials, though utilized since antiquity, have recently increased significantly in sophistication, as novel solutions are being vigorously developed in various areas, such as in the medical industry (Huebsch & Mooney, 2009). Also the field of nanomaterials has experienced huge advancements in recent years, also pushed by an increased understanding of the significant potential of bio-based and biomimetic solutions (Ashby, Ferreira, & Schodek, 2009).

3.1 The Fragmented Nature of Natural Sciences

Why is the growing demand for impact challenging for traditional scientific study, and how does design fit into the picture? The role of design will be examined more closely later on, but first some preliminary connotations. Materials research is likewise affected by an increasing need for impact, but the required holistic solutions are nevertheless hard to achieve. There is still a lot to learn for example from natural systems. In natural structures, which many biomimetic materials draw inspiration from, one can notice that materials are always part of some comprehensive design they are functioning within. Organisms utilize materials and design inseparably and contributively, usually through hierarchical structures that serve many purposes. Bird's feathers form its wings for flying, repel water, and provide coloration and insulation. (Bhushan, 2009) The properties of spider silk support the geometrical shape of the spider web it is used in (Cranford, Tarakanova, Pugno, & Buehler, 2012). Materials in nature thus seem to always serve a purpose in connection to a design, in order to create an effect aiding in survival.

During the era of industrial production materials science and product design have mostly been separated efforts carried out by experts from different disciplines. On top of gaining significance in today's research, a drive for bridging design and (materials) science has been present in human activity also in the past. Many of the great fundamental thinkers, including Aristotle, Galileo, Leonardo da Vinci, Isaac Newton, and Louis Pasteur were involved in generating basic theories and practical applications simultaneously, which was driven by their desire to create a specific "effect" (Stappers, 2006, 2007), relatable to how nature composes materials (the basic elements) and design (their utilizations) in unison. Leonardo da Vinci for instance became a prime example of a crosscutting "Renaissance man", who proficiently combined aspects of art and science, as well as design and engineering in his work.

Da Vinci's times were, of course, drastically different from today. The Renaissance brought forth a shift in education through the restructuring of the liberal arts (McKeon, 1968), which culminated in the 19th century as entailing education in *beaux arts*, *belles letters*, history, natural sciences, mathematics, philosophy, and fledgling social sciences. During these centuries also abstract formal logic became more emphasized through the Cartesian revolution, at the expense of more practical and worldly expertise (Toulmin, 2001).

By the end of the 19th century, as the rate of progress increased, advances in knowledge and methodology resulted in the development of new subjects. Consequently, the circle of learning was divided and subdivided into an increasing number of fields, ultimately resulting in a "patchwork quilt of specialization". (Buchanan, 1992, pp. 5-6) The development of new highly specialized subjects increased the ability to advance deep knowledge, but it simultaneously increased narrowness of scope and disconnection between different fields of study. This specialization, contributing to the fragmentation of knowledge, lead to subjects losing "connection with each other and with common problems and matters of daily life from which they select aspects for precise methodological analysis”. (Buchanan, 1992; McKeon, 1972, pp. 168-169) This precise, analytical and theoretical approach was also emphasized through the ideals of Cartesian thinking, which was a view long dominant in the field of sciences (Toulmin, 2001).

As a result, the degree of specialization seems today incomprehensibly deep, as the disciplinary niches appear increasingly precise and cryptic. Working solutions, such as products or applications, are however mostly compilations of knowledge from these specialized fields, and in addition to scientific relevance, they possess requirements related to practical gaols. The widely acknowledged approach of interdisciplinarity is trying to tackle these challenges, but still, the goal of integration seems difficult to attain. Additionally, the question is not solely about combining theoretical knowledge from different sources, but also about connecting theory with practice.

Richard Buchanan (1992) for example claims that the search of an integrative discipline completing the arts and sciences has become a central theme of intellectual and practical life. The British scientist and novelist C.P. Snow (1959) also demonstrates a similar kind of view in his book “The Two Cultures and the Scientific Revolution”, as he distinguishes the approaches of science, and that of arts and humanities as the “two cultures”. This dichotomy, he claims, functions a major hindrance for solving the world’s problems. For it is natural that in a world where knowledge has traditionally been very scattered, dealing with complex and interconnected problems seems challenging.

3.1.1 Implications of the Fragmentation in Natural Sciences

The fragmentation of knowledge seems especially stark in natural science, which entails nowadays highly specialized fields in areas such as biology, chemistry and physics, and to which the field of materials science also belongs. Materials science itself also constitutes of numerous sub-branches, such as the aforementioned fields of biomaterials and nanomaterials.

Thomas Kuhn describes the characteristics of traditional natural sciences in his landmark publication from 1962 “The Structure of Scientific Revolutions”, which tries to explain how scientific progress fundamentally functions. It challenges the long-standing linear view of scientific progress, arguing that actual breakthrough ideas able to disrupt accepted thinking happen outside of the everyday gradual processes of “normal science”, described by Kuhn also as “puzzle-solving”. He states that this puzzle-solving nature of science leads to situations where scientists rarely scrutinize the actual utilitarian potential of ideas. Instead, scientific work is mainly pursued because it can be pursued, and because it makes an attractive challenge that puzzles the minds of the researchers in the scientific community. These scientific puzzles and their solutions may not be evaluated by the personal satisfaction of a researcher, but must be accepted as solutions by many. The evaluating group however, does not consist of a heterogeneous cross-section of society as a whole, but is rather the well-defined community of the scientist’s professional peers. Mainly because puzzle-solving is regarded as an end in itself, and because of its isolation from other fields of society, sees Kuhn natural science not traditionally being a process of evolution towards any broader goal. He points out that at the same time in social sciences for example, the choice of research problems needs to be defended with implications to wider issues, like for instance to the effects of racial discrimination. Thereafter Kuhn also states that, “If we can learn to substitute evolution-from-what-we-do-know towards what-we-wish-to-know, a number of vexing problems may vanish in the process” (p. 170).

Kuhn’s work has been of great influence (Garfield, 1987), but likewise the target of criticism. Nevertheless, some of his core arguments, although composed decades ago, seem to still resonate today. Discussing with various academics and representatives from industry brings light to some of the challenges, which originate from a high degree of specialization in research. Discussions were carried out with professors and researchers from different fields of materials science and design, with project coordinators from interdisciplinary projects, with design consultants, and with specialists, team leaders and managers from internationally operating companies that have a strong focus on materials and design.

Materials science studies the properties of materials and how those properties are determined by the material's structure. Materials scientists mostly work in laboratories conducting research for investigating and developing the materials they study. Generally speaking, scientists quite casually select the direction and focus of research, as it is mainly based on their hunches and estimations regarding which material properties could potentially be interesting and worth of study. This is common practice, although scientists are not experts in exploring prospective trends, challenges, user needs, or contexts of use, which would be beneficial to take into consideration in the development of future materials. (O. Ikkala, personal communication, June 11, 2013)

The prevalent situation seems to be that scientists are good at doing science, but lack abilities for exploring meaningful future possibilities enabled through the science. Ikkala (personal communication, June 11, 2013) also states that nowadays it has become increasingly important for scientists to evaluate what their research could potentially enable. He notes, however, that the evaluation of "enabling" in scientific discourse is often slightly insufficient. Scientists are generally not trained for exploring contingent futures, in order to broadly contemplate what trajectories of research to follow in terms of meaningful application development.

Hence "the coulds" and "the shoulds" ought to be evaluated concurrently when exploring possible applications and directions for research. Österlin La Mont et al. (2013) conducted an investigative student project on the communicational challenges in a larger interdisciplinary research project, and additionally remark that a common feature in scientific research seems to be the alleged existence of solutions, but without the presence of questions they seek to answer (personal communication, December 4, 2013).

Often it seems that the improvement of relatively isolated parameters, such as the increase of tensile strength, is enough of a goal to be pursued in materials science. The science of developing new materials is complex, but nevertheless it should be remembered that rarely is one single property an end in itself in practice, as solutions usually require a holistic approach for being effective and useful. In the case of novel material utilization, many big challenges are systemic and lie in material ecologies. For instance in terms of sustainability, systemic solutions, which for example relate to material efficiency, recycling, and reuse, outperform narrower solutions that may include changing to a new advanced eco-material (Montalvo, Díaz López, & Brandes, 2011).

Novel materials will thus require broader solutions to be adopted, as material cycle operations and application development processes are influenced by multiple stakeholders. The utilization of novel materials therefore depends on many intertwined factors relating to their varied properties. Ashby, Ferreira and Schodek (2009) for example divide the properties of materials into altogether seven categories of primary material characteristics, of which each contains several qualities that determine the technical, perceptual, and associative qualities of materials. Essentially, as they point out, all of these qualities influence the usability of a material in applications and products.

In the case of biomimetic materials, researchers have to some extent embraced the multifunctional qualities of solutions found in nature. For tackling complex issues related for example to commercialization, production, and sustainability, which are affected by many factors on top of a material's basic technical properties, the need for an even more holistic approach seems still evident. The drive for connecting materials science broadly to other fields of knowledge, in order to identify plausible applications and their wider implications, is mostly carried out incompletely in the laboratories, where the cornerstones of new materials and technologies are laid. The complicated nature of these issues creates a need for integrating of a broader perspective into the context of materials science. This would hopefully enable more comprehensive evaluations of the goals and uses of materials research.

3.1.2 Challenges for Interdisciplinary Work in Academia

The challenges of fragmentation are often approached through interdisciplinary cooperation between experts from different backgrounds. The aim is to create more complete solutions by using the diverse knowhow of a team. The integration of different perspectives through interdisciplinary collaboration is often listed in the mission statements of forward-looking institutions, such as Aalto University, but in general, a divide among disciplines still seems entrenched in academia.

The issue relates partly to the ambiguity of the term "interdisciplinary". Sabine Seymour (personal communication, July 2, 2013) and Juan Hinestroza (personal communication, July 30, 2013) both state that broadly crosscutting initiatives in academia are still rare, and that even highly regarded universities for example in the U.S., such as MIT and Stanford, tend to lack truly integrative approaches that would bridge very distinct disciplines, such as design and scientific research. Harri Toivonen (personal communication, August 15, 2013) argues the same, but mentions the MIT Media Lab as a rare exception, although it is as well clearly tech-driven. Marco Steinberg (personal communication, August 9, 2013), previously a professor of architecture at the Harvard Graduate School of Design, also confirms this perception, and explains it by saying that although many U.S. universities claim to have an interdisciplinary approach, the view of what is considered "interdisciplinary" is quite narrow. Steinberg states, "You have biochemistry doing stuff with molecular chemistry doing stuff with physics, but still, it is restricted to a certain kind of shared scientific culture." He thus stresses that collaborations between totally different fields, with different working cultures, are truly very rare.

This situation is persistent partly due to the fundamental rules academia works in. Discussing the matter with professor Hinestroza (personal communication, July 30, 2013) brings good insights to this. "The reward system of the academic environment is also bias towards being a lonely person and working by yourself", he states. Hinestroza points out that interdisciplinary collaborative work is often seen as something taking time away from publishing papers, which is regarded as the most important demonstration of one's contribution in the academic world. Hence it seems as if the fundamental structures of the academia would function against deeper forms of crosscutting work, especially between practices inhabiting two very distinct working cultures. Hinestroza thus talks about the "different currencies between design and science", by referring to the underlying problem of a drive towards totally different goals: design towards practical outcomes and prototypes, science towards research papers. Hinestroza sees the situation as an implication of the rooted traditions of academia, originally formed in order to educate a totally different world more than a hundred years ago. He himself is strong advocate of interdisciplinarity, running projects entailing chemists, physicists, engineers, and designers at Cornell University. Through these projects he has realized the importance of working on interdisciplinary interfaces. "You need to make a difference by working on those interfaces, and those interfaces have so much richness that places that understand their value, will be the leaders in twenty years time", Hinestroza says.

4 Alternative Views on Scientific Research and the Inclusion of Design

The fragmented nature of natural sciences has its roots in certain historical developments, as previously shortly described. Although times have drastically changed, and challenges have become increasingly complex and entwined, natural sciences are still to a large degree working with the traditional norms characterized by specialization and fragmentation.

In industrial research and development processes, design has traditionally been included into the process at the stage when commercial applications are generated for new technological inventions. Industrial design has its roots in the requirements of mass production (Buchanan, 2011), and therefore its foundations often lie on a modernist view on product development in academia respectively. In product development, design has thus traditionally been used collaboratively with engineering, and due to its age-old role as a "stylist" of products, design is often still seen as something to be implemented in the latter stages of a product development process. This approach suggests a linear approach in research and development processes, which has, traditionally in industry, been initially pushed forward through results from scientific research, and ended with the styling of products through design.

This linear model also includes the linear view scientific research, which usually starts with “basic research” (or “fundamental research”), which is described in the Frascati Manual by OECD (2002) as follows,

> *Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view (p. 77).*

In natural sciences, research is aimed at the investigation of natural phenomena, as in chemistry or physics. The assimilation of basic scientific research into new technologies and engineering purposes takes place through “applied research” (Hoddeson, 1981), which can be described as follows,

> *Applied research is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective. (OECD, 2002, p. 78)*

Applied research thus uses results from basic research as basis for the development of applicable technology (Kiikeri & Ylikoski, 2004). The separation of scientific research into basic and applied traditionally also entails a perception of linear and systemic progress, from understanding fundamentals of phenomena towards utilizing this understanding for the development of usable technologies, as originally portrayed by Vannevar Bush (1945).

This perception is, however, somewhat problematic. The definitions of basic and applied research are usually quite abstract, resulting in overlaps and difficulty in distinction, especially since a reference to the objectives of research do not usually include a breakdown of whose objectives are talked about (Kiikeri & Ylikoski, 2004). Andrew Webster (1991) also claims that the separation between basic and applied research is becoming irrelevant, especially in the context of interdisciplinary work. Donald Norman (2010) argues that the linear progression of research and development processes is inherently incorrect by saying,

> *The traditional folklore of research and development holds that there is a smooth, steady chain from pure, basic research to more applied research, to advanced products, to commodity products. As a large number of studies of research and development have shown, this nice, logical progression does not exist. Yet the myth persists. (p. 11)*

Despite its problems, the linear view of scientific research has been long taken as a norm. There are, however, deviant views on the nature of scientific research, and how knowledge can be created. Gibbons et al. (1994) for example separate two modes of scientific research: "Mode 1" and "Mode 2". According to Gibbons et al., Mode 1 is the traditional disciplinary production of knowledge, which is mainly driven by the sake of scientific knowledge alone, and can thus be compared to basic research. This traditional view of research also entails its linear advancement and separation into discrete disciplines. They state that Mode 1 refers to knowledge production including a lot of rules and norms, which ultimately "determine what shall be count as significant problems, which shall be allowed to practice science and what constitutes good science" (p. 3). The evaluation of research in Mode 1 is achieved through a peer-review system.

Mode 2, on the other hand, Gibbons et al. (1994) describe as knowledge production achieved in a context of application. Knowledge is produced reciprocally in interdisciplinary groups, and is distributed to stakeholders through the process itself. In Mode 2, knowledge production happens through a heterogeneous set of skills and experience, and is therefore not judged through a peer-review process, but through the context of application by a mixed group of stakeholders. Hence, Gibbons et al. argue that Mode 2 research always emphasises the usefulness of results, and their value to the stakeholders or to society in general. Mode 2 should, however, not be confused with applied research, since it is not as such preceded by basic research, and its final results are typically beyond the boundaries of a single discipline, unlike in Mode 1. As they also note, it is not enough in Mode 2 to just bring pieces of knowledge from different disciplines together, but instead, this knowledge needs to be integrated through a specific context of application.

Gibbons et al. (1994) also describe how academic professionals in universities usually account for Mode 1 knowledge creation, whereas Mode 2 happens more in heterogeneous organizations. Thereby Mode 2 research is mainly launched by reasons coming from outside the scientific community, and it is performed in a context with various stakeholders, which need to be taken into account. As with today's rising demand for impact also in scientific research, as described earlier, universities have also engaged more in Mode 2 knowledge production, evaluated by a mixed group of stakeholder rather than peers, as the need for the relevance in research has grown.

Donald Stokes (1997) has likewise introduced an alternative model for scientific research to counter Bush's linear idea, which depicts similar concepts as the model of the two modes described by Gibbons et al. (1994). Stokes creates a quadrant model for scientific research, the principles of which he highlights by creating analogies to famous scientists. He recognizes the two extremes of research, by associating basic research with quantum physicist Niels Bohr, who concentrated only on fundamental problems, and applied research to inventor Thomas Edison, who focused primarily on the development of applications. Stokes argues that this abrupt dichotomy of basic and applied research would no longer serve the demands appointed to science. He states, "It is no longer believed that a heavy investment in pure, curiosity-driven basic science will by itself guarantee the technology required to compete in the world economy and meet a full spectrum of other societal needs" (p. 58). Stokes approaches this problematic by suggesting a third category of research, which he associates with chemist and microbiologist Louis Pasteur, who not only broadened the understanding of fundamental knowledge, but also applied it through the development of vaccines. Thus Stokes identifies this category of research to be concerned with understanding scientific principles and their applications simultaneously, naming it “use-inspired basic research”. He describes this mode of research as “basic research that seeks to extend the frontiers of understanding but is also inspired by considerations of use” (p. 74).

4.1 Possible Benefits of Linking Industrial Design and Materials Science

What is interesting to notice about Mode 2 knowledge production by Gibbons et al. (1994), and about use-inspired basic research by Stokes (1997), is that they can be used to link the approach of design to scientific research. Kari Kuutti (2007) argues that design can be highlighted as an exemplary manner of Mode 2 knowledge production, as it largely fulfils the criteria for it. The idea of use-inspired basic research likewise justifies why design could be placed in connection with scientific study, as the coupled strive not only towards the generation of new knowledge, but also towards a desired effect, would make use of the strengths of the design approach (Stappers, 2007). Hence the inclusion of design in parallel with scientific research can be seen as valuable in interdisciplinary impact-driven research projects.

Through the growing emphasis on impact in research, the diversity of perspectives is seen increasingly valuable also in academia. The trend in industry has been the same, although it has moved towards more heterogeneous approaches through interdisciplinary work already earlier, as research and development processes have become more holistic, networked and integrative throughout the last decades (Rothwell, 1994). Modern technologies have become increasingly complex, which has promoted the convergence of practices, and lead to emerging conjunctions of even traditionally distant disciplines, such as design and science (Stappers, 2007). This can induce very fruitful collaborations, since as Buchanan (1992) sees it, design is, in fact, a “liberal art of technology culture" that is free of any specific subject matter, but instead integrates theoretical and practical knowledge from arts and sciences for productive purposes.

The simple reason for specifically industrial design practices being relevant for particularly materials science is the connecting element of materiality, and the drive towards ultimately tangible applications and products. Despite having its roots in product design, the field of industrial design has evolved towards a more holistic, systemic and strategic direction. This has, however, actually provided it with methods that give it sufficient depth for approaching also issues related to more upstream research and development processes, included for example in scientific research. The industrial design practice is still strongly concerned with integrating these more holistic aspects to the creation of tangible applications and products.

Integrating design in parallel with research is seen as increasingly valuable from the perspective of materials science, which is, as mentioned, being challenged by a growing need for impact and applicability, not only through applied, but also more basic research. Approaches that drive the exploration of possible applications and research directions could thus be valuable throughout different stages of research processes. A design approach could provide new insights to these questions, and challenge the scientists' perspectives, which might be biased towards already established ideas. Scientists tend to for example comment on the applicability of their results in research papers mostly briefly and without extra investment. (A. Gröschel, personal communication, December 13, 2013; O. Ikkala, personal communication, August 12, 2013) Thus also Pieter Jan Stappers (2006) argues that these "generative activities" used for contemplating questions of applicability in science "…are only presented as a small part somewhere between the introduction and the literature review" (p. 13).

There seems to also be an increasing interest from design schools and designers to work in the realm of materials science, and in the context of natural sciences in general. Yet there are no firmly established perceptions of the character of such collaborations: the evaluation criteria of collaborative outcomes, as well as the processes and methods of collaboration, are still somewhat uncharted territory, especially in academia. Many design schools have developed speculative design approaches exploring the implications of science and technology, but reciprocally collaborative efforts together with scientists towards a common gaol have been more rare. (I. Koskinen, personal communication, September 18, 2013; Stappers, 2007)

Driver, Peralta, and Moultrie (2011) also highlight that little academic work has been conducted exploring how design could contribute to scientific research, although substantial evidence suggests that design has clear value in the development of new technology in industry. After all, much of new technology initially originates from scientific research. Hence it can be seen as peculiar, how unconventional it still is for designers to work together with scientists, also in the context of materials science, especially since reports like Lord Sainsbury's 2007 review of science and innovation in Britain already indicate great potential in it. "Evidence suggests that the use of design helps scientists to develop commercial applications for their work while it is still at the research stage or at the outset of the technology transfer process" (Sainsbury, 2007, p. 151). Driver et al. consequently studied how design and science could collaborate and how it could benefit scientific research. Using related literature and interviews conducted with scientists as basis, they identify five potential ways, in which design could contribute to scientific research, which include communicating research results, exploring applications for new technologies, depicting scenarios of use, creating demonstrators, and challenging the scientists' perspectives of research.

Albeit rarer in academia, industry has traditionally approached the collaboration between design and materials science more open-mindedly. As Seymour (personal communication, July 2, 2013) and Hinestroza (personal, communication, July 30, 2013) note, some examples of this exist among larger technology companies and research organizations, such as DARPA, which is known to work in a very interdisciplinary way, connecting for example engineers, materials scientists, and designers. Hinestroza for example comments on the meaning of disciplinary differences in organizations like DARPA that, "These agencies that don't care about these divisions, they are mission oriented", thus clearly indicating a way of working, which resembles the characteristics of Mode 2 research, and use-inspired basic research.

Also Kari Hiltunen (personal communication, October 10, 2013), senior manager at Nokia (now Microsoft), explains how the company has positive experiences from their design team working cooperatively with their materials engineers. For example the material for the seamless "unibody" covers in the Lumia mobile phones was created through collaborative efforts between design and materials science.

Additionally, the rise of the Italian furniture and design industry in the mid 20th century can be partly accredited to joint ventures between design and materials science. An early explorer of polymers in household products, Kartell, for example still strongly collaborates with Bayer Material Science in product development. Also B&B Italia can be mentioned as a good example in this context, as it was founded in the 1960s as a result of explorations of using polyurethane as a material for sofas. (TDM6 - The Syndrome of Influence, 2013; Verganti, 2009)

An important reason for exploring the collaboration between design and material science is simply the presumption that design could work contributively in parallel with materials research, as well as the fact that these collaborations have not been investigated much in academia. Important drivers include the identification of meaningful directions of research, and the enhanced implementation of scientific research in useful applications.

One essential factor is to thus tackle the dilemma of science, which concerns the purposeful utilization of research. The case of novel nanomaterials highlights this situation well. Ashby et al. (2009) remark how nanomaterials have developed through significant advances in materials science, and their use is expected to have huge consequences in various industries, and society accordingly. They also note that because nanomaterials are quite recent inventions, the design field tends to still lack understanding regarding what these materials are, and how they could be effectively used. Within the scientific community the fundamental scientific knowledge exists, but there is no understanding of how these materials should be used for the development of useful applications, or for addressing societal needs. Hence Ashby et al. describe the situation as “a technology looking for an application” (p. xiv). Therefore it is meaningful to explore, how issues like these could be approached.

5 An Overview on the Relation Between Design and (Materials) Science

If design is seen as something that could help science in creating impact, not only in industry, but academia respectively, then how could this be achieved? Before going further into the characteristics of the design approach, a scrutiny on the general characteristics of, and relation between, design and (materials) science is in place. The goal is not to formulate thorough explanations of what “design” and “science” are, but instead to look at some of their general qualities and connotations for finding areas, where the design approach could complement the approach of scientific research.

If we first look at some historical factors, natural sciences, formerly known as “natural philosophy”, have existed as an established practice already for millennia (Grant, 2007), whereas design on the other hand has been recognized as a discipline for a much shorter period of time, despite the fact that people have been designing objects since the beginning of humanity.

During the early days of civilization, design was mostly manifested through crafts, and was thus strongly linked to understanding the characteristics of materials. In fact, many craftsmen advanced the knowledge about materials through utilizing them for the production of tools and other objects. Thus “materials science” and “design” were strongly linked. During the fourteenth, fifteenth, and sixteenth centuries, as the new liberal arts developed, design was, however, regarded rather as a servile activity, performed through the practical knowledge and intuitive abilities of artisans and craftsmen (Buchanan, 2001).

As design has slowly developed into an established discipline in modern times, the relation between design and science has become an interesting subject for scholars, and substantial research has been conducted in order to understand the commonalities and differences between them (Peralta & Moultrie, 2010). Especially during the 1960s, many design scholars tried to interpret design in similar ways to science, but today the aim has shifted towards respecting their differences, and seeing design rather as a "design discipline", with its own "designerly" ways of knowing (Cross, 2007b; Cross, Naughton, & Walker, 1981). These designerly ways of thinking have slowly gained ground in being recognized as different from, but as powerful as, scientific ways of thinking (Archer, 1979), even being labelled as one of the "broad areas of man's concerns" (Archer, 1981, p. 34) next to sciences and humanities. Donald Schön (1983) suggests an own "epistemology of practice" for design, which could be utilized for targeting "situations of uncertainty, instability, uniqueness and value conflict" (p. 49). Also Nigel Cross (2001) sees that design can stand on its own as a field of knowledge, and that it should therefore try to recognize its own "intellectual culture".

These differences also reflect on how the objectives of design and science are defined. Generally speaking both disciplines strive to enhance our understanding over the world and make it more controllable for us, in order to improve the human condition and the well-being of people. On a more detailed level it often seems that the "design" is hard to define precisely, as definitions tend to usually exhibit ambiguity and vary depending on source. Sometimes definitions of design are even contradictory. Wolfgang Jonas (2001) tries to explain design by highlighting what it not is, by saying,

> *Design is not art because it does not aim at individual expression, but instead to serve various stakeholders, even though there are all of those intuitive, creative, and individual components. Design is not technology*

> *because it deals with fuzzy, discursive criteria rather than objective criteria, even though design shares many functional objectives. Design is not science because it does not offer new explanatory models of reality, but changes reality more or less purposefully, and yet the experimental process of research resembles the design process (pp. 65-66).*

As Jonas points out, design has similar qualities with other disciplines, despite being inherently different from them. In terms of products for example, which can be examined in the case of industrial design and materials science, design usually makes considerations for a products usability, usefulness, and desirability (Buchanan, 2001), keeping in mind also its feasibility and viability (Brown, 2009).

Design's angle of approach is wide, and thus descriptions remain vague. A relatively pragmatic portrayal of the aims of design is provided by The International Council of Societies of Industrial Design (n.d.), which says,

> *Design is a creative activity whose aim is to establish the multi-faceted qualities of objects, processes, services and their systems in whole life cycles. Therefore, design is the central factor of innovative humanisation of technologies and the crucial factor of cultural and economic exchange.*

Definitions of science are, on the other hand, mostly more solid. Natural sciences can be describes as belonging to,

> *…any system of knowledge that is concerned with the physical world and its phenomena and that entails unbiased observations and systematic experimentation. In general, a science involves a pursuit of knowledge covering general truths or the operations of fundamental laws (Encyclopaedia Britannica, 2014a).*

Furthermore, materials science can be defined as entailing, "…the study of the properties of solid materials and how those properties are determined by a material's composition and structure" (Encyclopaedia Britannica, 2014b).

These descriptions highlight some general features regarding what design and (materials) science aim at, and what they operate with. The definitions of science usually seem more rigorous than those of design, but then again it is more in the character of science to create generalizable definitions anyway. For as natural sciences are concerned with establishing plausible explanations about physical phenomena, its outcomes need to be based on the notions of validity, proof, logical reasoning, and empirical measurement. This contrasts with design, which seeks to create a functioning effect in a potential future, generated rather through inspiration and proven through demonstration. All in all, these factors create differences between design and scientific research that affect multiple aspects such as their aims, accepted techniques, views of success and evidence, profile of practitioners, and work culture. (Stappers, 2006, 2007)

Additionally, because design is actually more concerned with effect than medium, it does not have a specific subject matter (Buchanan, 1992), but instead entails multiple inputs, which include considerations for example regarding industrial, societal, social, cultural, and economical issues. Hence the "products" of design are not merely restricted, as traditionally thought, to symbols and things, but encompass nowadays also actions, environments and systems, because even physical objects would not have significant meaning without these broader considerations. This does not remove the importance of physical embodiment in products, but it gives perspectives for making also products more successful. (Buchanan, 2001)

Experimentation is, however, a feature uniting both disciplines. Design practice and scientific research have a shared experimental approach on problem solving (Krippendorff, 2007), and proceed experimentally through what could also be described as "tinkering" (Bonsiepe, 2007). This experimental quality manifests itself for example as mock-ups and prototypes in design, and as scientific experiments in science. Stappers (2006) states that design uses prototypes in a similar manner to how science uses experiments: for testing presumptions and adjusting work accordingly. However, principles of validity, proof, and repeatability are again important for scientific experiments, whereas prototyping in design is more free and serves goals distinct in each context.

5.1 The Presence of Design in Scientific Research

The aforementioned characteristics of design and (materials) science are rather general connotations, but if we inspect more fundamental aspects of their relation, the situation becomes quite tricky. A relatively well-known portrayal of the difference between scientific research and design is provided by Herbert Simon (1969), who describes it by saying that "natural sciences are concerned with how things are", and design, on the other hand, with "how things ought to be" (p. 114). Hence Simon argues that natural sciences are concerned with natural objects and phenomena, and design with artificial ones. Therefore, science's primary method of working is through the analysis of information, and design's through the synthesis of knowledge for achieving wanted outcomes, for as "… 'synthetic' is often used in a broader sense of 'designed' or 'composed'" (p. 4). Simon thus states that, "Design ... is the core of all professional training; it is the principal mark that distinguishes the professions from the sciences" (p. 111).

Farrell and Hooker (2012) however criticize Simon's aforementioned separation, through an argumentation that highlights science, in fact, partly as a design activity. Starting with Willem's (1990) statement that "All human-made things, material and immaterial, were designed at one time" (p. 44), Farrell and Hooker claim that the argument of design and science producing metaphysically distinct types of things, is simply untrue. If all human-made things are artificial, and thereby designed, then scientific outcomes are as well designed abstract and physical artificial artefacts: theories, laws, instruments, technical procedures, and so on. However, it should be again noted that scientific artefacts have different requirements from those of design in terms of format, regulations, degree of freedom, and so forth. Farrell and Hooker still continue that both, design and science, employ creative problem-solving, as well as constitutive and functional reasoning strategies, thus concluding that "there is not a 'design intelligence' in contradiction to a 'scientific intelligence'" (p. 487). Error identification and experimental investigation are crucial parts of science for re-evaluating research. Design uses similarly iterative processes and prototyping for misfit-search and identification. Additionally, Farrell and Hooker argue that outcomes of science, as results of human thinking, are as well based on synthesis, not just analysis. They conclude by stating, "In sum, both design and science use design processes and reasoning strategies to produce artificial objects, therefore, they are not different in kind" (p. 494).

Design is also said to deal with ill-defined, ill-structured, or "wicked problems", and science with mere puzzle-solving and "tame problems" (Rittel & Webber, 1973). Farrell and Hooker (2013) also contradict this assumption by claiming that design problems and scientific problems actually both present a varying degree of wickedness and tameness. They again stress that science is not a discipline restricted to pure logic, but shares aspects of ambiguity with design, rather helping in uniting the approaches, than dividing them.

The view of scientific research as a "designerly" activity that contains also aspects of ambiguity, is also supported by Ranulph Glanville (1980), who identifies many similarities in the processes of design and scientific research, and suggests a complete "U-turn" by stating that design thinking should actually be the model for scientific study. Later Glanville (1999) even argues that scientific research is a form of design activity, and that scientists actually act as designers and design their scientific experiments. This is somewhat congruent to the way Ikkala (personal communication, June 11, 2013) describes the rather intuitive manner, in which material scientists for example determine the direction of research according to personal guesses and estimations.

Also science historian Peter Galison (1997) and sociologist Karin Knorr Cetina (1999) recognize scientific practice being considered as fundamentally constructivist and imaginative in quality. They also highlight the importance of materiality (Galison, 1997) and artefacts (Knorr Cetina, 1999) in scientific research practice. Michael Polanyi likewise explored the imaginative aspects and tacit knowledge of scientific study. Polanyi (1958) designates the imaginative nature of science to the "logical gap", which he describes as existing between accepted knowledge and a new significant discovery or innovation. According to Polanyi, logical reasoning is not enough to cross this gap regardless of how thorough factual knowledge there may be of a given situation. Polanyi describes "illumination" as the process through which scientists imagine new concepts as subjects for investigation. He says,

> *Illumination…is the plunge by which we gain a foothold in another shore of reality. On such plunges the scientist has to stake, bit by bit, his entire professional life. (p. 123)*

6 Essential Reasoning Strategies in Design

In regards to the relation between design and natural science, what could be highlighted as the main assets of design that could benefit scientific materials research? Cross (2011) argues that design has not traditionally been regarded as needing any special abilities, because design is an inherent part of human activity, and because designing things is natural for humans. Perhaps for this reason, as Buchanan (1992) notes, sciences have regarded design mostly as an "applied" version of their own knowledge, spurring difficulties in the communication between designers and scientists. Cross points out, how the ability to design things used to be a kind of collective or shared skill, but has recently received a status as something more exceptional. Thus he argues that there is a special kind of design ability that can be considered a specific kind of expertise.

How can this expertise of design be used in the context of science and materials research? As mentioned, science can be seen as a constructive and creative practice (Knorr Cetina, 1999) that approaches discoveries for example through experiments and imagination, similarly to design. This can bring unwanted ambiguity to scientific processes, and induce uncertainty to decision-making. As these are, however, essentially also characteristics of design, they simultaneously justify why it could be worthwhile to bring design in connection with science, especially as it is mostly very natural for designers to deal with situations of risk and uncertainty (Schön, 1983; Stappers, 2007).

Logical skills and intuition are both present in scientific research, the former just being more emphasized and the latter left more to chance, which also creates opportunities for design to have an impact on research (Stappers, 2007), since design is usually referred to as dealing with controlled imagining and intuition (Cross, 2011). Also Chris Rust (2004) recognizes this, by identifying the "creative dimension" in science, and therefore a possibility for design to contribute to it, thus arguing that collaboration serving both could be initiated. He states,

> *A central problem of science is how to recognise and define worthwhile subjects for investigation. For one thing, we may be faced with a myriad of opportunities and no means to decide which are going to be fruitful. (pp. 76-77)*

Rust sees that scientific research can benefit from designers' ability "to imagine new scenarios, and to create a practical environment for us to experience them by producing experimental artefacts" (p. 78). He states that design could help in selecting, or even generating, directions for scientific research. Rust (in Krings & Watson, 2013) also notes that as design is about changing the environment, it creates new questions, which researchers also from other fields can take advantage of.

Practical knowledge and intuition (and imagination) are thus aspects often emphasized about design when contrasted with science, as can be noticed also from Rust's (2004) description that highlights the "imagining of scenarios", and the "creation of practical environments and artefacts" as functions of design that could support science. These aspects can also be present in scientific research, but they are factors essentially relevant for design, and they are often also utilized differently in design compared to science. In fact, these are also the same attributes Buchanan (2001) mentions as reasons for why design was left out of the liberal arts after the Renaissance: because design was performed using practical knowledge and intuitive abilities. This highlights the nature of design's knowledge and logic: a form of practical knowledge, which can be understood for example through Aristotle's notion of "phronesis", and a form of logic, which follows the principles of "abductive thinking".

6.1 Practical Knowledge and Phronesis

The British philosopher Stephen Toulmin has written about the importance of practical knowledge in contrast to abstract, formal and analytical knowledge. Toulmin (2001) sees the "Cartesian revolution" as a major reason for the emphasis of analytical and formal knowledge over practical knowledge in scientific thinking. He notes, however, that there has been a tradition in the past of also valuing practical knowledge, concerned with things that are specific, local and temporal, in contrast to traditional scientific knowledge, which rather emphasizes things that are general and timeless.

In Book Six of "The Nicomachean Ethics" Aristotle (trans. 1996) defines five virtues of thought: "techne" (art or technical skill), "episteme" (scientific knowledge), "phronesis" (prudence), "sophia" (wisdom), and "nous" (intelligence). Toulmin (2001) inspects the three forms of knowledge related to the first three virtues, namely techne, episteme and phronesis. Out of these, techne, as translated, refers to the art and technical skill regarding how something is done. Episteme, on the other hand, is logically constructed and teachable, and hence often translated as scientific knowledge. The echo of these two notions can still be heard clearly in our vocabulary as "technology" and "epistemology".

The third form of knowledge, phronesis, usually translated as prudence, is interesting in terms of design (Kuutti, 2007): it is something that enables to act right and wisely in the world, in connection to what the situation requires. Like design thinking, it is a kind of practical and worldly knowledge emphasizing decision-making in context, through which it is also concerned with the variation of things, rendering it individual on each occasion. Unlike in science, Aristotle claims that although some general or technical skill is presupposed in terms of practical knowledge, one has to still "…consider what is suited to the circumstances on each occasion…" (1104a9). This makes phronesis different from scientific knowledge, episteme, or technical skill, techne, as they address matters of pure logic and habit that can be repeated and taught, whereas phronesis is affected more through experience. In regards of techne for example, the ends are always fixed, whereas in phronesis the end of an action is chosen according to occasion. (McNeill, 1999) Aristotle describes phronesis as follows,

> *It is not science, because matters of conduct admit of variation; and not art, because doing and making are generically different, since making aims at an end distinct from the act of making, whereas in doing the end cannot be other than the act itself: doing well is in itself the end. It remains therefore that it is a truth-attaining rational quality, concerned with action in relation to things that are good and bad for human beings. (1140b1)*

Phronesis thus entails the ability of achieving certain ends, but distinct from techne, it also includes the ability of determining good ends in regards of living well in general. Thus phronesis is also associated with political science, although Aristotle states their essence is different. As Toulmin argues, through developments such as the aforementioned Cartesian revolution, episteme, and hence analytical and formal knowledge, was raised above techne and phronesis in sciences. He states that epistemic knowledge has thus come to dominate knowledge creation, which has resulted in challenging consequences. Toulmin however sees a new coming for practical philosophy, which could balance the overly emphasized formal rationality through knowledge resembling phronesis.

As highlighted, Kuutti (2007) sees a clear connection with phronesis and design. Truly, both are considered to deal with practical solutions, with the means of achieving them, but also with determining the right problems, for which solutions are sought. Indeed, also in design almost every process is different including variation, although similarities for example in terms of methods and means of approach may exist. This, however, renders design also more ambiguous and less discussable in scientific terms, as it does not necessarily deal with scientific repeatability, but with individual contexts, just like phronesis. On top of the link with design, Kuutti also sees a shift from episteme-related knowledge more towards phronesis-like knowledge, as suggested by Toulmin (2001), comparable with the increasing emphasis of Mode 2 over Mode 1 research, which is evident through the increasing need for impact in scientific research. A more practical attitude in university teaching has been observable for example through the increasing appreciation of entrepreneurship, highlighted through related courses and university-based start-up accelerators. These all emphasize the importance from practice-based learning and practical skills, as well as design thinking, which has simultaneously risen in importance and credibility as a discipline. This practical phronesis-like design approach could thus also be valuable as a creator of knowledge in connection with research.

6.2 Intuition and Abductive Thinking

In descriptions of design, the notion of intuition is often highlighted as being an integral part of its approach. Cross (2011) sees that the “intuitive” approach designers take enables them to make decisions and proposals without the need for thorough rational explanations or justifications. This does not mean the design process would be totally irrational and random, but it refers to a certain capability of design to advance in situations of incomplete knowledge and uncertainty (Schön, 1983; Stappers, 2006, 2007). "Intuition" can be actually thought of as a manifestation of the reasoning process of design, which may be better described as "abductive thinking". Abductive thinking is the essential logic of design, and it differs from inductive and deductive reasoning mostly emphasized in scientific research. (Cross, 2011)

The American philosopher Charles Sanders Peirce (1931) first conceived the notion of abductive thinking, and highlighted the three types of reasoning, by stating, "Deduction proves that something must be; induction shows that something actually is operative; abduction suggests that something may be" (p. 171). Peirce claims that abduction actually is logical inference with a clear logical form, although it is very little confined by logical rules, because it states its conclusions problematically and conjecturally.

Lionel March adopted the notion of abductive reasoning into design. March (1976) sets it apart from the logic in science, by pointing out that,

> *Logic has interests in abstract forms. Science investigates extant forms. Design initiates novel forms. A scientific hypothesis is not the same thing as a design hypothesis. A logical proposition is not be mistaken for a design proposal. Speculative design cannot be determined logically, because the mode of reasoning involved is essentially abductive. (p. 15)*

March claims that deduction and induction apply logically only to analytical and evaluative work, whereas the action of synthesis, associated strongly with design, does not have an acknowledged way of reasoning.

Kees Dorst (2011) also argues that abduction is the core of design thinking. He contrasts it with deduction and induction, and depicts two forms of abduction: abduction-1 and abduction-2. Dorst uses the framework for abduction in design by Roozenburg and Eekels (1995) to describe this matter.

As deduction works from general principles towards individual results,

DEDUCTION: What + How = ?????

In deduction, the things (“what”) and their working principles (“how”) are known in a situation, which enables the prediction of results. For example, if the material is known, and its exact technical properties are known, it is possible to predict its behaviour in mechanical tests.

INDUCTION: What + ????? = Result

In induction, in case of a new material for example, the material itself is known, but its technical properties and how it behaves might be still unclear. The results of mechanical test are observed, and hypotheses of its working principles, causing the material’s beahviour, are created.

and induction from individual results towards general principles using hypotheses, they function as the analytical reasoning strategies for predicting and explaining phenomena in the world. Hence in scientific research, as Dorst puts it, “…inductive reasoning informs ‘discovery’, while deductive reasoning informs ‘ justification’” (p. 523).

Dorst explains that abduction does not deal with statement of fact as an end result, but instead with the attainment of value. He thus calls abduction also the foundation of productive thinking.

As abduction-1 deals with conventional problem solving, which aims to

ABDUCTION-1: ????? + How = Value

Abduction-1 is linked with regular problem solving. The aimed value and how it is achieved are known, jus the “what” that defines the solution is missing. For example, for selling more of a new porous material (value), a company decides to create a range of insulating panels (how). The “what”, meaning the panels themselves, still need to be developed.

create a concrete solution that fulfills the wanted end value through a decided angle of appraoch, it depicts the usual process through which designers and engineers mostly operate. Dorst however explains that the second form, abduction-2, is much more complex, as it is much more open-ended.

Dorst states that abduction-2 is closely associated with design thinking, and especially with conceptual design, as it highlights situations that are fuzzy, open and complex, and thereby clearly distinct from regular problem solving.

ABDUCTION-2: ????? + ????? = Value

In abduction-2, the only known factor is the end value that is aimed at. How it is achieved, and what is needed for achieving it, are both unknown. For example, a company has a new porous material and wants to sell more of it (value). They do not know, how they will sell more of it, and thus they do not know what they should do for achieving this.

Dorst argues that the way design approaches this complicated situation is through the development or adoption of a "frame". Dorst explains a frame as an inherently complex statement, which is used for creating a novel standpoint that serves for approaching a situation in a new way. According to Dorst, the key thesis of a frame can thus be expressed as, "IF we look at the problem situation from this viewpoint, and adopt the working principles associated with that position, THEN we will create the value we are striving for " (p. 524-525).

This induces is a situation, where the "what" and the "how", which function as the constituents of the end value, are created in parallel. Thus they cannot be approached through linear problem solving, but instead, they must be approached through iterative proposals and tests. Dorst states that the most logical way of approaching such a complex problem space is to start with the only known attribute, which is the end value, and use it for the creation of frames, which enable to unwrap the problem in a backwards direction. Once a feasible frame is created, it can be used for the creation of concepts that highlight concrete questions, which can be approached through abduction-1: now the reasoning happens forward, as the “what” and the “how” are matched and tested, for evaluating if they are able to generate the wanted value.

Linking this to the aforementioned examples, the company first needs to frame the problem space for developing concepts, which aim to increase the sales of the new porous material. The framing and concepting process (abduction-2) results in the idea of a new range of insulating panels, which shifts the process into regular product development and problem solving (abduction-1).

This framing, reframing, and testing creates an iterative and nonlinear approach present in design, which makes it essentially different from analysis and regular problem solving. Despite its complexity, framing can still be a simple and quick process, especially for more experienced designers. A more thorough process is needed if the situation entails a core paradox, consisting of opposing views and standpoints. This induces the need for the restructuring of the frame and thus of the whole problem space. The tackling of paradoxes is again a speciality of design, as they cannot really be approached directly, but rather explored through the broader problem space they are situated in. Thus the peripheral boundaries of the paradox can be searched for inspiring new frames that can provide potential approaches for tackling the underlying problematic. (Dorst, 2011)

This explorative approach of design can bring forth new data points and novel experiences, which spur the intuitive logic of abduction. As also Stappers (2006) points out, designers keep themselves sensitive and in connection to the surrounding world by collecting visual material, which serves the purpose of fortunate encounters. These findings, Stappers states, come forth as “inspirational things you weren’t looking for” (p. 15), which in fact can be used for providing clues for possible new frames.

7 The Design Approach Is Future-oriented, Nonlinear, and Integrative

Design's core reasoning strategies, the practice-based knowledge associatable with the notion of phronesis, and the abductive reasoning, can be used for pinning down further aspects of design that are relevant for collaborating with materials science, which include design being future-oriented, nonlinear, and integrative in nature.

As Simon (1969) describes, design is simply about changing situations into preferred ones. Thereby design is factually concerned, not necessarily with how things are, but how things should be in the future. This idea can be linked with Aristotle's notion of phronesis for highlighting that design is not only concerned with feasible means, but valuable ends as well, which again demonstrates that its approach is future-oriented.

The use of abductive reasoning also enables design to take an indirect and nonlinear approach on a problem space, enabling it to deal also with complicated issues by reframing them. The nonlinear approach of design manifests itself also in its processes that can freely fluctuate between different stages of work, depending on what the situation requires. This explorative process enables the quick iteration of ideas and reframing of assumptions, which supports the creation of new approaches for problematic situations.

Through its abductive thinking, and its practice-based approach, design aims for holistic outcomes. For achieving usable, useful and desirable solutions that work in a certain context, knowledge from other disciplines needs to be integrated into concrete solutions (Stappers, 2007), because "artefacts never work in the abstract" (Krippendorff, 2007, p. 72). The drive towards a practical and concrete effect, thus actually inflicts the need for a more or less holistic approach. Through its methods, design can tackle complex, sometimes even paradox problems (Dorst, 2011). Although it is not exclusive for design to deal with "wicked problems" (Farrell & Hooker, 2013), it still has a unique set of tools for tackling such situations of value conflict (Schön, 1983).

7.1 Design Targets Possible Futures

There is no doubt that scientific research is one of the most important drivers enabling us to create the technologies of the future. If design too is future-oriented, then what could its role be in the creation of the future?

Grand and Wiedmer (2010) see a close and dualistic relation between design and science, in which design functions as the imaginator and creator of possible future realities (Bonsiepe, 2007; Jonas, 2007), and science as the constructor of reality and objectivity (Daston & Galison, 2007). Through this role, they associate design practice and design research with an approach they call "design fiction", contrasting it with scientific research, which they also consider a design activity, calling it accordingly "research as design". They argue that seeing scientific research from a design perspective is particularly important today, because fundamental debates exist not only concerning the world's current condition, but possible futures as well. They point out how these debates are often highly complex in nature, involving a wide variety of different parties with "multiple perspectives, interests, concerns, issues, and approaches" (p. 564). Design could function as a facilitator in these complex debates. Grand and Wiedmer argue that design should be approached as a scientifically relevant, forward-looking, creative way of knowing, and should thus be regarded as relevant as scientific research in general. They state that,

> *The opportunities of rethinking the role of design in scientific research, as well as of re-defining scientific research in the perspective of design, are thus not only appropriate within the boundaries of traditional laboratory settings, but might actually become a way of understanding, describing, structuring and creating the experimental systems, which our societies need to deal with their most controversial, essential and complex questions and challenges. (p. 569)*

Wolfgang Jonas (2001) sees that design operates through alternating between the perspectives of present and future for identifying valuable courses of action. As the future is unknown, Jonas describes design as a way for reducing unwanted contingency and absorbing uncertainty for the creation of novel solutions. For achieving this, he says, design utilizes iterative feedback cycles between theory and practice, and between forward and backward perspectives. Jonas sees design as a future-oriented bifurcated process, which uses forecasting and backcasting for mapping prospective scenarios, used as basis for decision-making.

Forecasting is activity, where prospective futures are mapped by analyzing possible advancements of events from the present to a certain point in time, using "best educated guesses" (Hiltunen, 2012). Backcasting is the opposite of this: it starts with the creation of desirable futures and then works backwards mapping out the required steps of getting there (Brandes & Brooks, 2007; Holmberg & Robèrt, 2000; Kokkonen et al., 2005). This is similar to how design's reasoning alternates between the "backwards" approach of abduction-2 and the "forward" approach of abduction-1 (Dorst, 2011). Jonas (2001) describes the connecting role of design that bridges present and future by saying that design "should be conceived as an expert discipline of a special kind: for integration, relation, and meaning" (p. 66).

7.2 The Nonlinear Approach of Design

The abductive reasoning strategies of design, especially abduction-2, support a rather nonlinear process, as problems are approached by exploring solutions through possible frames. For as only the wanted end value of a process is known, the problems and solutions need to be figured out in unison, as they cannot just be concluded linearly from the starting points. (Dorst, 2011) Likewise, once a plausible frame for a possible solution is created, it is iteratively tested whether it works or not. Therefore solutions are usually created in parallel with ongoing grounding research (Kumar, 2012). Through its nonlinearity, this kind of process can be linked to the idea of use-inspired basic research

(Stokes, 1997). Consequently, the starting points of the design process do not set up the search for an optimum solution to a given problem, but instead they mark the basis for a journey of exploration, which hopefully leads eventually to the discovery of something essentially new that is able to fulfil the needed core value that originally initiates the process (Cross, 2011).

Common challenges in science include the identification of valuable trajectories of research (Rust, 2004), and how the results from research could be used in a meaningful way. The explorative approach of design can be helpful for these question, as it takes a broad perspective in the identification of challenges and opportunities. This wide angle of framing, through which a problem space (or "opportunity space") is observed, can provide good ideas regarding the direction of research, and the utilization of new technologies.

The task can still be very complicated, because the future is hard to predict, as are also the prospective needs of users and industry. Application development for materials, which are still at earlier stages of research, can also be challenging, as the potential of these materials might not be fully known, or knowledge might be restricted to only certain characteristics. For the material choices in design depend on a wide range of material properties, related to technical, perceptual, and associative qualities (Ashby et al., 2009). Simply put, it is challenging to evaluate what immature technologies, such as new materials, should preferably be applied for, and, which direction they should be developed towards. Therefore the situation needs to be explored from various angles, which helps in attaining a more holistic understanding.

The act of problem identification is fundamentally interwoven with the eventual solution (Cross, 2011), and thus the role of the designer is to function also as the "architect of the problem" and the "formulator and framer of questions" (Steinberg, 2013). That is why the early phases of the design process are often described as the "fuzzy front end", as they mostly appear as very chaotic, unpredictable and unstructured (Koen et al., 2001). Often constant framing and reframing of the problem characterize this phase, as plausible angles of approach are searched. This phase is, however, particular and essential for the design process, and although designers are mostly credited for their solutions, it is often the ability to find the right problems that makes good design possible (Lawson, 1994).

In abductive processes the relation between problem and solution is essentially complex. Attempted solutions can define the problem itself, thus creating objectives through the design process, rather than just working through a predefined brief (Cross, 2011). By envisioning preferred futures, it is possible to identify the most crucial current questions that still need to answered in order to get there. Thus the study of current developments can help to predict probable futures, but developing preferred futures can highlight where we currently are in relation to them.

The design process thus uses possible solutions as research, and eventual outcomes can also be used to represent actual problems. Raimo Nikkanen explains the design process briefly by saying, "The core idea of the design approach is to deal with the problem and the solution at the same time" (personal communication, April 15, 2013, own translation). Also Vijay Kumar (2012) identifies similar characteristics in design projects and states,

> *Although the idea of a process implies a linear sequence of events, this can be misleading. Many projects are actually nonlinear. For example, a project may begin with a sudden brainstorm (Explore Concepts) and then proceed 'backwards' to research and analysis to validate and improve the idea, followed by further exploration and iteration. (p. 9)*

Kumar emphasizes that the process is iterative in nature, rather than "a sequential push". He remarks how design processes can start with a certain intent and advance to research, concept design, and prototyping, just to come back to the starting points for reflective analysis. Ideas and prototypes can be used as basis for research and feedback, which can be used for further analysis. By working on many stages at at once, and by integrating theory with practice, design tries frame the process, as depicted in Figure 7.1.

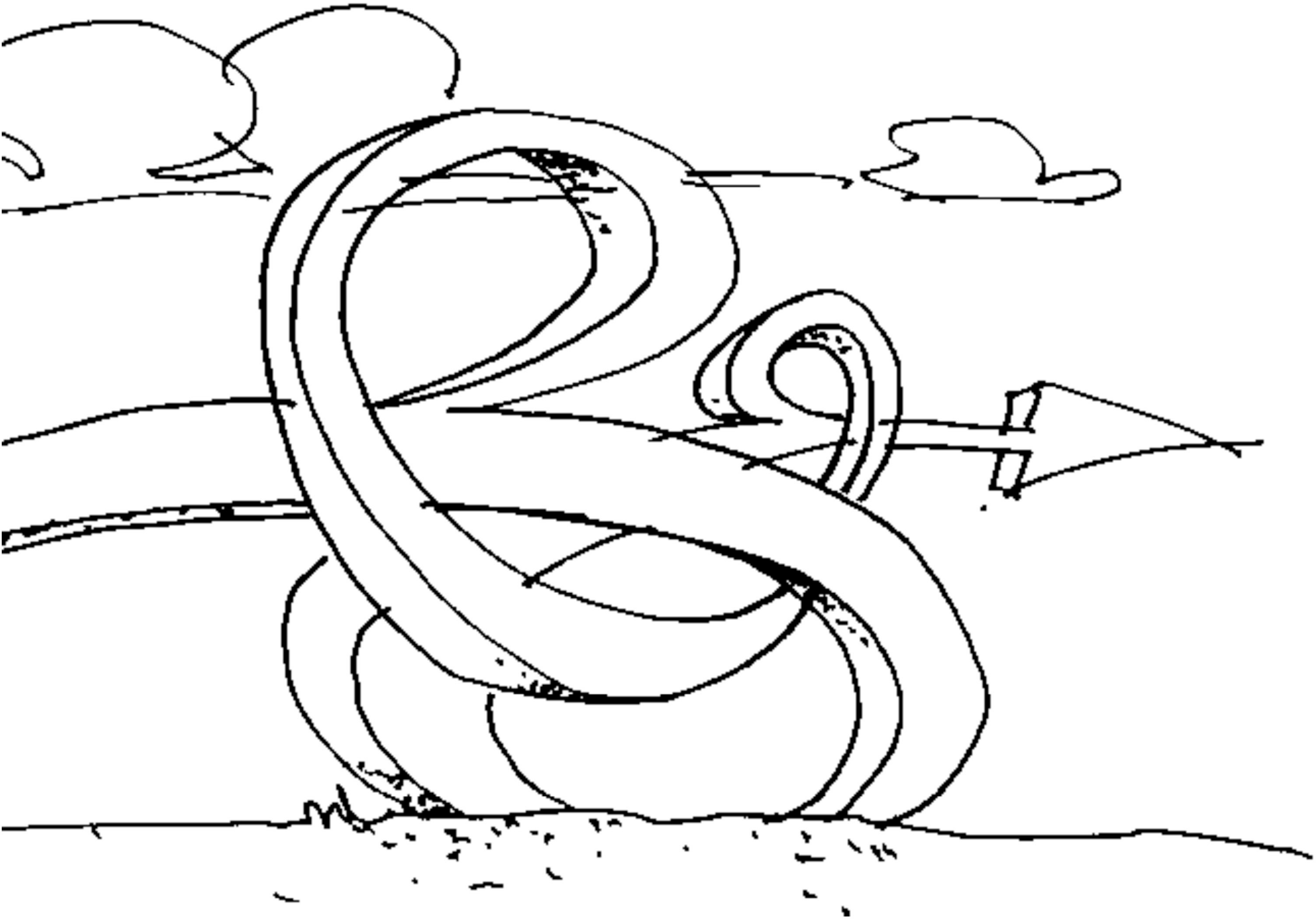


Figure 7.1 The design process works on many levels simultaneously: "up in the clouds" yet "firmly on the ground". Illustration by Turkka Keinonen. Adapted with permission.

Steinberg (personal communication, August 9, 2013) highlights the importance of prototypes as an essential element of the nonlinear process also in complex systemic challenges. He says that simple prototypes can facilitate information gathering at early stages of work. Such explorations can be first executed on a small scale for making them less risky. Steinberg stresses that although the first steps might be small, they should be ambitiously enough connected to a roadmap: "How could this small thing lead to this big thing?" Thus despite its nonlinearity, the process drives towards an overall goal, and it can be divided into rough stages (Figure 7.2). Steinberg also says that in projects with many unknowns, a good way to start is to "learn by doing" and by "doing something". This can be an effective way for opening fuzzy problems. Creating different concepts and prototypes can thus be useful for identifying a meaningful direction for the process. As architect Richard MacCormac puts it,

> *I don't think you can design anything just by absorbing information and then hoping to synthesise it into a solution. What you need to know about the problem only becomes apparent as you're trying to solve it. (MacCormac, 1976)*

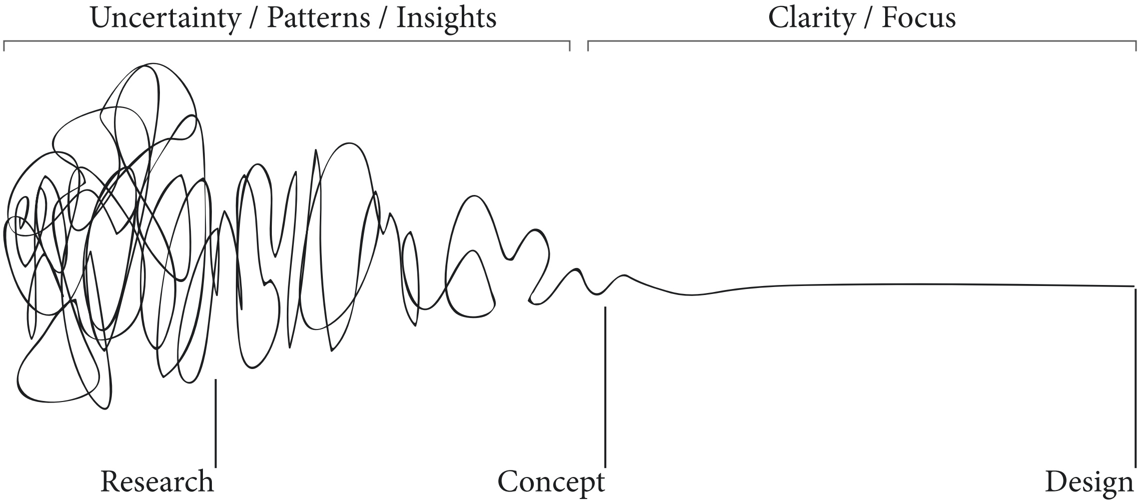


Figure 7.2 A rough sketch of the design process. (Newman, n.d.) Used under CC BY-ND 3.0 US.

7.2 Design Aims for Integration and Holism

Design is an integrative discipline, as it aims for impact through practical solutions, which are constructed using knowledge from various fields. The manner in which design targets complex issues through abduction-2 reasoning is also rather holistic, as the problem is approached through a broad scrutiny of the (peripheral) space it is situated in. Hence design is an integrative and holistic discipline. This is different from traditional Mode 1 scientific research, which by contrast is rather specialized and focused.

For generating solutions that work in practice design integrates knowledge, and for identifying relevant problems and opportunities design approaches situations holistically. The integration induces iterations between theory and practice, and between the current and the future (Jonas, 2001).

Design utilizes its integrative approach for dealing with relation and meaning as vehicles for innovation (Jonas, 2001; Norman & Verganti, 2012; Stappers, 2006; Verganti, 2009). By bridging disciplines, and relating things and contexts, design tries to enhance communication (Jonas, 2001), and aims thus not only at creating individual objects, products or services, but also their systemic and strategic coalescence (Boyer, Cook, & Steinberg, 2011; Manzini & Vezzoli, 2003). This is achieved, for one, by working on multiple stages of the processes simultaneously (M. Steinberg, personal communication, August 9, 2013), and connecting the broader perspective to more down-to-earth tests of practicality, which is achieved for example through prototyping (M. Steinberg, personal communication, August 9, 2013; Stappers, 2006, 2007).

Roberto Verganti (2009) explains how design-driven innovation is pursued by communicating with “key interpreters” from different fields such as design, natural and social sciences, and the art world, in order to take part in a holistic “design discourse” that grants the possibility to interpret the current zeitgeist for innovation development. This enables design to innovate through meaning change, whereas engineers and scientists innovate through technology development. The generation of meaning is an integrative process, taking into account various aspects of society.

Developments in the watch industry from 1960s to 1980s can clarify the idea of meaning change. Up until the late 1960s, wrist watches were though of as pieces of jewellery, crafted by expert clock smiths typically working in a Swiss watch company. In the 1970s the first digital watches emerged, produced by the Japanese, and they took the market through a change in technology, but likewise by a change in meaning: watches changed from jewellery into less expensive plastic tools. The Swiss retook the industry in the 1980s, as Swatch introduced their cheap colourful watches that functioned rather as fashion accessories, than as jewellery or tools, yet again causing a change in meaning. (Norman & Verganti, 2012) These innovations required a sense of technology and its utilization, in connection with broader aspects relating to user needs, the market, industry, and even cultural factors.

The integrative nature of design, and its drive for effect and comprehensive solutions, is one of the main reasons it can function contributively with more specialized fields from natural sciences. Working in the fissures between disciplinary silos, "where the grand challenges of today are found" (Boyer et al., 2011, p. 21) is therefore one of the objectives of design, for it requires special expertise to fuse knowledge from different areas. Design thus absorbs knowledge from other fields and integrates it by confronting and contextualizes it. This not only empowers design to generate effect, but it is of value for other disciplines as well. The integration of knowledge strives to generate outcomes, which are more than the sum of their parts, as they may themselves generate new knowledge through assigning meaning to its components. (Stappers, 2007) For design is, as Krippendorff (2007) says, about "making sense of things (to others)" (p. 69).

7.2.1 The Integrative Strengths of Design Practice

Stappers (2006, 2007) has studied the integrative abilities of design in connection with more specialized fields, such as disciplines from natural sciences. He claims that practice-based design activity can lead to new knowledge just like the experimental testing of hypotheses in scientific research. This knowledge is of no less value than knowledge reached through scientific means, which is why, as Stappers states, designers should be brought to the process of knowledge creation.

Stappers (2007) is able to highlight strengths designers possess that originate from industrial practices, and which are of great value in the context of scientific research. He claims that in regards of these strengths, designers are mostly able to excel above engineers, and that they can be helpful especially for more explorative research performed in interdisciplinary groups. Stappers (p. 83) lists these strengths for designers as,

- *They can communicate with all specialisms involved*
- *They can integrate the (often mismatching) inputs from specialisms*
- *They can act in the absence of complete information*
- *They retain focus on realizing the product throughout the process*

These functions, and also concrete prototyping, are related to the confronting, integrative and contextualizing role of design (Stappers, 2007). It should be noticed that the word “product” in the last point of the list can refer to a multitude of outcomes and values, which the design process aims to produce, including tangible products, but also for example environments, services, and systems (Buchanan, 2001).

Bridging people and knowledge from different disciplines makes it possible to deliver more holistic solutions, which consider the needs of various stakeholders, such as users, technology developers, and business. Dealing with uncertainty in situations, where decisions need to be made with a limited amount of information is a key element of the design practice (Schön, 1983), making designers apt for decision-making in such circumstances. This is why the design process is usually explorative in nature (Cross, 2011), and therefore it may shift perspectives through its course, as problems are reframed through iterations (Dorst, 2011). Still, the design process strives to keep focus on the broader goal, which is approached from various angles through the explorative process. The eventual result may also be totally different than originally planned, but still something that reaches the wanted value.

Stappers (2006) also emphasizes the diverse media and methods used in design by stating that, "Typical of designing is the iterative spiral of generating and evaluating, sketching and reviewing, modelling and testing, brainstorming and discussing" (p. 13). These methods are used for bringing theories, insights and methods from various disciplines together. Thus insights, picked from different disciplines, are used for creating syntheses, which often afflict compromises between these different perspectives. Sometimes these compromises may not be liked by the other disciplines, but the outcomes may still be of value to them. The concepts design creates are also preferably manifested through concrete prototypes, which put the gathered insights to test in practice. (Stappers, 2006)

8 Using Explorative Prototyping in the Context of Materials Science

As concluded in the previous chapter, prototypes can be a valuable tool in the integrative processes of design. When knowledge is forced into a concrete form through prototypes, it is contextualized and confronted with reality, which is an efficient way for exploring solutions and finding important information. (Stappers, 2007) "Explorative prototyping" can be a valuable method for design in the context of materials research, as it embodies both of the aforementioned reasoning strategies of design: the practical knowledge manifested through Aristotle's phronesis, and the logic of abductive thinking.

Prototyping plays an important role in the nonlinear and explorative processes of design, as they represent concrete manifestations of potential future applications and products. Prototypes not only integrate technical knowledge of how a product may be constructed, but they also integrate cultural and societal aspects, which tell about the potential future they are situated in. Thereby prototypes also make a statement for certain values to be strived for, and thus they not only manifest technical means, but also desirable ends.

At fuzzy early stages of technology development processes, which the research and development of new materials largely also belongs to, design can use prototyping as a tool for testing and concretizing different ideas, frames, and angles of approach. Learning is also an important result of prototyping, as attempted solutions often provide new insights that can be used in the following iterations. Although prototypes usually depict possible solutions, their role is thus to also bring forth essential problems.

Cross (2011) explains how the various means of prototyping in design can shed light to ambiguous situations by saying, "The activity of sketching, drawing or modelling provides some of the circumstances by which the a designer puts him- or herself into the design situation and engages with the exploration of both the problem and its solution" (p. 12). As prototypes embody versatile information, they are at best also assessed by a versatile team, which requires an integrative approach from experts representing different fields of knowledge.

8.1 Prototypes Are Versatile Sources of Knowledge

Marco Steinberg (personal communication, August 9, 2013) points out how design can approach even broad challenges, for example concerning the meaningful utilization of novel materials, by peeking into the future through tangible prototypes. In industrial product development processes, prototypes traditionally refer to early versions of products, which are used for testing specific aspects related to them, such as their usability, performance, or manufacturability. In design processes prototyping has a broader meaning. Ulrich and Eppinger (1995) define prototyping as "an approximation of the product along one or more dimensions of interest", and continue that thereby "any entity exhibiting at least one aspect of the product that is of interest to the development team can be viewed as a prototype" (p. 291). Therefore, they argue that everything from sketches, mathematical models, simulations, and individual components to fully functional preproduction versions can be considered as prototypes. Therefore in design practice, it is not false to refer to even drawings and cardboard models, on top of almost final products, as prototypes, for this versatility of tools can be considered a strength in design. (Grand & Wiedmer, 2010) Also additive manufacturing technologies, such as 3D printing, have recently become more common and accessible, thereby broadening the possibilities of prototyping, as they enable the quick production of even complex structures and forms not previously possible.

Prototypes can thus take many forms, as they range from three-dimensional artefacts to two-dimensional visualizations. They can be either physical, for concrete tests and experimentations, or analytical, for evaluations achieved mostly through intangible models. Additionally, prototypes can be either comprehensive or focused, depending on whether the whole product or application is tested in its entirety, or just certain attributes of it. (Ulrich & Eppinger, 1995) Ulrich and Eppinger state that prototypes are used mainly for four purposes, which are,

- Learning
- Communication
- Integration
- Milestones

One of the most important aspects of prototypes is to function as tools for learning. Design uses prototyping also at early stages of the process for "thinking through doing", since rendering ideas tangible can bring forth totally new problems or ideas. Drawing and building things may also take time, but they actually help in making processes faster, for concrete experiments often function well for testing ideas and solutions, which can save a lot of effort and trouble later on in the process. Tangible prototypes, either built or visualized, can be more easily evaluated, refined, and enhanced than more abstract ideas, which makes them an important source of information. (Brown, 2009; Ulrich & Eppinger, 1995)

Prototypes also enhance communication and shared understanding. Putting ideas and solutions into a concrete format breaks disciplinary boundaries, as tangible things are much easier to comprehend and discuss about. Different aspects of prototypes may be more important for different stakeholders or team members, depending on their background or expertise. Prototypes thus effectively connect people from different fields, and they can be therefore considered useful “boundary objects” that bond the diverse members of a team together, simultaneously containing different pieces of information for everyone. (Keinonen, 2006; Star & Griesemer, 1989; Ulrich & Eppinger, 1995)

Prototypes thus also integrate knowledge from different areas. This is especially the case with comprehensive physical prototypes, as they are usually composed of various parts and functions that need to be fitted together. Therefore prototypes often highlight a wide array of decisions instead of just one theory or point of view. Fitting knowledge together from various fields will also enhance the understanding of individual disciplines. For when knowledge is put into context through prototypes, people from different fields are able to perceive their expertise in relation to that of others. (Stappers, 2006, 2007; Ulrich & Eppinger, 1995)

Prototypes can also manifest milestones in processes, and highlight achievements through tangible outputs, which are used for demonstrating progress. This is naturally the wanted goal of prototypes: to drive the process through iterative knowledge creation, which is also important for lifting up the motivation of team members. (Ulrich & Eppinger, 1995)

There are different needs for different prototypes at different stages. The goal might not be to create the most finished version early on, nor is it needed to create sophisticated working models when ideas are still investigated and refined. Prototypes should evolve through iterations, as possible solutions are tested and readjusted. The main purpose of prototypes is, after all, to bring forth new knowledge aiding in the design process. Especially at early stages of processes, the prototype should not be overly refined, but contain just enough information for enabling the step to the next level. (Brown, 2009) It is thus not necessary to be too picky or too thorough with prototyping. Different techniques provide different information regarding the problem at hand, and they can be refined as the process advances towards a potential solution.

8.2 Prototyping the Future Through Concept Design

Technology development processes are mostly time-consuming, and may take even over ten years (Kokkonen et al., 2005). Design approaches such far-reaching objectives usually through concept design (also referred to as "concepting"). Grand and Wiedmer (2010) highlight the "creation of possible futures" and the "materialization of those futures" as essential functions for future-oriented design, as potential futures can thus be "…explored, tested, evaluated and improved through a constant attempt to materialize their central features" (p. 571).

Concept design is concerned with these themes. Concept designs are usually imaginary prototypical demonstrations of possible future products, which are carefully constructed through inspecting their prospective contexts. As Turkka Keinonen (2006) describes, concept design "can create a map of the future and add landmarks to it" (p. 24). He argues that concept design does not aim directly at detailed specifications related for example to products and their production, but instead tries to outline the fundamentals of the following more detailed design processes. Concept design can be fuzzy to approach, since its objectives are ambiguous and not clearly confined. Concepting can, however, be approached through framing processes, as used in abduction-2 reasoning. (Dorst, 2011) Concept design has a rather holistic approach, linking practice from industrial design with more investigative methods from research (Keinonen, 2006).

Basically, concepts are used for defining the design challenge and mapping the alternatives in the initial stages of a design process. Concept design allows the exploration of even radical ideas that step out of everyday requirements. The open-minded exploration of future possibilities can eventually lead to new products and applications that embody something fundamentally new. In case the developed concepts are too radical for the time being, for example due to reasons related to technology or to the state of the market, an idea bank can be created for storing ideas for later on, as conditions evolve. (Keinonen, 2006) Concepting is therefore used for targeting also very distant futures through so called "vision concepts". The timeframe the concepts are aimed at can thus be very long, from several years to even over ten years. (Keinonen, 2006; Kokkonen et al., 2005)

As with prototypes in general, concept design also promotes the creation of a shared vision, for it is collaborative in nature. Usually concepting is done in interdisciplinary groups that combine expertise from different fields. Concepts that render potential ideas tangible, make their early evaluation more efficient: questions can be posed more accurately, required information can be defined more precisely, and already acquired knowledge can be evaluated more thoroughly. Concepts can facilitate discussion and shared understanding about obscure future products and applications, because they can be examined as if they already existed. Words can also have multiple meanings, especially for people from different fields. Concepts that close these communication gaps can minimize the risk of misunderstanding. (Keinonen, 2006)

Concepting also enhances a group's competence, as it is a task that requires practice to attain and sustain. Learning is an important part of the concepting process, as it is with all prototyping processes. Old routines should be challenged in order to develop new approaches, expertise, and skills. Concepts do not have the same pressure to succeed as actual products, which enables freedom of exploration and boldness in approach, since learning also happens through failures. This permission to fail is an important factor. Open-minded approaches can also facilitate new processes and cooperation. Teams or organizations that usually do not collaborate can work together and learn from mutual processes. In short, concept design promotes creative problem solving, interdisciplinary cooperation, and learning from others. Concept design can also function as a platform for learning, by introducing for example new technologies, business opportunities, or working processes. (Keinonen, 2006)

Concept design can also be used for expectation management, as the portrayal of concepts can influence people's views of future products. The process of introducing new products can thus begin before they are available. Such activities can be used for directing the image of the organization or of an entire industry. If a concept is seen as interesting, it can attain media attention for a project without much investment in marketing or public relations. Communicating interesting concepts can therefore also be used to raise interest in potential collaborators, and make cooperative projects an attractive opportunity for them. (Keinonen, 2006)

As with regular prototyping, concept design does not only relate to the final outcome itself, but also the capabilities an organization or a team build through the process. One important goal is to connect diverse disciplines that work with different subjects, scales and terminology, making the creation of a common language that narrows the gap of communication a key factor. Concept design can thus be a good platform for exploring collaborative work. Concepts can also be important for demonstrating the impact of scientific research, as they can highlight potential applications or products, eventually enabled through the research.

8.3 Design-Driven Prototypes in Scientific Research

Explorative prototypes can function in the context of scientific research for instantiating ideas from different disciplines, and they can thus be describes as "physical hypotheses" (Stappers in Overbeeke, Wensveen, & Hummels, 2006) that function as embodiments of theories. Additionally they can be referred to as “working hypotheses”, which are tangible manifestations of knowledge that are tested, refuted or proven to work, and accordingly, adjusted. Through their unifying role, prototypes work as a test bed for the ideas, theories, and decisions made in the research process. The confrontational quality of prototypes is especially important, for it makes experts from various disciplines gather around the same table, dropping their respective jargons. Hence prototypes themselves can be generators of knowledge, as long as insights can be extracted from them. The various ways of representing and visualizing, which designers utilize, are able to render these ideas accessible for everyone involved. (Stappers, 2006, 2007) Stappers (2007) thus states,

> *Prototypes and other expressions such as sketches, diagrams and scenarios, are the core means by which the designer builds the connection between fields of knowledge and progresses towards a product. Prototypes serve to instantiate hypotheses from contributing disciplines, and to communicate principles, facts and considerations between disciplines. They speak the language of experience, which unites us in the world. Moreover, by training (and selection), designers can develop ideas concepts by realising prototypes and evaluating them. (p. 87)*

Prototypes can thus function as one of the core actions, through which collaboration between design and materials science is mediated. Usually, much of the data is hidden or implicit in prototypes. As long as the information does not disappear in them, they can be great sources of knowledge to everyone involved. Therefore it is useful to make the knowledge embodied into prototypes explicit, and extracting information out of prototypes can thus be a valuable skill to learn for experts from various disciplines. (Stappers, 2007)

Prototypes generated through design test also the design itself, not just the theory they are based on, as they go beyond it. Sometimes the requirements for advancing knowledge for purposes of scientific research may also contrast with good design. The solution is usually to keep the design relatively simple. (Koskinen et al., 2011) Relatively simple designs in prototyping also “…make it possible, to a certain degree, to isolate and even manipulate systemically critical variables" (Overbeeke et al., 2006, pp. 64-65) The goals of design and scientific research usually differ, and hence different kinds of prototypes may serve the other better, as compromises could blur the knowledge contained in them. (Overbeeke et al., 2006) In the context of science, the goal of design is, however, to explore possible applications and trajectories of research through concrete prototyping. The aim is not to make scientific experiments as such, as they are another case, but rather concrete explorations that can lead also to new scientific experiments, if something interesting is found.

As mentioned, design functions as a way for integrating, confronting and contextualizing research from science, and prototypes are one of the best embodiments of this. Pure laboratory results may not tell that much about a material's utilization in the real world, as this is affected by a multitude of factors, whereas laboratory tests mostly look into discrete parameters. Contextualizing knowledge from materials research through prototyping may bring forth crucial information relevant outside of the laboratories, but forgotten inside them. Natural science works through generalizations of knowledge, but there may be factors in actual applications or products that are hard to generalize. Therefore, certain aspects need to be contextualized through concrete experiments. (Koskinen et al., 2011; Stappers, 2007) This confrontation and contextualization may also happen at a relatively small scale, despite the scale of the challenge.

Prototypes are valuable also in broad, complex and systemic challenges. Steinberg (personal communication, August 9, 2013) for instance stresses the importance of even small-scale quick experiments in the face of broader challenges, because they are concrete action. Prototyping combines both ends of the process, realization and research, as it aims to implement initial ideas with the goal of receiving information through them. Steinberg explains how simple prototypes open up problems and help out in the planning process, which cultivates the implementation process, which again contributes to the planning, and so forth. Prototypes are thus essential representations of the nonlinear and iterative process, and work as good vantage points to assess the overall direction of work. Steinberg also notes how even quick prototypes make the analysis of an idea easier: if something works it can be scaled up a notch, and then this new “amplified” prototype is again evaluated. The process of prototyping is also an essential part of the process roadmap, and it can be utilized on many levels. Steinberg states that a basic idea in prototyping is that once you do stuff, you try to react to it and reshape it at the same point. He sees that in the scientific context, prototyping can be especially helpful as the translator between scientific research and the use environment’s interaction.

Practical Research

9 The Approach and Background of the Case Studies

The practical research of this thesis highlights three case studies, describing three different processes that belong to two distinct projects, in which industrial design practices have been collaboratively utilized for contributing to materials research and development. The case studies describe the initial stages of longer processes, as the projects are currently, at the moment of writing, still ongoing. Because they describe work done at early stages of the projects, none of them depict outcomes that could be referred to as “final results”, but they rather try to give a portrayal of these initial processes.

The processes have entailed certain fuzziness, some more, some less. The main reasons for this have been that collaborative processes between design and materials science are, especially in academia, still somewhat uncharted territory, and that early stages of technology development (as with new materials) usually entail a lot of ambiguity anyway. The goal is, however, to crystallize some core insights regarding design’s collaboration with materials science.

Although the projects have been different in nature, the basic goal in both has still been to develop meaningful concepts for applications and products regarding the materials developed in them. The scientists have sought insights for example regarding what could be done with the materials they develop, and how people might use and give value to products in the future. The motivation behind both questions is the same: to find fruitful ideas for the utilization of new materials. They also highlight different perspectives: the first being a material-driven (or technology-driven) approach, the second a user-driven (or human-driven) one.

The goal of the design-driven approach has been, for one, to create a more comprehensive outlook that combines these aspects of “what” and “how”. For only one isolated perspective might not lead to wanted results: a strictly material-driven approach might not drive to sufficiently innovative ideas, and a purely user-driven approach would not care about the utilization of specific materials, if alternative ones could function better in a given situation. Such matters need to be approached by keeping multiple perspectives in mind, and describing the approach as combining "material push" and "user pull" would not be too far off.

The exploration of applications at a stage, when materials are still under research and development has also been tricky. For the properties of immature materials might not be very clearly defined, and thus assessments regarding their applicability are also rather rough approximations. Utilizing design at such early stages of materials development can help in creating interesting concepts, which can also direct the further development of materials. Materials do not solely inspire application development, but potential applications can also inspire materials development. This bifurcated situation can be tricky, as the solutions and the questions are mainly highly entwined. Hence the projects' aim has initially not only been to find solutions to the situation, but also essential problems, since without them the direction of work would be hard to define.

As the case studies relate to projects, in which new materials and their applications are developed in unison, they highlight processes that entail a reciprocal relationship between design and materials science. This differs from traditional linear models of research and development, and relates to the notions of use-inspired basic research (Stokes, 1997), and impact-driven Mode 2 research (Gibbons et al., 1994). What this essentially suggests is that design can also be used, in collaboration with scientific research, as a way for creating knowledge. Therefore, the described cases can be associated with the notion of "research through design" (Frayling, 1993), and as the main method of exploration is characterized by the construction of different prototypical things, such as visualizations or physical prototypes, it can be more accurately described as "constructive design research" (Koskinen et al., 2011).

Prototypes of various kinds thus become the key means through which knowledge is constructed (Koskinen et al., 2011). Thus the main focus of the case studies is on processes related to "explorative prototyping". As was highlighted in the theoretical research of this thesis, explorative prototyping combines some of the core assets design utilizes for tackling tricky situations: the nonlinear process and practice-based knowledge. The case studies reflect how design is utilized, especially in terms of explorative prototyping, to contribute to scientific materials research.

The reflection also makes a comparison with the aforementioned analysis by Driver et al. (2011), which reflects on how industrial design practices could contribute to scientific research. Driver et al. (p. 27) conclude that design is able to contribute to scientific research by,

- *Assisting with communication and dissemination of research*
- *Exploring applications for new technology*
- *Visualizing scenarios of use*
- *Creating technology demonstrators*
- *Challenging scientists' perceptions of their research*

Therefore these factors will be also looked in the analysis of the case studies.

9.2 The Projects and Materials Related to the Case Studies

The two projects the cases are derived from are very different in quality, the other being a smaller self-initiated project carried out together with one materials research group (the Molecular Materials group), and the other a larger strategic opening executed in collaboration between three research organizations. The cases are also chosen so that they would highlight very distinct uses of explorative prototypes: the first case relates to the modelling and 3D printing of biomimetic structures at the macro-scale, the second to the concretization of possibilities of nanomaterials though the development of concepts, and the third to the physical prototyping of a concept through material and manufacturing experiments. The materials inspected in the cases are in different stages of development, some being more mature than others, which justifies the use of different approaches. Next there are short descriptions of the overall nature of the projects the case studies are derived from, as well as some basics regarding the materials that are explored in the case studies.

9.2.1 Project: Molecular Materials [MM]

The Molecular Materials group is a research group functioning at Aalto University's Nanotalo research facility. The group operates in the field of materials science, and consists mainly of physicists and chemists. The group aims for one at functional materials that are based on self-assembly and its hierarchies. The group's main subjects of research are for example the use of "polymers, conjugated polymers, polypeptides, liquid crystals, cellulose nanofibers and other carbon-based materials as structural units in supramolecular assemblies". (Aalto University, 2013a) The group deals for example with the research and development of nanomaterials. A nanomaterial can be described as,

> *A natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm (European Commission, 2013).*

In many cases, the small particle size provides nanomaterials with exceptional mechanical qualities, a large relative surface area, and the possibility for effective functionalization, which refers to altering the material's qualities by changing its surface chemistry (J. Hinestroza, personal communication, July 30, 2013). The Molecular Materials group is also interested in biomimetics and bio-inspired materials, and subjects of study include for example nacre (mother of pearl), nanocellulose, and spider silk.

The collaboration with the Molecular Materials group was initiated, as they were interested in working with designers. The group's leader, academy professor Olli Ikkala (personal communication, June 11, 2013; November 15, 2013), briefly explained, how the academic world and the industry of Finland are both currently experiencing changes, which consequently also affect the employment of scientists in the field. A couple of decades ago, it was a common for material scientists to work for a larger Finnish company for most of their career. However the times have changed, and job opportunities are becoming more uncertain. Hence it is important to explore new opportunities by open-mindedly utilizing the collaborative potential of two strong fields of Finnish knowhow: materials science and design.

The MM project has mainly dealt with the exploration of applications for the materials studied by the Molecular Materials group. As the group mainly researches and develops novel materials, they operate at the very beginning of materials development processes, which adds trickiness to application identification. Therefore, the first stages of the MM project have been characterized by a rather explorative approach. Some of these aspects are explained in the first two case studies, which deal with the MM project.

9.2.2 Project: Design Driven Value Chains in the World of Cellulose [DWoC]

The DWoC project is a large strategic opening funded by Tekes, the Finnish Funding Agency for Technology and Innovation, and it aims at the development of new business ecosystems around wood-based cellulose materials. It is a collaborative effort between Aalto University, the Technical Research Centre of Finland, VTT, and Tampere University of Technology, TUT. During its first six months the project's core organization has entailed over fifty active members. The project's first phase takes 1,5 years to complete.

The project aims to support the research and development of cellulose-based materials by a strong design-driven approach. The objective is to develop innovative cellulose-based applications, and systemic solutions for business and industry. Concepts are developed through the perspective of eco-design for enhancing the sustainability of material ecosystems. The refinement of existing knowhow and the development of new knowledge thus aim to elevate the innovation potential of the Finnish forest industry, and the sustainability of material systems also on a global scale. (Tekes, 2013)

The project's design team has had a multifaceted role as it has collaborated with teams from business, foresight, and technology in a highly interdisciplinary manner. The goal has been to initiate close design-driven collaborations with groups working with materials research and development. The project contains multiple technological focus areas, as cellulose is developed as a raw material for various different applications. Due to the project's multifaceted nature, work has been done in various scales and stages. One case study describing explorative prototyping as a means for developing applications for foam formed pulp is highlighted from the DWoC project.

9.2.3 Materials: Cellulose and Nanocellulose

Cellulose is a natural polymer. It is a basic structural unit of for example plant cell walls, forming about 33 % of all vegetable matter, and thus the most abundant biopolymer on earth. Wood consists 40 – 50 % of cellulose molecules, which first chain up and stack into elementary fibrils, which stack further into cellulose nanofibrils. Also the nanofibrils like to attach, forming increasing aggregates that eventually, after also bonding for example with hemicellulose, lignin, and pectin, form natural fibres, such as wood fibres. Wood fibres can be used as a raw material for pulp, which is traditionally used for applications such as paper or cardboard. (Encyclopaedia Britannica, 2014a; Kettunen, 2013; Moon, Martini, Nairn, Simonsen, & Youngblood, 2011)

Cellulose-based materials have interesting properties in terms of application and product development. As they are mostly extracted from plant-based sources, they are renewable and biodegradable. Also efficient recycling technologies for cellulose materials exist and are currently developed further. Cellulose-based materials can be used for the production of applications such as paper, cardboard, yarns, textiles, foams and biocomposites.

The cellulose nanofibrils on the other hand are usually addressed as nanocellulose, which has its own special properties due to its small particle size. There are different kinds of nanocelluloses, of which this thesis deals with nanofibrillated cellulose (NFC) that consists of spaghetti-like fibrils (Figure 9.1).

In nature, nanocellulose provides strength to plant cell walls. NFC is extracted from natural fibres for example through grinding or fluidization. The NFC fibrils are usually 5-60 nm in diameter and several micrometres in length, thus having a high aspect ratio. They are also heterogenic, strong, pliable, and prone to aggregation. (Kangas, 2012) Aggregation happens especially when NFC dries, rendering the bonds between the fibrils very strong. NFC is also extremely biocompatible and hydrophilic (water absorbent), forming easily gels at already low concentrations (Kangas, 2012): NFC gels mostly have a dry matter content of only 0,8 % – 2 %, with the rest being water.

The potential uses of NFC have been evaluated to be very broad. Studies so far have shown that NFC could be used for applications such as smooth and transparent films, strong bionanocomposites, sanitation applications with absorbing qualities, fibre supplements in foods, highly porous structures such as aerogels, paper and cardboard, coatings, and functional surfaces. (Future Markets Inc., 2012; Kangas, 2012) Due to its large specific surface area, it can be also modified and functionalized in various ways, and made for example antibacterial (Andresen et al., 2007), conductive, pressure sensing (M. Wang et al., 2013), water repellent, oil repellent, oil absorbing (Jin et al., 2011; Korhonen, Kettunen, Ras, & Ikkala, 2011), and even fluorescent (Díez et al., 2011).

NFC thus has theoretically broad possibilities for applications, which however have, until now, remained mostly scarce. Despite the fact that nanocelluloses have been studied for around three decades, little breakthrough applications or products have emerged out of the alleged wonder material. (J. Ketoja, personal communication, May 12, 2014) Renewable and sustainable cellulose-based biomaterials, such as NFC and wood fibres, can be extremely valuable for global bio-economies as well as for the Finnish forest industry, making them still interesting subject of further research.

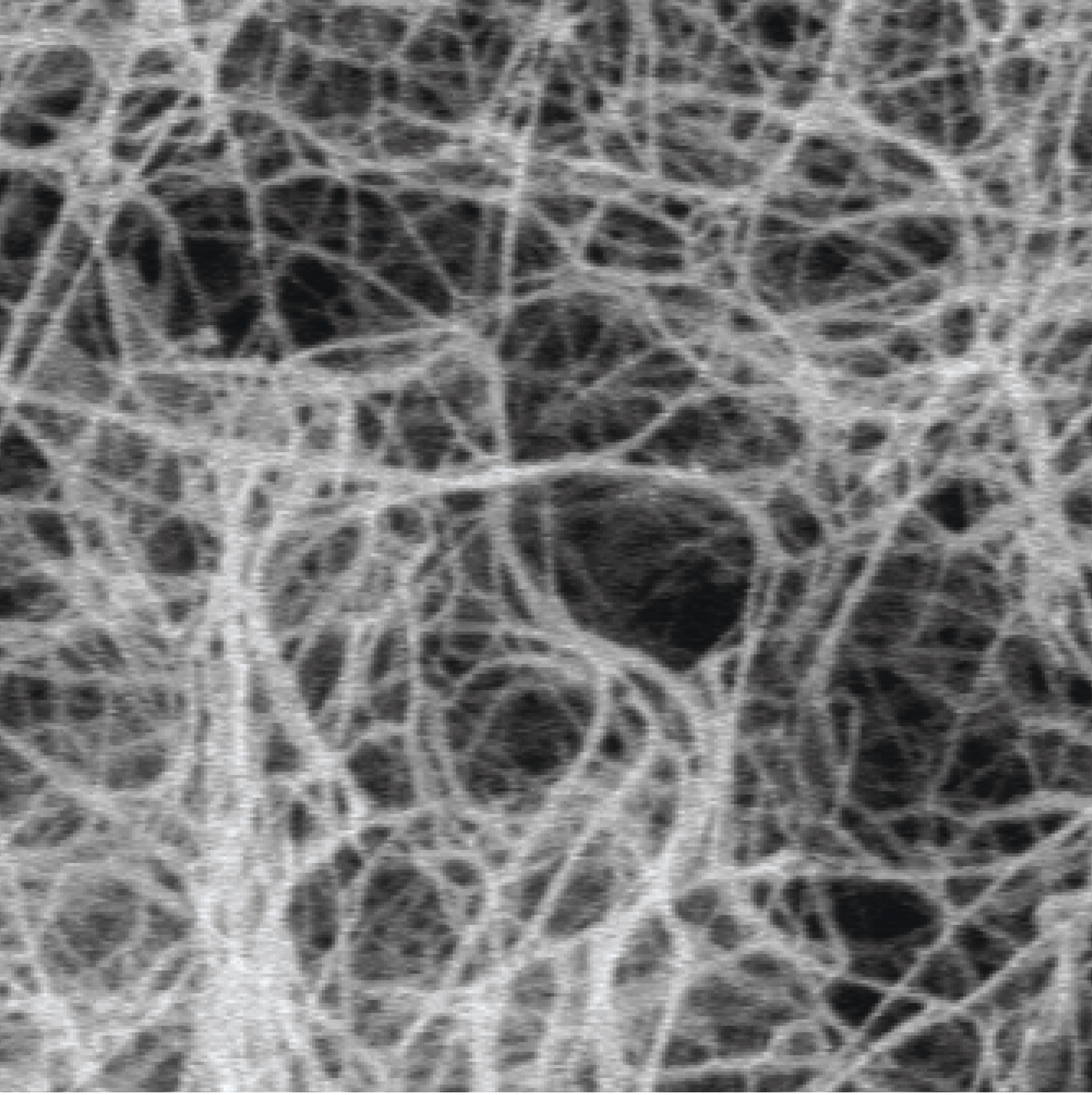


Figure 9.1 An electron microscope image of an NFC nanofibril network. (Kettunen, 2013, p. 43). Adapted with permission.

9.2.4 Materials: Nacre and Synthetic Nacre

Nacre (mother of pearl) is a natural nanocomposite present for example in the crusts of seashells. There are various types of nacre, but the so-called sheet nacre has a three dimensional brick-and-mortar structure, which constitutes of inorganic calcium carbonate (CaCO3) platelets in a matrix of organic biopolymer (protein), typically keratin, collagen and chitin. (Bhushan, 2009; Espinosa, Rim, Barthelat, & Buehler, 2009) The structure can be seen in Figure 9.2, although the protein layers between the platelets are almost not visible as they are very thin.

The platelets (about 5-8 μm in diameter, and 0,5 μm in thickness) form strength providing lamellae, which are embedded in thin layers of the viscoelastic protein (20-30 nm in thickness) that provide ductility. Despite the fact that 95% of nacre's structure is composed of brittle calcium carbonate, and 1-5% of ductile biopolymer, its fracture toughness is about 3000 times higher than of monolithic calcium carbonate (Espinosa et al., 2009; Malkin, Yasaee, Trask, & Bond, 2013; R. Z. Wang, Suo, Evans, Yao, & Aksay, 2001). Nacre, as many other natural materials, has a hierarchical structure. This means that certain structural features are present in different length scales, which plays a key role for achieving these exceptional qualities. (Espinosa et al., 2009)

Nacre's brick-and-mortar structure restricts transverse crack propagation. This requires the interfaces to be weaker than the platelets, for otherwise the material would experience a brittle type of failure. The structure of nacre promotes the interlamellae sliding of the platelets, which consumes fracture energy and leads to increased toughness and tensile strength. (Bhushan, 2009; Espinosa et al., 2009; R. Z. Wang et al., 2001)

Also the shape of the platelets enhances the material's properties. The platelets have a discrete hexagonal shape, and, despite being generally described as flat, actually display significant waviness. As the platelet layers slide in case of deformation, the waviness causes them to climb on each other, which creates progressive platelet interlocking and resists the sliding. The wavy "dovetail" structures of the platelets thus enhances the strength and resilience of the ma-

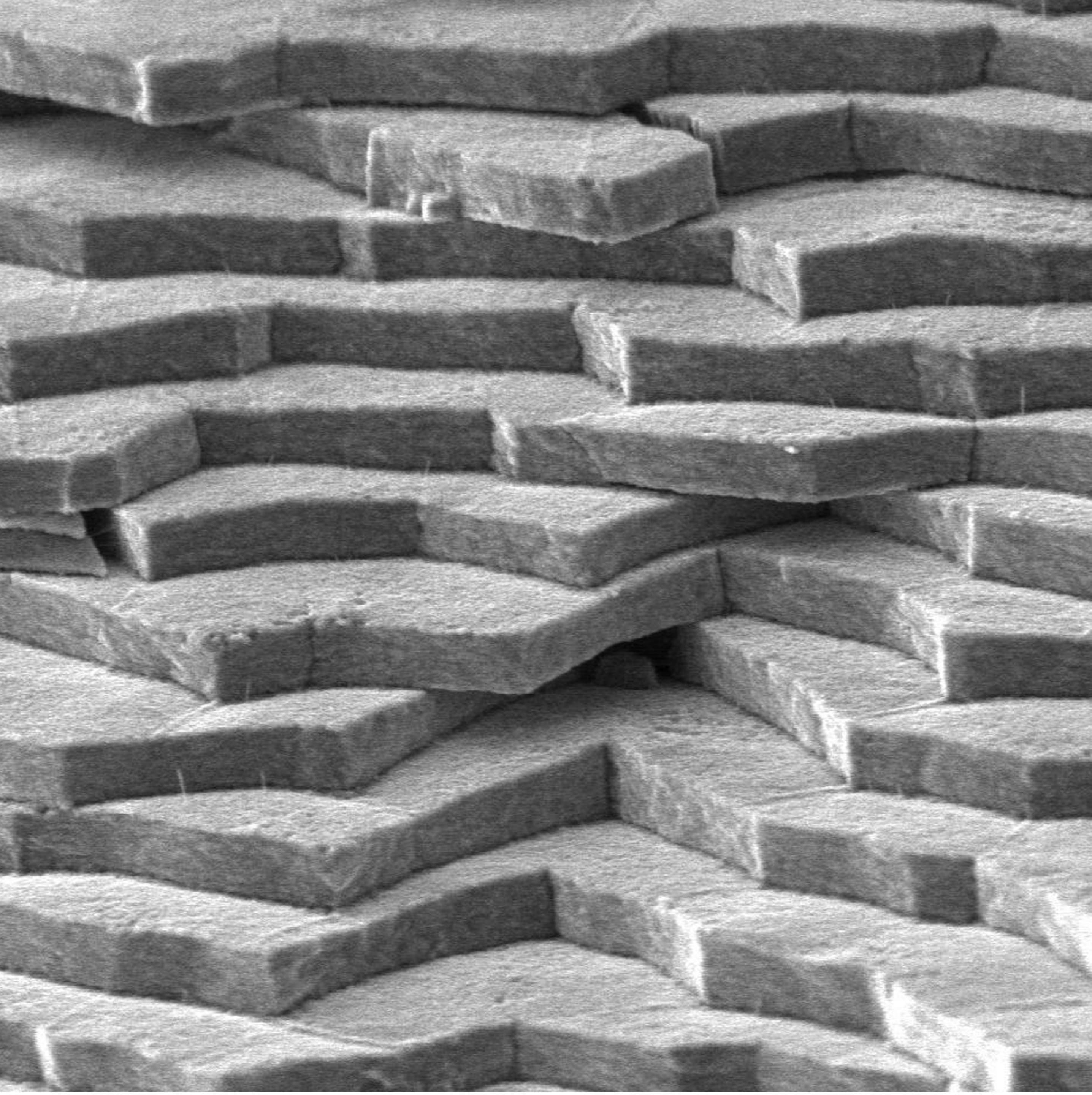


Figure 9.2 An electron microscope image of nacre from the bivalve Pinctada maxima. (Mallet, n.d.). GEROM / SCIAM, Université Angers. Adapted with permission.

terial. (Espinosa et al., 2009)

Through this structure, marine molluscs have developed a ceramic material that is simultaneously very strong and tough, and thereby outperforms man-made engineering ceramics. It highlights how efficiently the structural design of a relatively simple "tiles and glue" arrangement has been put to use for achieving qualities far beyond its base materials' properties. (Bhushan, 2009; Malkin et al., 2013)

The Molecular Materials group has worked on the development of synthetic nacre. Synthetic nacre has been produced for example by using nanoclay platelets in a polyvinyl alcohol (PVA) matrix, mimicking the calcium carbonate – protein structure in actual nacre. Synthetic nacre has displayed interesting properties mechanically, but also as a gas barrier and heat shield. The mechanical properties have, however, not yet been as impressive as in natural nacre, but the material is currently being developed further. (Walther et al., 2010)

10 Case I (MM): Nacre Geometry

The "nacre geometry" case depicts the design and prototyping process of a biomimetic geometry that was inspired by the structure of nacre. This case study differs from the other two, in the sense that the goal has not been to directly use the abovementioned materials, but rather to utilize nacre as an inspiration for a material structure. The goal of the process has been to explore via prototyping, whether a similar geometrical structure as in natural nacre could be scaled up to the macro-scale, and still display similar properties. There is reason to assume that a scaled-up nacre structure could have interesting properties, as the effect the particle size has on the object's mechanical properties is relative to the object's overall size (Bazant, 2004). In case a nacre-mimetic structure could be scaled-up successfully, the principles of nacre could be perhaps utilized also in larger scales and structures with alternative materials. One interesting perspective would be to make stronger and tougher structures using cheap bulk materials, resembling how nacre, of which 95 % is brittle calcium carbonate, displays a 3000 higher toughness than pure calcium carbonate. Additionally, the properties of high-end materials could perhaps also be enhanced even further if used in a nacre-like composition. Thus the structure could perhaps have potential for a variety of applications.

10.1 The Design Process of the Nacre Geometry

The idea of prototyping the structure of nacre at the macro-scale arose in the beginning of the MM project after researching the basic properties of the material. The nacre platelets are often depicted as flat in scientific representations, although their waviness is apparently essential for enhancing their mechanical properties (Espinosa et al., 2009), which inspired to prototype the interlocking wavy structure of the material. Another interesting aspect was to test whether a nacre-like structure would display beneficial mechanical properties also at the macro-scale.

A plausible way of prototyping a nacre-mimetic structure would be to model a suiting 3D geometry using CAD, and then produce it using additive manufacturing processes. The brick-and-mortar arrangement of strong platelets in a ductile matrix could be achieved with multimaterial 3D printers.

The interlocking of the platelets, achieved by their wavy structure, has been featured in some publications. However sometimes this structure is displayed in a rather irregular and organic manner (Barthelat, Tang, Zavattieri, Li, & Espinosa, 2007), and other times rather as 2D representations (Dimas, Bratzel, Eylon, & Buehler, 2013; Espinosa et al., 2009). Here the goal was, however, to design a producible and coherent 3D structure.

The practical design task was to translate the wavy interlocking structure into a rather simple platelet geometry and grid structure, which would preferably be also easy to model, analyse, and produce. A simple geometry would also enable a wider option of manufacturing methods next to 3D printing. The idea was to create a polygonal shape that would mimic nacre's wavy "dovetail" structure. The process began by sketching geometries that could work in a similar manner to the pseudo-hexagonal wavy platelets in natural nacre. A good option was to provide the platelets with a cross-section of uneven thickness, which could interlock laterally with its neighbouring platelets if placed into multiple layers. Small gaps in between the platelets would have to be reserved for the ductile glue (the matrix material).

The exact design of the platelets required more detailed geometrical studies of the interlocking mechanism, which were first precisely drawn, and then modelled by CAD. The resulting platelet geometry consisted of a hexagonal solid, of which every other edge was slightly higher, and every other slightly lower, with its centre as the thinnest part (Figure 10.1). This way, when placed into a layer structure, the platelets would overlap and interlock laterally. The interlocking would become more efficient with more platelets and layers. In order to achieve this effect, the relations between the edges and the centre points had to be carefully evaluated and modelled. Important details included also the aspect ratio of the platelet, the exact height relations of the edges and centre points, and the relative size of the platelet gaps that would contain the ductile glue material. Also a grid structure for the platelets and glue needed to be designed in order to create an actual sheet of the material.

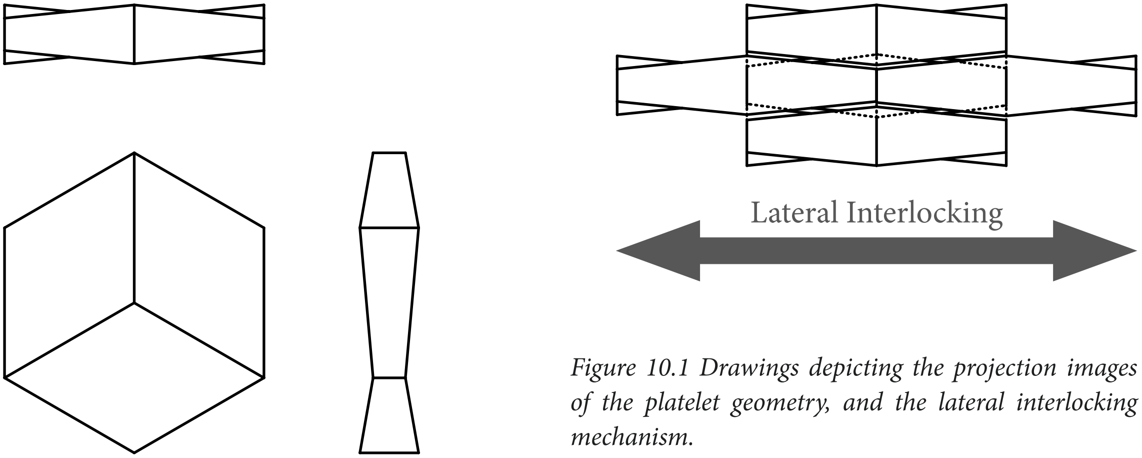


Figure 10.1 Drawings depicting the projection images of the platelet geometry, and the lateral interlocking mechanism.

10.2 Collecting Feedback with the Prototypes

Throughout the design process the structure was constantly analyzed regarding its potential applicability. After modelling the first nacre-mimetic platelets, a small bunch was printed out in order to explore them as tangible objects. These first printed models were not optimized in all detail, and neither did they form coherent sheets, as they were printed without the ductile "glue" in between. The first prints can be seen in Figure 10.2. Printing the first physical "nacre-platelets" was still extremely fruitful, as they enabled to explain the structural idea of the nacre geometry effectively to others. The initial 3D prints were useful for facilitating interviews with various experts, which provided valuable insights for example regarding the structure's potential applications, options for its constituent materials, and possible means of manufacturing (in addition to 3D printing).

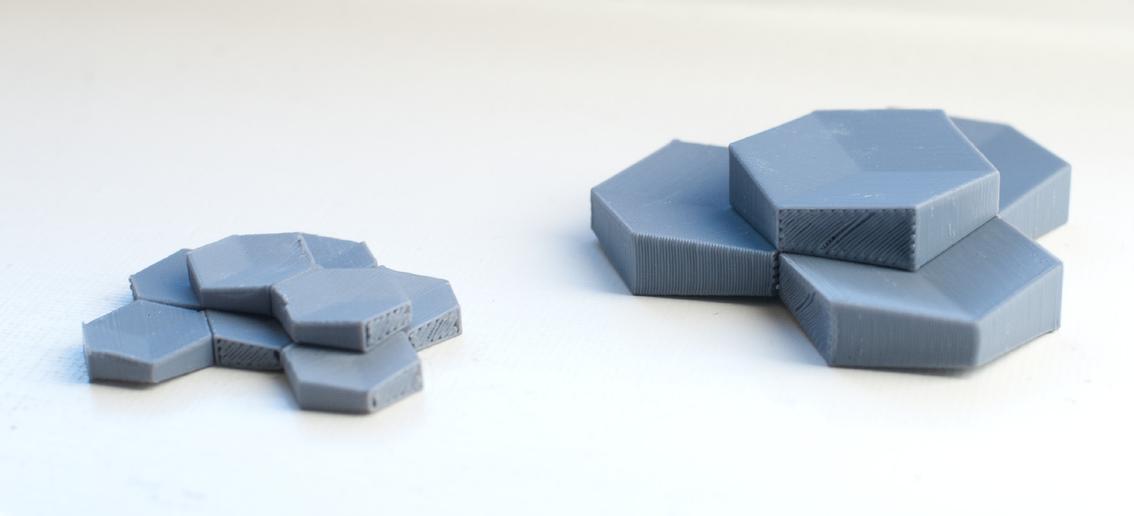


Figure 10.2 The first nacre platelets used in connection with interviews were 3D printed in two different sizes and without the ductile glue material in between.

Interviews were conducted with experts from aeronautical engineering, materials engineering, materials science, fluid mechanics, and automation. In general the experts encouraged developing the structure further as they saw potential in it. Basically the discussions revolved around the actual design and prototypes, how the structure could be tested, and what kind of applications could be further looked into.

Timo Brander (personal communication, December 13, 2013) from aeronautical engineering considered the structure interesting, but remarked that the materials used for its components should be chosen according to application. The context of use would also determine the size of the platelets and thus also the method of manufacturing. If the structure would display good mechanical qualities, and also function as a gas barrier and heat shield, as its nano-scale counterparts, it could be utilized for example as a covering shell structure in spacecrafts. There it could be used as a "sacrificial layer", which could protect from impacts and heat during demanding landing phases.

Timo Kiesi (personal communication, December 13, 2013) from materials engineering saw potential in the structure, but also emphasized that further development would depend on the application it would be optimized for. Kiesi pointed out that especially in heavy industry more conventional materials and structures are favoured, as they have been tested and proven to work, and thus applications should be sought outside of this area. He however mentioned that some specific applications for example in private cars could be examined. If the structure would be stronger and tougher in comparison to its constituents, and thus promote the economical use of materials and lighter structures, a potential application area could be the fuel containers in hydrogen cars, which have been challenging to design due to the hydrogen containers' heavy weight. An interesting area of application could also be the armour in bulletproof vehicles. These are still largely produced using heavy metal plates or even concrete. If the nacre geometry could provide an equally strong, yet lighter structure, or a structure with varying material layers providing additional properties, it could prove to be beneficial in comparison to other current solutions.

10.3 Further Development of the Nacre Geometry

After the initial interviews the structure was develop further. The platelet geometry was refined and made thinner (Figure 10.3), and the CAD model was adjusted for 3D printing a coherent sheet of the structure, including the hard platelets and ductile glue material, by using a multimaterial printer. The idea was to use these prints for initial mechanical tests, for getting a better understanding of its properties next to mere estimations. A Stratasys Connex 350 3D printer, which is capable of printing multiple materials simultaneously, was utilized for the following printed prototypes. The printing process of the "nacre sheet" was a learning experience of its own, as the geometry proved challenging for the printer. After a few iterations they however succeeded. A printed "nacre sheet" can be seen in Figure 10.4.

The usefulness of the data received from the first mechanical tests was uncertain, as the materials used for printing were not necessarily very suitable for the cause. The Stratasys printer can print a harder and stiffer polymer, and softer more ductile one, but it was not clear whether they would have the right properties in order to work similarly to actual nacre. Thus the first mechanical tests with the printed sheets did not turn out as hoped. The first three-point bending test and a tensile strength test showed that the structure and/or the printed prototypes still required development, as they inflicted catastrophic failures to the structure (Figure 10.5). The conclusion was that the printer's materials did not suite the cause, for either the contrast between the two materials was not sufficient, or the materials did just not work as they should in order to achieve nacre-like mechanical behaviour. Thus it was decided to investigate alternative printing materials, or altogether alternative means of manufacturing.

Next to the mechanical tests, structural analyses were also initiated in collaboration with researchers from fluid mechanics by using mathematical models of the geometry. The goal for this was to get supporting structural data, as the mechanical tests are dependant on the materials available for printing.

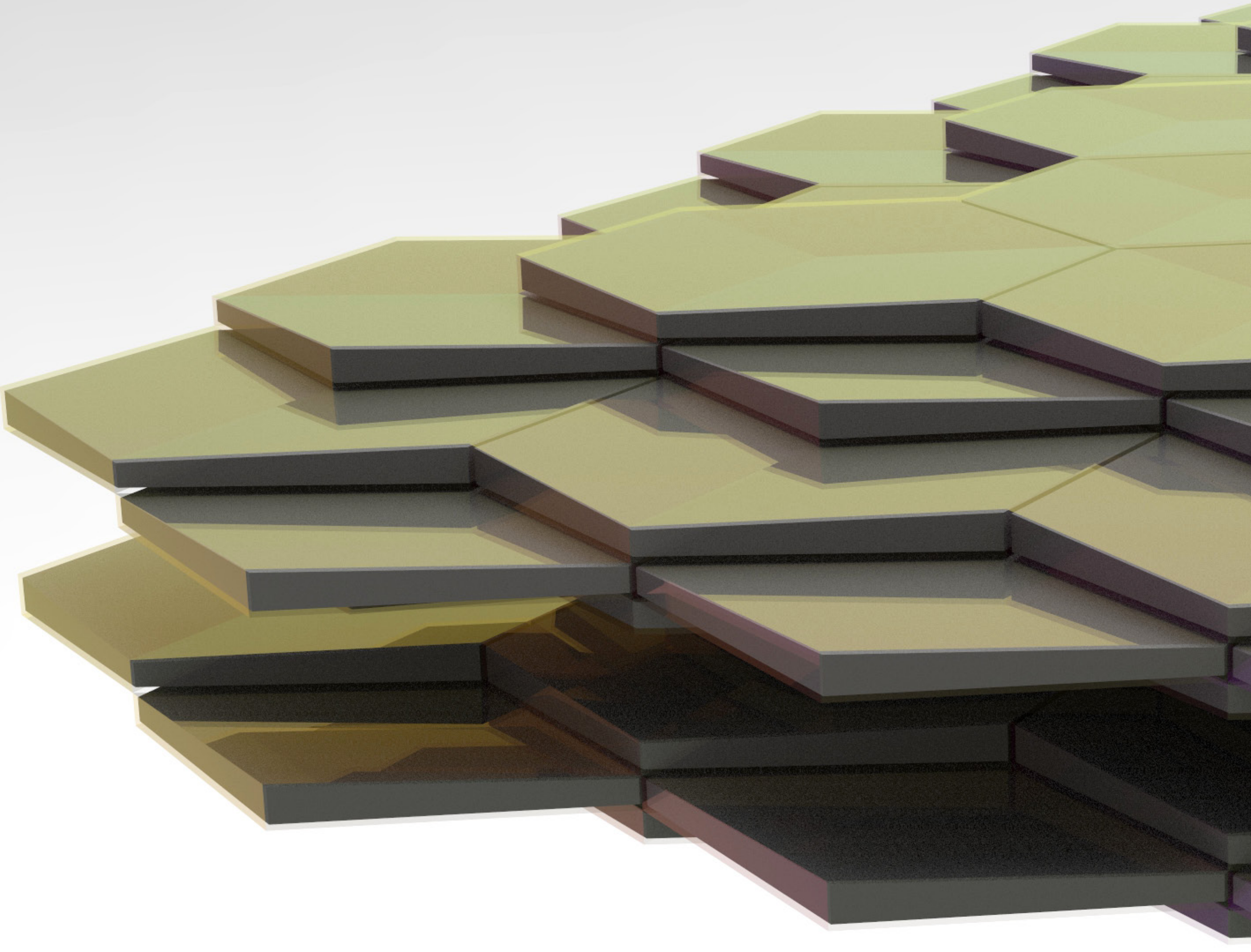


Figure 10.3 The improved "nacre sheet" prepared for 3D printing, which entailed thinner platelets and the ductile "glue" material. Rendering by Wycliffe Raduma. Adapted with permission.

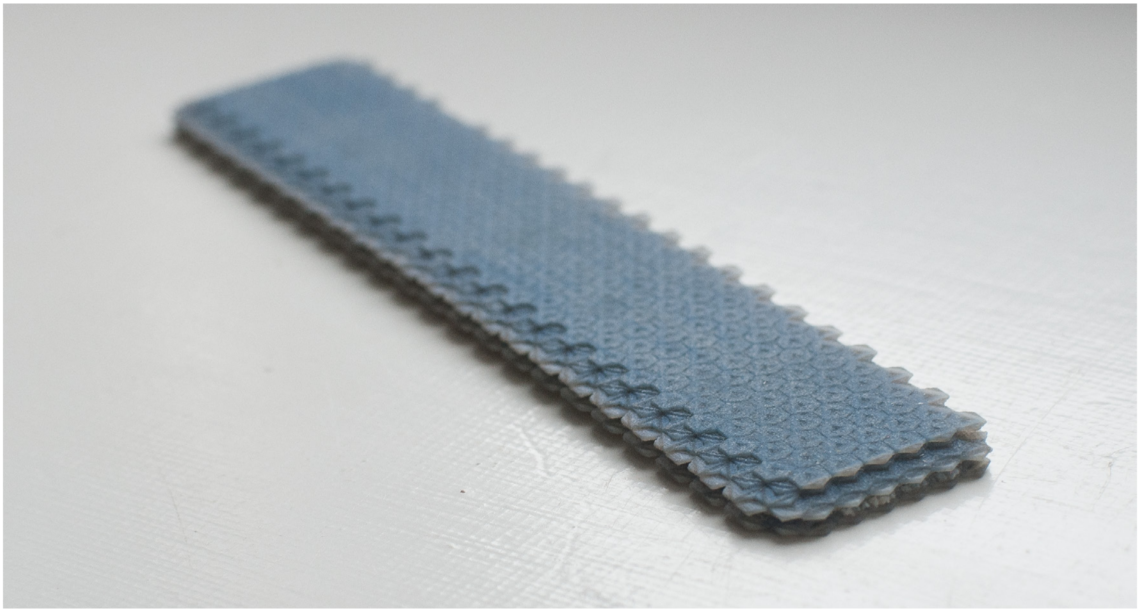


Figure 10.4 The first "nacre sheets" were printed by using a light-coloured polymer for the hard platelets, and a darker polymer for the ductile "glue" material.

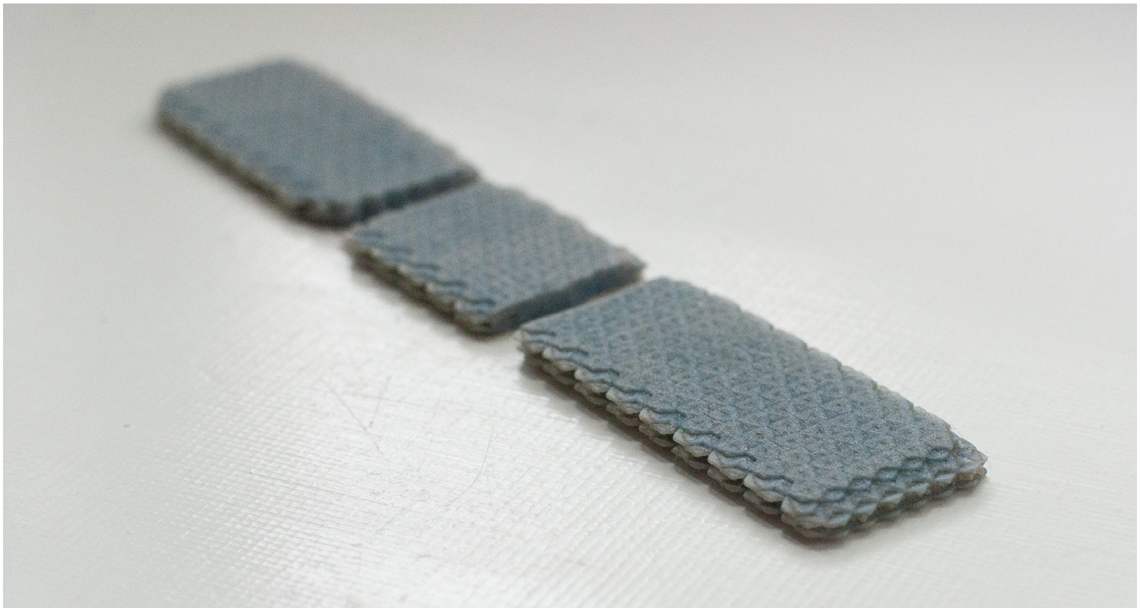


Figure 10.5 The printing materials in the first "nacre sheets" were not suitable, as the structure experienced catastrophic failures in the initial bending and tensile strength tests.

10.4 Insights from the Nacre Geometry Design Process

In the case of the nacre geometry, explorative prototyping was a central part of the process: various methods of prototyping, such as drawing, modelling, and 3D printing, were used for investigating the potential of a macro-scale nacre-mimetic structure. Here explorative prototyping did actually not differ much from scientific experiments, as similar structures are researched, developed, and tested also among materials scientists. As Bonsiepe (2007) claims, experimentation and tinkering are essential in both design and science, as they both seek to proceed according to “let’s see what happens when we do this or that” (p. 29). Basically, the nacre geometry advanced also in this manner: a curiosity concerning the structural properties of nacre initiated a research and development process. In the case of concrete structural investigations, the interests of design and materials science can be particularly overlapping, and the approaches may also complement each other, for example through science’s rigorous methods for testing and analysis, and through design’s drive for hands-on execution and applicability.

As Ulrich and Eppinger (1995) describe, prototypes can be either physical or analytical, and their role is, among other things, to advance learning and communication. These aspects were present in the design process of the nacre geometry. The drawings and CAD models that were used for understanding and creating the geometry, and the mathematical analysis models that were used for evaluating its properties, are examples of analytical prototypes. The 3D prints, which are physical prototypes, were essential for facilitating discussions with experts from other fields, and for learning through practical tests. Learning also happened as the initial mechanical tests proved unsuccessful, as they highlighted the need for re-evaluating the used printing materials. Further studies will be made, as various experts have thought that the structural idea of the nacre geometry is indeed interesting.

The discussions with specialists from different fields have been central for understanding the factors affecting the structure’s further development. The communication with various specialisms is also what Stappers (2007) highlights as an essential characteristic of design. Here, these discussions have provided insights regarding alternative manufacturing materials, alternative manufacturing technologies, and potential applications for the structure. They also relate to each other, as applications largely define the properties the structure should have, which define the materials used for it, which furthermore define the manufacturing technology used for its production. Once further simulations and mechanical tests have been made, and the understanding of the structure's properties has increased, these issues will be looked into in more detail through concept development. This way design tries to integrate knowledge from different fields for identifying meaningful applications.

As mechanical tests will continue together with researchers from the Molecular Materials group and the Department of Design, and work will go on with scientists from fluid mechanics, the process has triggered further cooperation between designers and materials scientists. Interdisciplinary collaboration has been reached fairly easily in this case, as the structural exploration of materials is clearly a common interest between design and materials science. The case also concerns the study of a rather tightly framed structural concept, which may have also facilitated collaboration. Finding plausible applications for the structure is another case for itself, and could prove to be trickier.

Nevertheless, comparing to Driver et al.'s (2011) analysis of how design practice can benefit scientific research, in this case the design approach has led to the quick prototyping of even relatively complex structures for example through 3D printing, and has thus contributed to the creation of demonstrators of possible new structural solutions. The structure itself apparently also contains novel aspects in terms of nacre-mimetic structural studies, and hence in a sense, it has been able to also challenge the scientists' perception and triggered further research. Additionally, exploring meaningful applications for the structure has been constantly kept in mind as well, and the further development of the structure will be guided also through ideas regarding meaningful applications.

11 Case II (MM): Concept Design for Nanomaterials

The second case study depicts a concept design process that aims at exploring potential future applications for NFC and synthetic nacre. The goal of the concepting process was to lead to ideas that would be seen as interesting to take further, thereby highlighting ways of utilizing, and also directing the development of materials. The scientists stressed that the ideas could be also wild and unconventional, in order to lead to clearly novel application and product ideas.

The starting points of the process were fuzzy, because the goal was to create concepts for materials that are not yet mature, as they are still being researched and developed. Although some characteristics of the materials are known and fixed, others develop as research progresses. This can be a challenge for concept design, as the material properties function as a starting point for the concepting process, but on the other hand, interesting concepts can also inspire the development of the materials into a certain direction. This induces a reciprocal relationship between the materials and the concepts, which can be complicated, as the situation cannot be approached very linearly.

As described in chapter 9.2, the materials in question can be also modified and functionalized, which gives them diverse properties. Thus the materials actually function as platforms for multiple material variants. This broadens their possibilities, but simultaneously it can again induce ambiguity, as an apparently wide range of possibilities can seem distractingly tempting.

In this case concept design functioned as a form of explorative prototyping, which aimed at formulating the situation, and making the following design work clearer. The concepts were framed through themes, which arose through preliminary research. The concepting process lasted for a couple of months, of which one month was spent at Nanotalo working in close proximity with the scientists from the Molecular Materials group, in order to get quicker feedback for potential concept ideas. Discussing the concepts with the scientists was important, as the physics and the chemistry concerning the materials is rather complex. Thus a brief familiarization with the materials through literature was not enough for an industrial designers to sufficiently evaluate the concepts' feasibility.

11.1 Concepts Function As Sources and Embodiments of Knowledge

As highlighted earlier, design can tackle complex situations by framing and abduction-2 reasoning (Dorst, 2011), which support exploration as they map possible solutions and problems simultaneously, thereby formulating a clearer focus for work. The only set value and objective given in the beginning of the MM project was to develop meaningful application or product ideas for NFC or synthetic nacre, which are two materials that are still being developed, and that have, or could have, a wide variety of different properties.

In order to create meaningful product concepts for the materials, also their potential usefulness, usability, desirability (Buchanan, 2001), as well as feasibility and viability (Brown, 2009) would need to be taken into account. Hence the question is not only "what" is done out of the materials, but also "how" they are applied for achieving certain goals, for without any good reason for someone to use a product, it will not be used, although it would be made of an "exciting new material". A case like this is de facto complex, as the process starts without a clear view of "what" and "how". Therefore it requires an explorative approach of the problem space, which can be done through a (conceptual) design approach (Cross, 2011; Dorst, 2011; Schön, 1983). The process aims at defining the challenges more precisely by concretizing possible solutions for the situation.

Concept design can have multiple stages. Initial concept designs can function as "well-educated guesses" of ideas that could potentially be fruitful, but their main purpose is to facilitate discussion, and to function as a focal point for collaborative reflection. For in a concepting process, the first stages are often utilized for the analysis of the context, and for the exploration of opportunities through these preliminary concept ideas (Vezzoli, 2007). After these exploration phases, the most fruitful concepts are developed further.

In order to compose the initial well-educated guesses, some preliminary research needs to be done. In this case the research was approached through a rather broad angle, as the situation was rather open-ended. Thus on top of studying the materials in question, insights were also gathered through foresight studies and trend reports, in order to get a picture of the potential future the concepts would be situated in. In addition to studying reports and books done by foresight agencies and futurists, also interviews were conducted with Elina Kiiski Kataja (personal communication, August 19, 2013), foresight specialist at the Finnish Innovation Fund, Sitra, and with Elina Hiltunen (personal communication, September 12, 2013), futurist and consultant. The interviews helped in forming a good picture of relevant trends on a global, but also on a national Finnish scale. The research was used rather as inspiration for the exploration and framing process, than as factual information that should be followed rigorously.

Despite the research, finding a balance between a "reasonable" and a "bold" idea proved challenging, as the plausibility of the ideas was hard for a designer to evaluate. One reason for this was the broadness of some topics (the trends) and the particularity of others (the materials), which needed to be bundled together into feasible concepts. Thus it was reasonable to develop initial concept ideas that could be used for facilitating discussion with materials scientists and experts from other fields, which could lead to a clearer view regarding the most promising trajectories to follow. The initial concepts could be used as triggers for debate, as the possibilities of the materials could be assessed more easily through suggestions regarding their potential use.

Therefore, in ambiguous situations one way of advancing is to frame the challenges, and approach them through preliminary proposals. These proposals, meaning the initial concept ideas, work actually as studies extending the preliminary research, as their goal is to spark evaluative discussions regarding the direction of the process. This way concepts function as explorative prototypes that make ideas tangible and integrate aspects from different perspectives, such as materials research and future studies, in order to facilitate the analysis of the next steps in a situation when knowledge is limited. Concepts can thus also function for the creation of a shared vision by indicating, towards which direction the process should be taken (Keinonen, 2006). Thereby they embody the results of initial evaluations, thus also being sources of new knowledge.

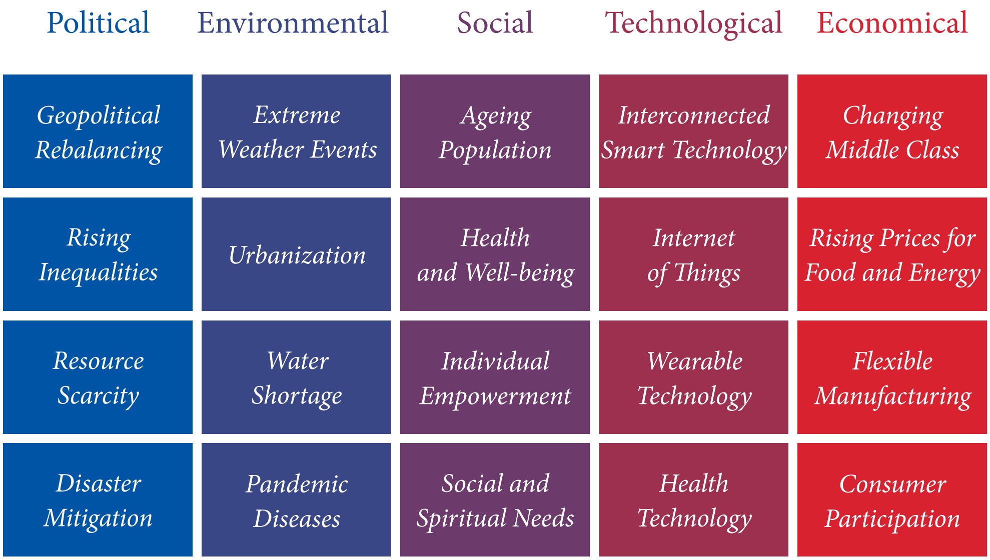
11.2 The Created Concept Ideas and Their Evaluation

For assessing the generated concept ideas more thoroughly it was decided to gather an evaluating group of experts from different fields, in order to discuss the direction that should be taken. Presenting the concept ideas in a visual and understandable way could give more concreteness for reflection, and something tangible to talk about. The evaluating group would preferably consist of a mixed crowd of experts, because visualized concepts, just like other prototypical outputs, integrate different factors in them, and are best assessed through a multitude of perspectives.

The evaluating group mustered for the concept idea discussion consisted of a professor and three researchers from materials science who have expertise in the materials in question, a professor from industrial design, a research fellow with expertise in sustainable design, a product and service designer, and a futurist. The idea was to keep the event informal and open, so that the evaluators could freely ask questions and comment in the middle of the presentation. This was emphasized, because the ultimate goal was, after all, to spark discussion and debate among the evaluators through the concept ideas, instead of presenting final outcomes to a passive audience.

The presented concept ideas were not very polished, but kept rather rough for emphasizing their preliminary status, in order to stimulate people's own imagination and their receptivity for building on top of them and for discussing them more openly. Often very refined ideas may come across as final ones and thus spark solely criticism instead of also inspiring people's own interpretations of them. Therefore also the format of the prototypes is essential in regards of what information they are supposed to provide and bring forth.

Eleven concept ideas were chosen to be presented for the discussion. The goal was to present a mixed bunch of proposals that would diversely look into the possibilities of NFC and synthetic nacre. The concept development process had been directed by framing work through specific themes, and through the data collected from the trend report research. These same themes were used to categorize the concept ideas in the presentation. Also some of the identified trends, that had either directly or indirectly inspired the process, were presented alongside the concepts (Figure 11.1). The themes and trends were intended to give context to the presented concept ideas. Next there will be a short description of the concept ideas, which are ordered under the themes of packaging, road and transportation, clothing and wearables, and spaces and furnishing.



Political	Environmental	Social	Technological	Economical
Geopolitical Rebalancing	*Extreme Weather Events*	*Ageing Population*	*Interconnected Smart Technology*	*Changing Middle Class*
Rising Inequalities	*Urbanization*	*Health and Well-being*	*Internet of Things*	*Rising Prices for Food and Energy*
Resource Scarcity	*Water Shortage*	*Individual Empowerment*	*Wearable Technology*	*Flexible Manufacturing*
Disaster Mitigation	*Pandemic Diseases*	*Social and Spiritual Needs*	*Health Technology*	*Consumer Participation*

Figure 11.1 A PESTE analysis on some of the identified trends that either directly or indirectly inspired the created concepts.

11.2.1 Packaging

Sprayable Packaging is a packaging concept that answers to rising trends related to flexible manufacturing, including for example personalised and on-demand products, made possible through additive manufacturing technologies. Packaging solutions could be brought to the same level of flexibility as the production of products. The sprayable packaging concept was inspired by the way spiders "package" their prey: by wrapping strong filament around them. Plastic wrappings obviously already exist, but could the naturally aggregating and strong NFC fibrils be used for producing sticky filament-like spray, which could be utilized for wrapping products, or even attaching objects in situations of transport? In contrast to plastic wrappings, this packaging concept would use a biodegradable material for packing, but also attaching objects flexibly, similar to how Spider Man shoots webs from his wrists.

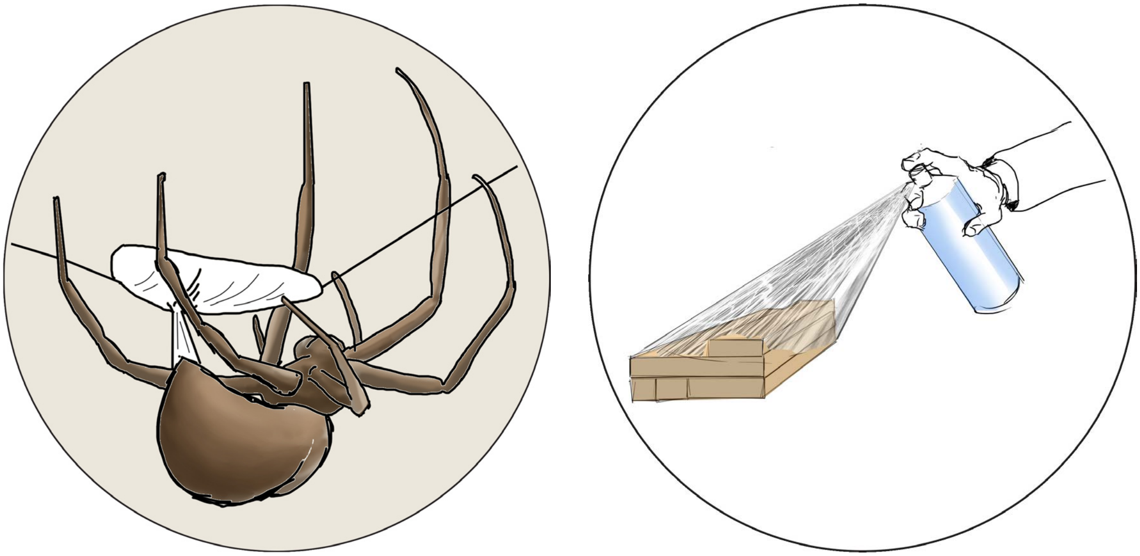


Figure 11.2 Sprayable NFC filament could be used for flexibly packing and attaching products and objects, similarly to how spiders use their silk to pack and attach prey.

NFC Water Containers are water management vessels that are able to collect, store and filter water efficiently. Instead of being made of a hollow shell structure, these water containers are made of solid pieces of NFC. The concept utilizes NFC's natural hydrophilic properties to its advantage. As NFC is able to hold very high amounts of water per solid content, water could be stored in its structure in a "solid" form. This could lower the risk of spillage in case of container damage, which could make transportation safer. Hydrophilic NFC could also be used for absorbing water from air humidity in areas with little fresh water. The nanostructure present in NFC could simultaneously be utilized for filtering and purifying the water from impurities. Hereby these multi-purpose water containers, functioning for collecting, storing, and filtering water, could be efficient and valuable in catastrophe areas and locations with little access to pure drinking water.

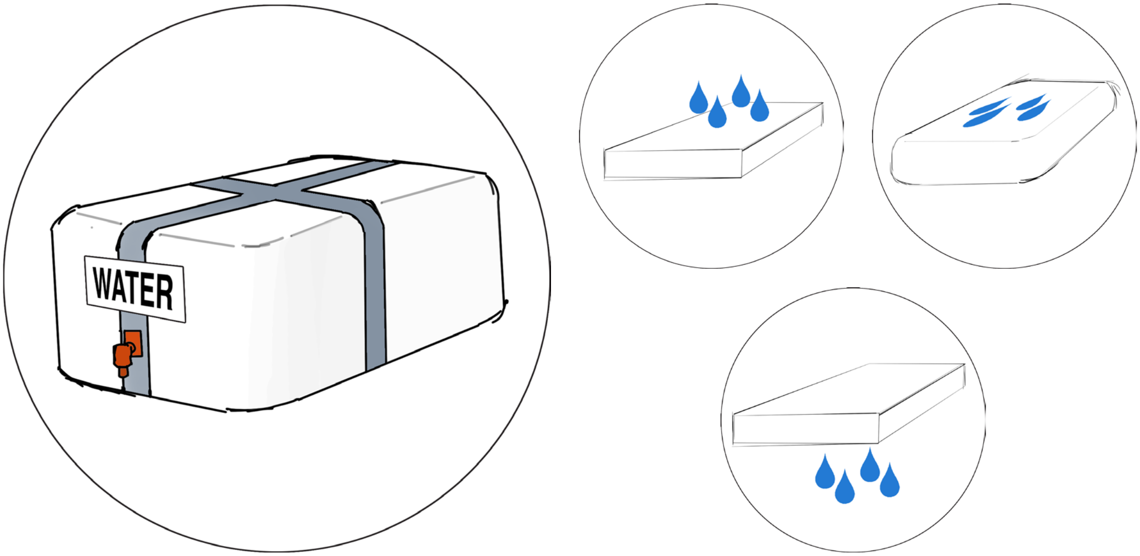
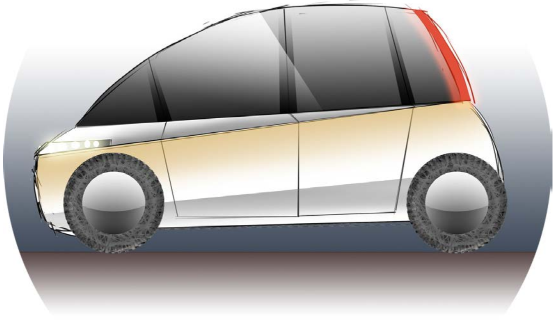


Figure 11.4 NFC Water Containers could be used for collecting, storing, and purifying water in catastrophe areas or places affected by drought.

11.2.2 Road and Transportation

NFC Smart Tyres uses NFC as a component in tyre structures. Cellulose-based materials are already used in rubber tyres, and also nanocelluloses have indicated benefits in regards of mechanical properties and manufacturability of rubber composites (Xu, Gu, Luo, & Jia, 2012). The concept introduces tyres as a more active component of the vehicle, enhancing safety, fuel consumption, and air filtration. NFC is seen as a good material for the production of filters (Kangas, 2012). Could car tyres be equipped with filters that could clean street dust whilst driving? Another aspect of the concept is to make the tyre profile reactive to conditions. Resembling the water carrying veins of a leaf, the tyre could make use of NFC's natural hydrophilic properties, by "pumping up" and increasing the tyre's profile in moist conditions, thus also increasing friction. In dry conditions the tyre could be smoother thus lowering the friction. Thereby the tyres could be safer in wet conditions, and consume less fuel when driving on dryer roads.



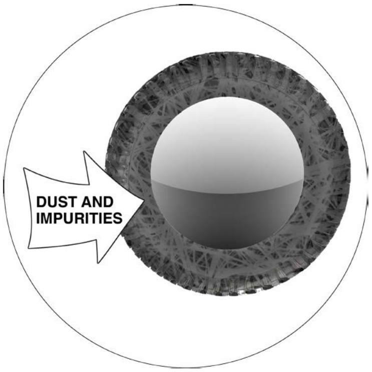


Figure 11.5 NFC Smart Tyres could function as dust filtering active components of tomorrow's vehicles that adapt automatically to changing weather conditions, through a profile strcuture resembling the veins of a leaf.

The Reactive Road Sign concept is about rendering the signage on roads reactive to changing conditions. Nanomaterials, such as NFC, can potentially be modified to become fluorescent (Díez et al., 2011), and change colour through outside stimuli (J. Hinestroza, personal communication, July 30, 2013). The concept builds upon these ideas by suggesting functionalized NFC-based paints and coatings for road markings and signs, which could, for example, change the speed limit or sign colour, or enhance the visibility of signage as conditions change. Thereby the signage could be matched to prevailing weather conditions, such as rain, making it more easily noticeable. Signs in remote areas would not need digital displays for this to be possible, and the technology could also be applied on asphalt markings.

Figure 11.6 NFC-coated Reactive Road Signs could react to changing weather conditions.

11.2.3 Clothing and Wearables

The Nanomaterial Helmet basically highlights the idea of using nanomaterials for the production of protective gear such as helmets, as NFC and synthetic nacre have properties that could potentially be beneficial in such applications. The materials possess for example theoretically good mechanical properties, such as strength and resilience, and NFC apparently also has structural characteristics that promote shock-absorbance (O. Ikkala, personal communication, September 30, 2013). On top of being shockproof and lightweight, helmets can have requirements such as insulating, noise reducing, anti-bacterial and frost proof, depending on the context of use. Theoretically, NFC and synthetic nacre could also function well for such varied purposes. This concept can be taken further by concentrating on some particular helmet type. Options included for example bicycle helmets, snowboarding helmets, cloud and scratch resistant visors for motorcycle helmets, and insulating and lightweight fire-fighter helmets.

Figure 11.7 Nanomaterials could potentially be used for various purposes in different kinds of helmets, such as in bicycle helmets, snowboarding helmets, motorcycle helmets, and fire-fighter helmets.

Movement Tracking Sports Clothing could be used in various sports for monitoring body movements through sensors integrating into the fabric. Athletes could check whether they perform exercises correctly or not. Training would be more efficient and safer, as the system could warn of incorrectly performed exercises. In gym training or physiotherapy for example, correctly performed exercises are key for progress and health. Such systems can, however, be produced also without special nanomaterials. Sensors and other components that can be integrated into clothing are already available on the market. In fact, there are already companies developing systems for precise movement tracking in sportswear. NFC can, however, be made conductive, and conductive NFC-based yarns could thus function as good platforms for smart textiles, making the sensors more seamless and integrated. Such smart textiles could perhaps also dynamically tighten up for supporting certain muscle groups if needed, making the clothing a more active component during exercises.

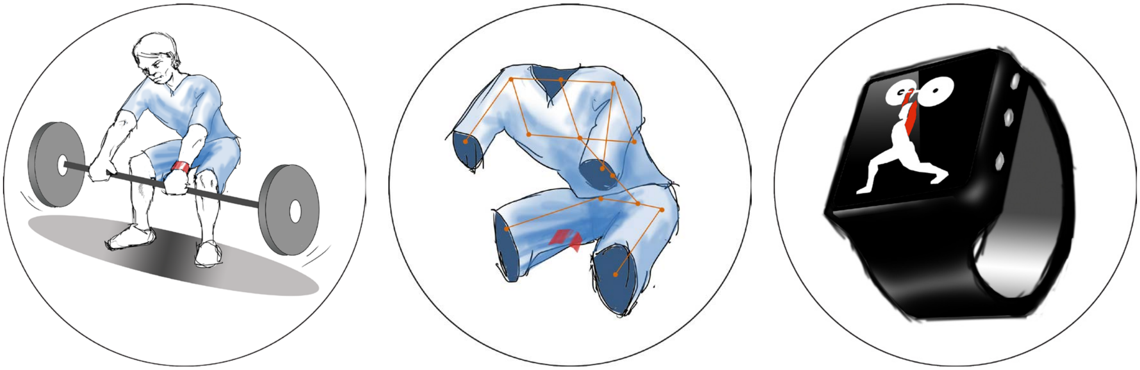


Figure 11.8 The sensors in the sports clothing could be wirelessly connected to devices such as smart watches, which could function as "digital personal trainers" for the user.

The Dynamic Cast is a concept idea for orthopaedic purposes. The idea is to utilize NFC biocomposite or synthetic nacre as materials in orthopaedic casts and orthoses, for producing strong, but simultaneously lightweight and thin structures, which could be used for supporting injured areas. NFC-based structures could also reduce skin irritation and promote wound healing through their breathing and absorbing properties. Furthermore, as most orthopaedic casts and orthoses are custom made and thus discarded after use (J. Lindahl, personal communication, January 20, 2014), cellulose-based solutions could be a sustainable alternative for oil-based materials widely used today. NFC structures could also be rendered antibacterial and conductive, making it perhaps possible to actively promote injury healing. The support could massage the injured limb, enhancing circulation and releasing pressure in the affected area. Additionally, as the injury would heal, the cast could concurrently loosen up and become gradually more flexible, facilitating early mobilisation that would support faster healing by letting the patient move the limp within safe boundaries. This could make rehabilitating exercises also safer to execute.

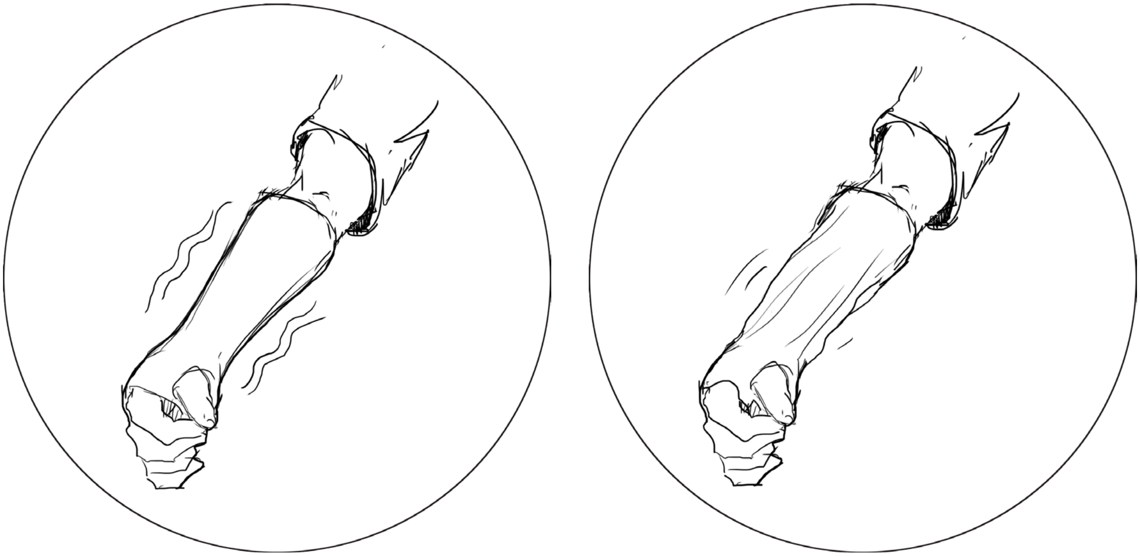


Figure 11.9 The Dynamic Cast could promote limb healing by enhancing blood circulation through massage, and by gradually becoming flexible enabling early safe mibilization.

Smart Skin is a mobile device concept that fits seamlessly around the wrist, feeling almost like an additional skin to the user. The concept makes use of the possibility to make conductive films out of NFC that enable the production of flexible and thin screens. The screen could also be equipped with advanced haptic properties. A dynamically changing haptic touch screens could communicate information to the user also by the sense of touch, enabling for example the development of "digital braille writing" for visually impaired people. An intuitive user interface, as well as a thin, breathing, and transparent NFC structure could make Smart Skin a seamless an unobtrusive device. These properties could be particularly beneficial for certain users, such as for elderly people, who may perceive current health monitoring devices stigmatizing, bulky, and cumbersome to use. Smart Skin would blend in with the user's wrist and clothing, making it less noticeable, but also easy to use.

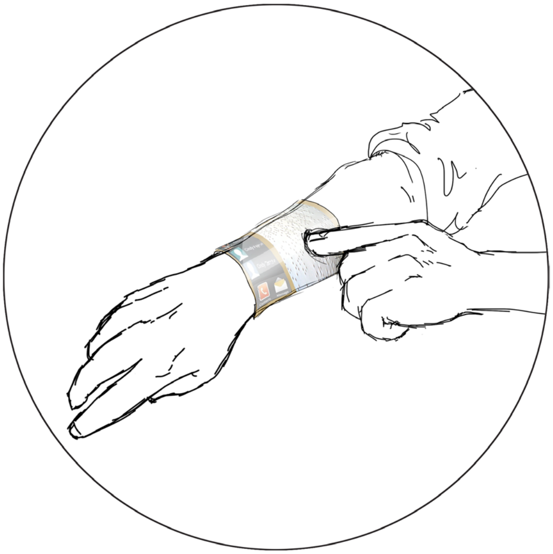


Figure 11.10 The Smart Skin is an unobtrusive mobile device concept with haptic capabilities, especially handy for certain user groups such as the elderly.

11.2.4 Spaces and Furnishing

Multifunctional Panels are indoor ceiling and wall panels. NFC could be used for producing porous panel structures that could have good acoustic and insulation properties. Additionally, the NFC structures could function as effective filters that could clean indoor air from impurities. As NFC can also be modified to have fluorescent and colour changing properties (Díez et al., 2011; J. Hinestroza, personal communication, July 30, 2013), the panels could function as sources of light, and as simple "screens" for communicating messages and instructions. They could be connected to the building's digital network, and, in case of emergency, lighten up and mark the route to the nearest exit. The Multifunctional Panels could thus be used for various purposes through the versatile use of cellulose-based materials, exemplifying a monomaterial construction. This could be beneficial also in terms of manufacturing and recycling.

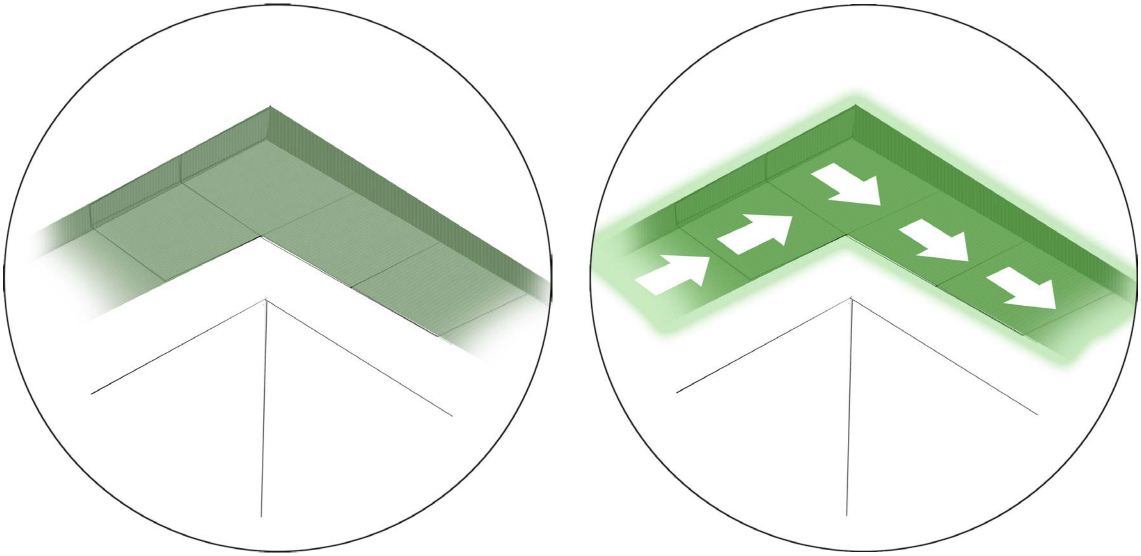


Figure 11.11 One function for the Multifuctional Panels could be to work as signage in indoor environments.

The Urban Beehive is a concept answering to the problem of declining honeybee populations worldwide. It promotes bee farming to city dwellers through a protective and filtering beehive structure. Synthetic nacre and NFC could be used for making the beehive strong yet light, and thus easily movable in urban environments. NFC could be used as filtering component in the beehive's structure for reducing the amount urban pollution affecting it. This could be beneficial for the honeybees and their survival in urban conditions. Naturally, the effects of pollutants on the bees could not be entirely removed, as the bees would also come into contact with impurities when outside of the hive.

Figure 11.12 The Urban Beehive's structure could be made out of synthetic nacre, with NFC-based filters reducing the amount of impurities inside the hive.

Self-assembling NFC is a conceptual idea of using NFC as a base material for creating self-assembling structures. For example moisture could be used for initiating the self-assembly process of NFC structures. As NFC is naturally hydrophilic, but can also be turned hydrophobic, a sheet of NFC could be, for example, left hydrophilic from some specific areas, while other areas would be treated to become hydrophobic. The hydrophilic areas of the sheet would function as the structure's reactive regions, and when coming into contact with moisture, they would absorb it and start expanding. This would cause the sheet to fold in a controlled origami-like manner. Structures could be thus stored and transported as sheets, and assembled easily on location, using only moisture as a trigger. This could make the assembly and construction processes easier also in certain challenging environments, such as in underwater. Also other triggers, such as electricity, magnetic fields, or temperature could be used for initiating the self-assembly process. The main idea of this concept is to make storage, transport, and construction of structures more efficient, by using a process of automated local assembly. Additionally, as the molecular structure of each part can be individually modified, the process could be efficient also for the creation of customized structures.

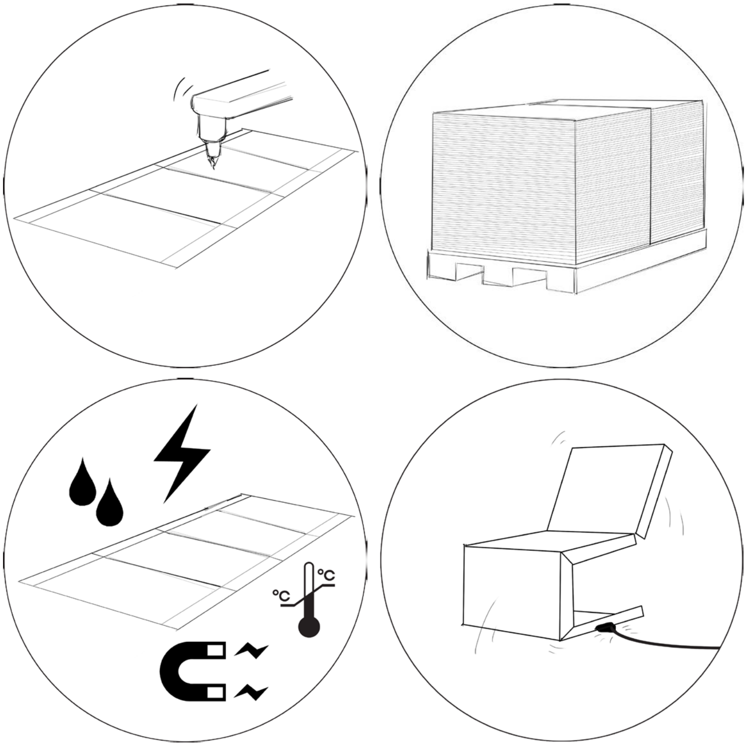


Figure 11.13 NFC-based self-assembling structures could first be modified, then transported in flat format, and then assembled on location using an appropriate trigger, such as moisture, electricity, temperature, or a magnetic field.

11.3 Continuing the Concept Design Process

The concepts sparked fruitful discussions regarding the direction that should be taken. As the evaluating group consisted mostly of experts from design and materials science, opinions were in some cases clearly divided by discipline. The designers seemed to regard the NFC Water Containers as the most interesting concept, mainly because it utilizes NFC's intrinsic hydrophilic properties (which are sometimes seen as a negative attribute) to its advantage, and because of its usefulness in areas struggling with water scarcity. The materials scientists favoured the Nanomaterial Helmet, as it makes use of the diverse mechanical properties of NFC and synthetic nacre, but without being too high-tech. Thus the Nanomaterial Helmet was chosen to be continued.

The decision to focus on the helmet concept basically created a new round in the design process, shifting the focus towards developing a more precise design around that concept. The framing of the situation through initial concepting enabled the identification of a more defined objective. This launched a new round of research that looked for example into the mechanics of helmets, causes of head injuries, and the shock absorbing qualities of different structures. One particular idea that was discussed further together with the scientists was a foldable bicycle helmet design. The idea was to create a light and strong structure using nanomaterials that would enable the production of an easily portable and storable helmet.

However, as research progressed it became clear that designing a protective helmet was more complex than anticipated. In fact, the helmet industry in general is facing today increasing challenges, as new research suggests that most current helmets do not sufficiently reduce the risk of concussion. An in-depth article from the Bicycling magazine (Barcott, 2013) highlights how this is the case with current bicycle helmets, and furthermore, how complicated the mechanics related to concussion prevention actually are. Additionally, a consensus statement on concussion in sports (McCrory et al., 2013) states that clinical evidence suggests current sports helmets do not prevent concussions, this being the case in various different sports, such as American football, ice hockey, and snowboarding. If helmets from even major manufacturers fall short in reaching some of their basic requirements, making a helmet foldable would not be much of an improvement. Some studies even suggest helmet usage increases the risk of accidents in bicycling (Fyhri & Phillips, 2013).

Thus in order to produce an improved helmet design, it would be crucial to tackle fundamental challenges related to head protection, instead of only developing a foldable structure for portability. In order to prevent concussions, the helmet should not only protect against impact, but also slow down the impact force thus slowing down also the movement of the head. This is, after all, a problem the whole helmet industry is struggling with.

The helmet design process thus continues with further research concentrating on the development of shock absorbing structures. One idea is to look into biomimetic structures, such as the foam-like peel structure of the pomelo fruit (Thielen, Speck, & Seidel, 2013), to be produced out of biomimetic nanomaterials for shock absorbing qualities. The development of the helmet's design has thus shifted more towards creating a highly protective structure, rather than merely concentrating on a foldable design.

11.4 Insights from the Concept Design Process

Abduction-2 reasoning is essential in concepting (Dorst, 2011), which was the case also in this process. Initial research and the identification of themes lead to frames, which were used for the creation of concepts that functioned for assessing the direction of the process. Concepting was used for asking, "What should we design?" (Keinonen, 2006) The pursued value of the process was to find meaningful applications for the nanomaterials in question. The process brought insights to how the materials could be used, and what kind of products such solutions could enable. The chosen direction also made essential questions and problems more articulate.

The concepting process highlights the nonlinear nature of design, as preliminary ideas are concretized so that they can be discussed and evaluated. The iterative design process starts a new round of more detailed research and development work, as a direction is chosen and the design challenge defined. Concept design requires also the integration of insights from different fields of knowledge. Therefore the process included also the study of possible future trends and trajectories of materials development, and an evaluation done with experts from design, materials science, and future studies. The selection of the Nanomaterial Helmet concept framed the process for further work, enabling a more defined and targeted approach.

The following design work may, however, not be any less complex. The resulting research proved that a multitude of factors need to be considered also in terms of a helmet's design, as its protective performance alone is composed of various interrelated determinants. The use-potential of NFC and synthetic nacre must still be analyzed in this context.

Additionally, if the helmet concept were to become a commercial product, a wide array of other factors on top of its protective qualities would need to be solved, including the materials' intrinsic technical qualities, visual qualities, tactile qualities, sound/smell qualities, associative qualities, health qualities, and environmental qualities. In this respect, the nanomaterials should prove some clear benefits in comparison to other materials, for example in terms of costs, performance, or usability. (Ashby et al., 2009) A new material rarely outperforms more established materials in every way, but some clear advantages should be highlighted.

The immaturity of the materials has been a challenge for the process. The situation would require the contextual testing of the materials, for evaluating aspects such as their technical performance, manufacturability, and perceptual qualities. The production of physical prototypes is extremely valuable for opening these questions. The process may, however, bump into a wall, due to the availability of the materials, or their stage of development, which may not yet allow the proper production of physical prototypes. During initial tests with NFC (which were actually done in the DWoC project, but applies to this case as well), it became clear that the material could not be moulded or formed, as it would bend and shrink dramatically during the process. Although new materials may theoretically have good properties, confronting them with reality may introduce problems. As Ashby and Johnson (2002) put it,

> *Vague rhapsodies about the wonders of a new material can serve to stimulate interest, certainly. But if you want to design with the material you need to know the bad news as well as the good. (p. 164)*

They continue that "emerging materials can have an awkward adolescence" (p. 164), and that it may take time to understand their true character and possibilities. Physical prototypes are useful for identifying feasible uses for new materials. Depending on the outcomes, the process may require a re-evaluation of the direction. If the materials do not for example suit a helmet after all, then the process experiences an iterative loop, and a more feasible direction is chosen.

Comparing to Driver et al.'s (2011) analysis, it can, however, be stated that the creation and concretization of possible directions through concepts can facilitate the evaluation of further work. Firstly, concepts can be used for exploring applications for new technologies, such as novel materials. Secondly, the concepts can visualize potential scenarios of use, as they are analyzed in regards of how they can answer to requirements of utilization. Thirdly, concepts may also challenge the scientists' perspective of their research, and their view of the direction it should be taken to, as they may highlight technological requirements not identified before. Fourthly, concepts may also prove useful for communicating the results or direction of research using concrete examples, through which these may be easier to understand than through abstract theories or data sheets. This way, concepting can be useful for sparking new collaborations, and for building expectations for novel applications and products (Keinonen, 2006).

12 Case III (DWoC): Physical Prototyping with Foam Formed Pulp

The third case study belongs, unlike the other two, to the DWoC project, and was performed in close collaboration between two designers and two materials scientists. The process of this case study relates to the development of applications for foam formed cellulose-based pulp. The foam formation process is able to produce porous structures with a varying degree of porosity. Thus it was decided to explore the material's applicability for indoor panels, as its structure could be beneficial for insulation and acoustic purposes. One other key advantage of the material is its renewability and recyclability, which enables also the development of sustainable products and business models.

The process initiated with the creation of a panel concept, which functioned as a driver for exploring foam formed pulp through prototyping. Therefore, despite that this case study belongs to a different project than the previous one, it in a sense continues from where the previous ended, as it highlights a process, in which a concept idea is developed further using physical prototyping. This was mainly possible because foam formed pulp is at a more mature level, as a material and as a process, than the nanomaterials highlighted in the previous case. Therefore it can be produced in larger quantities making prototyping easier. The prototyping process helped also to identify issues affecting the development of potential business models for indoor panels. This case study concentrates, however, solely on aspects related to the practical work done with the physical prototyping of the foam formed pulp panels.

12.1 Exploring a Material Through Physical Prototyping

The goal of the process was to test and apply pulp in novel ways. As many traditional applications of pulp usually come in flat form, such as paper and cardboard, the goal was to explore more versatile forms the material could be moulded into. Pronounced 3D forms would put the material more effectively to test, and thereby it would be possible to test also the boundaries of its moulding properties, and investigate how different forms could be manufactured. The goal of these experiments was to get a better picture of what the material could actually be used for. Additionally, challenging the material in new ways can spark ideas for further applications, since a core aspect of such practical experimentations is to also find something unexpected. This case is thus an example of practical experimentation and exploration that is crucial for developing an understanding for materials in design.

This approach stems from the tacit understanding of materials present in the practices of craftsmen, from which the design profession has originated. Here prototyping deals with the contextual understanding of materials and their behaviour, approached through concrete experiments, which results in practical knowledge of materials and their use.

Physical prototyping confronts materials in an unexpected manner with reality. The production of a specific product concept prototype also gives a reference point for reflection. Materials in even simple products, such as an indoor panel, can have a wide range of requirements, which affect its suitability in terms of (mass) production, moulding, acoustics, insulation, fire safety, sustainability, aesthetics, and feel. The contextualized exploration of materials, through which these attributes are investigated, involves the materials as they are, and brings forth their properties in a demonstrative way, including their positive and negative aspects. The materials' perceptive and associative qualities are also highlighted, which is often not the case in regards of theoretical data sheets (Ashby & Johnson, 2002). The process may also lead to the development of new material properties. In a sense the process thus bridges aspects from science and crafts, as it strives to develop a craft for novel materials.

In this case, the process concentrated on investigating the effects caused by the moulding and dyeing of the material. The idea was to experiment with two different panel designs, the other entailing rounder forms, and the other edgier forms. As the version with the rounder forms was prototyped first, this case study will concentrate on the process experienced with that panel design.

12.2 The Development and Testing of the Panel Design and Mould

The foam forming process basically starts by combining pulp with water, and with something that breaks the water's surface tension, such as a detergent. If the goal is to use colours, the pulp should be dyed before the process. Then the mass is mixed, and also air is introduced into it thus creating foam. The foam is processed into a solid object by pouring it into a tank that has a perforated bottom, through which the water from the foam is sucked out. The pulp fibres start to aggregate closer to the suction, meaning closer to the bottom of the tank. The density of the material can be affected for example through the duration of the suction, and the following drying process. The primary goal of the experiments was to test how the foam would form if the suction would be applied through a perforated mould. The prototyping process entailed roughly three iterative stages.

12.2.1 First Stage: Square Design and Plywood Mould

The first set of experiments were done with a square panel design entailing two "hills" of different sizes. The purpose of this first design was to find answers to very basic questions: how would the forms build up and what steps would the process entail. A two-part mould was made in order to pressure mould also thinner shell-like panels. Despite the fact that the process was wet and included oven drying, as the panels needed to be dried properly after the moulding, the decision was made to CNC mill the first mould out of plywood for its cheapness and easiness. Also a fabric cover was needed for the mould as the mould's holes would otherwise let the pulp through.

During the first test numerous challenges emerged, especially with the moulding process. After many cycles of wetting and drying, the plywood mould broke, and the suction remained ineffective for the foam to solidify properly. The drying process of the foam remained also slow and problematic.

The partly damaged mould was left with the scientists for further experimentation. The scientists managed to refine the process and produce the first intact prototypes. Although the prototypes were rough, they helped to identify that the lower form of the panel did not build up as well as the higher one. This led to the realization that the process functioned better if the forms would be of same height. Images from the first stage are in Figure 12.1.

12.2.2 Second Stage: Triangular Design and Gypsum Mould

A new panel design and mould were developed for the second set of tests. Firstly, the mould material needed to change to something that would withstand the conditions better. The choice fell on gypsum, as it is also cheap and easy to process. Secondly, the panel design was changed to avoid the problems present in the first one. The second panel still needed to challenge the material in new ways. The panel was thus given starker forms, but of even height, in order to search for the material's boundaries by simultaneously avoiding the uneven forming of the panel's shapes. The panel's visual appearance was less important than the moulding experiments, as the aim was to understand the possibilities of the material. Eventually the new design resulted as having an overall triangular form, with sweeping ridges flowing along its surface.

As we had only used white pulp in the first experiments, the idea was to also use colours for the second set, in order to test their feasibility in the foam forming process, and for producing panel prototypes with an enhanced material experience. Reactive dyes were used for dyeing the pulp.

The second set of experiments resulted in clearly improved prototypes. The prototypes formed much better than the first ones. Also only slight shrinkage was experienced in the prototypes during drying. The use of colours also brought a huge difference to the results, as they created a very different visual appearance in comparison to the regular white pulp. Mixing fibres from different colour batches also created shades with lively textures.

Problems still included the length of the drying process and the material of the mould, as the gypsum had started to soften up during the wet process. The mould was also heavy, and the fabric covering the holes caused unwanted furrows to the panel surface. Images from the second stage are in Figure 12.2.

12.2.3 Third Stage: Triangular Design and Perforated Plastic Mould

For the third stage of prototyping the mould material was changed to plastic. Plastic sheet was used for vacuum moulding a thin shell-like mould. The holes required for the suction were laser cut into the mould, in order to make them small enough not to need any fabric layer for covering them. This way the mould would be lighter, there would be no need for a wrinkling cover fabric, and the drying process would improve due to the denser perforation. Although the vacuum moulding process turned out challenging, a rough mould was successfully produced out of polystyrene.

The third set of tests, done with the perforated plastic mould, turned out very good. Firstly, the new mould withstood the foam moulding process very well, as the wet conditions did not affect the plastic. Secondly, the smaller laser cut holes on the mould, having a diameter below one millimetre, formed a nice dense texture on the panel's surface, which seemed to give the structure extra rigidity, but even more, it provided the panel with a nice feel. The third mould not only enhanced the process of moulding the foam, but also the structure of the material, thereby improving the texture and quality of the prototypes. Images from the third stage are in Figure 12.3.

12.3 Insights from the Foam Moulding Processes

The physical prototypes of the panel concept drove the moulding, manufacturing, and dyeing tests for foam formed pulp. The experiments resulted in insights concerning processes that affect for example the material's drying, shrinkage, stiffness, texture, and appearance. The insights thus entailed aspects related to both technical and perceptual qualities, taking into account the perspectives of a potential manufacturer and user. The prototypes helped also in gathering knowledge that influences the broader perspective, as insights regarding the manufacturing process enabled the creation of business models for the acoustic panels. The prototyping thus helped in generating new

First Stage of Prototyping

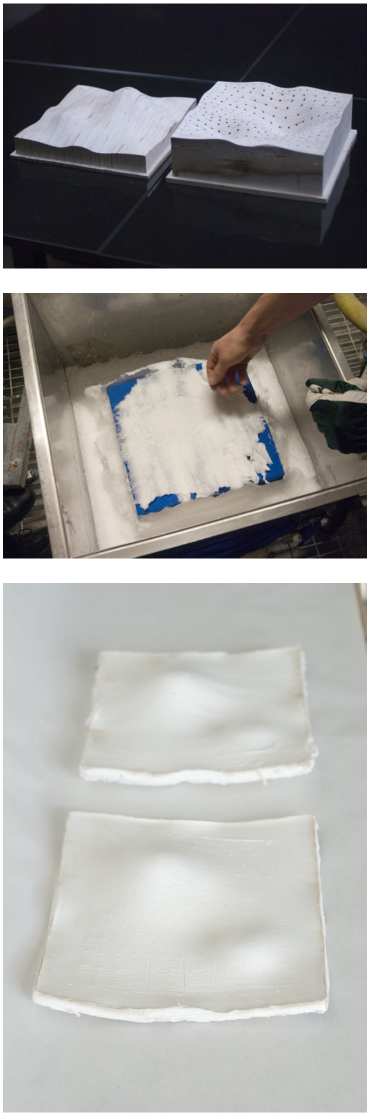


Figure 12.1 The first plywood mould (above), the first moulding attempts with foam formed pulp (middle), and the first prototypes entailing the square design (below).

Second Stage of Prototyping

Figure 12.2 The gypsum mould for the new design (above), the second set of moulding tests (middle), and the prototypes made of dyed pulp with a triangular design (below).

Third Stage of Prototyping

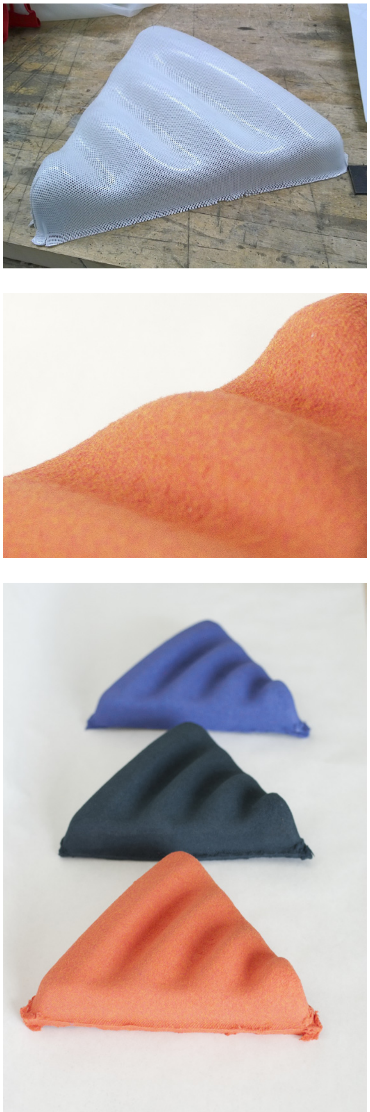


Figure 12.3 The third perforated plastic mould (above), the resulting nice texture on the panel surface (middle), and the third set of panel prototypes (below).

knowledge on many levels simultaneously.

Perhaps one of the most interesting aspects was, however, that the designers and scientists benefitted equally from the process. The panel prototypes functioned as a common goal to work towards, which enhanced the communication and collaboration between people from different backgrounds. Secondly, the contextualized exploration of the material provided important insights regarding its use and behaviour. This information can be used for developing the process further, and for generating even new product concepts for the material. As the scientists were able to acquaint the designers with a new material and technology, the designers were likewise able to make the scientists see their material and its use in a new way, for example through the use of colours, textures, and forms.

Actual products have many requirements. The following developments of the panel concept will thus have again new requirements for the prototypes. This will hopefully push the understanding of foam formed pulp even further, as for example issues related to fire safety need to be resolved. Hence, on top of generating meaningful applications for a material, concepts can be an effective incentive for the development of materials through contextualized prototypes.

The materials scientists involved in the process, Jani Lehmonen (personal communication, February 24, 2014) and Jukka Ketoja (personal communication, May 12, 2014), both state that the collaboration with designers was very beneficial. Ketoja and Lehmonen say that the design approach provided a wider perspective and novel ideas regarding the utilization of materials. For typically in materials science, the materials are optimized for predestined applications, such as, in the case of pulp, paper or cardboard. Ketoja notes how the iterative nature of design, in which changes of perspective may happen in the middle of the process, facilitates this approach. He sees the design approach as an adaptive learning process, whereas in sciences a change of perspective may often cause criticism. Lehmonen also notes that design's way of adapting to materials and processes differs from engineering, in which materials are often forced into a wanted form. The panel design was for example changed, as certain forms did not work as wanted, but into a direction that would yet again challenge the material. Lehmonen sees value in design operating with materials' intrinsic properties. This drive towards an "honest" use of materials, by utilizing their inherent qualities, derives mainly from the traditions of craftsmanship (Ashby & Johnson, 2002). Additionally Ketoja stresses the "human interface" and the "psychological aspects" important in design, which emphasize also perceptual qualities. Ketoja and Lehmonen both state how the use of form, texture, and colour, next to pure technical factors, has brought forth aspects related to the sensory experience of a material. Furthermore Ketoja notes that the "engineering perspective", related to problem solving, eventually becomes important also in the design process, as a prototype needs to be produced. This resonates with the way Dorst (2011) describes the relation between problem solving related abduction-1 reasoning, and concepting related abduction-2 reasoning. Most importantly Ketoja and Lehmonen however emphasize the importance of close cooperation on a common concrete objective, which has taught communication, helped to articulate relevant questions, and made use of people's different strengths for furthering the process.

Comparing the process to Driver et al.'s (2011) view of how design can contribute to scientific research, it can be said that design can, for one, help in the creation of technology demonstrators. Prototypes that are aimed to work in a specific context and are required to have specific qualities can be effective for showing the properties of a material. The panels were for example used in the Pulp and Paper Fair 2014 for demonstrating foam forming (Figure 12.4 and Figure 12.5). Prototyping may also bring forth new qualities or lead to new insights in terms of the material, especially through design's emphasis on also perceptual and associative qualities. This was exemplified by how the third mould's perforation affected the texture of the panel, and how the dyeing affected the material's appearance. The process was thus also able to challenge the scientists' perspectives of their research. Physical prototyping can provide a "craft for a material", which helps in understanding the material's properties in a more holistic way, and can also inspire new ideas for the material's use.

Figure 12.4 The colourful panel wall made with the panel prototypes at the Pulp and Paper Fair 2014. Photo by Tiina Härkäsalmi. Adapted with permission.

Figure 12.5 A close up of the panel wall at the Pulp and Paper Fair 2014. Photo by Eeva Suorlahti. Adapted with permission.

Conclusions

13 Explorative Prototypes as Mediators of Collaboration

The goal of this thesis has been to explore the collaboration between design and materials science by highlighting “explorative prototyping” as an approach for design to contribute to the research and development of materials and their applications.

A comparison with Driver et al.’s (2011) view of how design can aid scientific research shows that explorative prototypes can support early stages of materials research processes by assisting with the communication of research, by exploring applications, by portraying scenarios of use, by making demonstrators, and by challenging scientists’ view of their research.

The integration of design can support the early development of application concepts, which can portray potential ways of utilizing novel materials. These concepts can, however, also indicate what properties the materials still lack or should have, in order to make certain applications possible. These insights can also guide the research of materials. The design approach can thus not only bring forth solutions regarding the use of materials, but also problems that need to be solved before applications can be feasibly produced. The identification of relevant problems can be valuable at early stages of research processes, as it is the first step towards impact-rich research results.

The prototypes have been essentially “explorative”, as they have not only been used for testing predefined solutions, but also for gaining new (even unexpected) knowledge, for finding out feasible angles approach, and thus also for identifying essential questions related to the situations. These mutual processes between design and materials science thus aim to provide contributions also back to design practice and design research, for example by spreading knowledge of novel materials among the design community, and by portraying means for further interdisciplinary collaborations between design and science. Explorative prototypes can thus function as a means of constructive design research, informing design, materials science, and their collaborative efforts. In the following chapters, the results from the practical research will be first briefly summarized. Thereafter, the discussion is brought back to the broader more theoretical level regarding the collaboration between design and materials science.

13.1 The Reciprocity of Design and Materials Science in Prototyping

The practical research of this thesis depicts three case studies with different processes, different kinds of explorative prototypes, and different emphases. A technology/material –driven, and a human/user –driven perspective are, to a varying degree, present in the case studies. An effective combination of these perspectives can be basically referred to as a design-driven approach.

Case I takes a biomimetic geometry inspired by nacre as its starting point, which is clearly a material-driven perspective. Although the process mainly concentrated on the design of a specific structure, preliminary considerations for uses and applications were also made, and will be looked into in more detail as the process continues.

Case II depicts the creation of concepts, which were informed by the related materials and their potential developmental trajectories, but which were also strongly inspired by the information received from trend analyses and foresight reports. This introduced also a strong future-oriented human/user –driven perspective. The concept chosen for further development (the Nanomaterial Helmet) was among the most material-driven ones, but brought forth yet again new questions to be answered, which gave direction for further investigations.

Case III presents a balanced approach between technology-driven and human-driven perspectives. The material itself (foam formed pulp), and material-related processes, such as moulding, manufacturing, and dyeing, were explored, but driven by a clear product concept. The process did consider the end-user's needs (e.g. perceptual factors: colours and forms), and the manufacturer’s needs (e.g. technical factors: moulding and drying). The comparably mature state of foam formed pulp made this balanced approach possible.

All cases thereby presented a varying degree of “material push” and “user pull” combinations. In the development of applications for new materials, the relation between technology-driven and human-driven perspectives is thus firmly interconnected, which demands for an interdisciplinary approach. Although concepting usually precedes the building of physical prototypes in industrial design processes, in material exploration however, they can have a strong reciprocal relation. Concepts can crystallize future possibilities and inform how materials could be meaningfully utilized and developed, but likewise can the materials inspire the generation of concepts. As the concept and/or the material develop, this reciprocity may induce iterations to the process, which does not necessarily refer to attempts of solving the same problem using new solutions, but rather to changing the inspected problem itself, which is, as physicist Jukka Ketoja (personal communication, May 12, 2014) points out, quite particular for design.

Such iterative and nonlinear processes can be seen in different forms in design. Case I examines the design of a structure, which will eventually encounter iterations, as it is being refined for different applications (Figure 13.1). Probing different directions is often important at early stages of processes, including concept design. Early explorations thus often result in several concepts. The chosen concept(s) can be again refined to several more precise versions. Case II depicts how eleven concept ideas were created for nanomaterials. Although it was decided to continue the development of the Nanomaterial Helmet, a new round of research caused an iteration for further investigating the use of nanomaterials in helmet structures (Figure 13.2). The iterative approach continues throughout the design process, just at different levels of detail. This can be seen in Case III, where the mould structure and the design of the panel were changed as certain solutions did not work as wanted (Figure 13.3). Each iteration also provided different insights.

The interwoven relationship between physical prototype and concept,

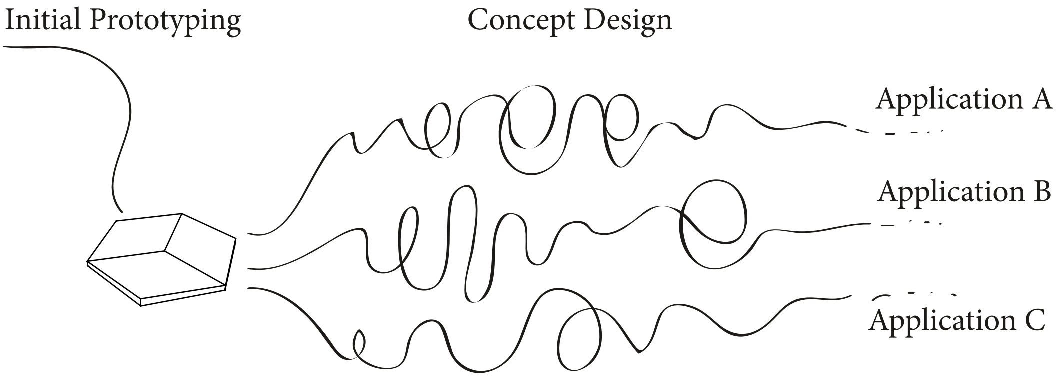


Figure 13.1 The further development of the structure in Case I depends on the application.

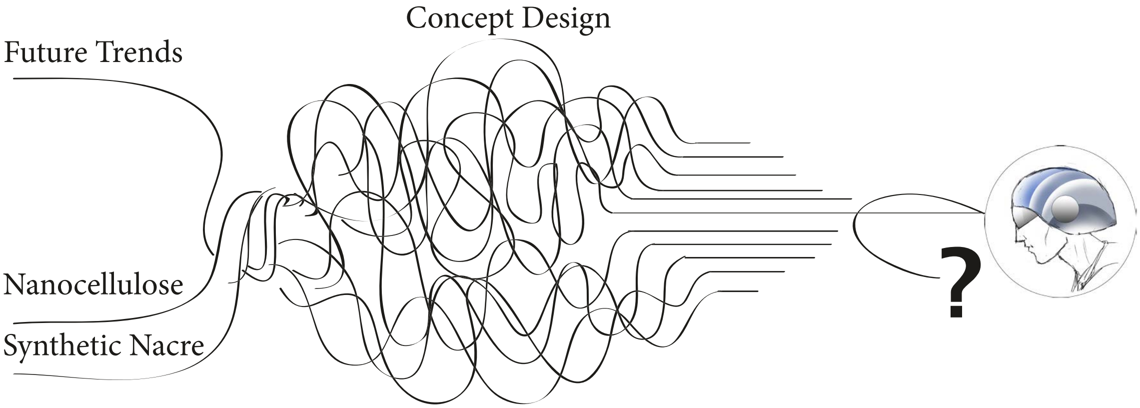


Figure 13.2 The concept design process in Case II.

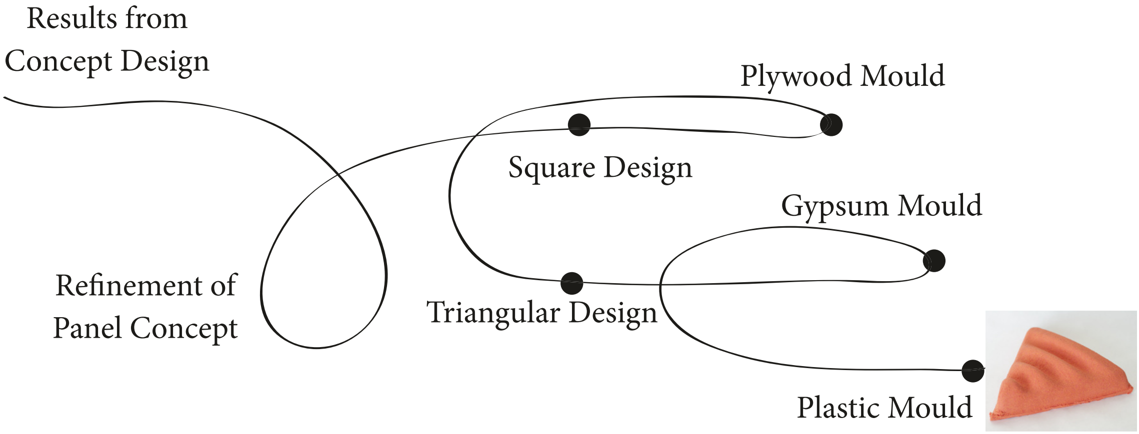


Figure 13.3 The panel prototyping process in Case III.

technology and human, material and user, and the present and the future generate a bifurcated process, which adjusts the focus through iterations. This can induce challenges, for in traditional research and development processes there is often a tendency of sticking to first solutions and chosen directions, although they may prove to be more of a burden later on in the process. Therefore constant calibration is required.

In such complicated processes, the close cooperation and communication between different specialists becomes valuable, which means that there should also be a reciprocal relationship between designers and materials scientists. As mentioned, Norman (2010) talks about the research-practice gap, with which he refers to the general difficulty of translating results from research into impact in practical applications and business. This gap can manifest itself also in processes between design and materials science, if input happens only into one direction: designers just generating superficial ideas without sufficient understanding of the materials provided by the scientists, or scientists just "handing down" materials for the designers without an understanding of the array of factors relevant for good design. Therefore, close collaboration and mutual respect between the disciplines is necessary for good results. Norman calls for "translational developers" to function as mediators between research and practice. Due to the integrative nature of design, and the ability of designers to communicate with different specialisms (Stappers, 2007), designers could take responsibility in "translational development", by using for example explorative prototyping as an approach for the translation of knowledge. This translation of knowledge could for example include the enhanced understanding of a material's potential for design, including an honest outlook on its properties: pros and cons, and a holistic view of its technical, perceptual, and associative qualities.

The tools present in industrial design practice can be used in versatile ways for the production of different explorative prototypes, which exist in various formats, levels, and stages, and which all have their purpose. In early planning and communication sketches, visualizations, and CAD models can be crucial for decision-making, and for the formation of a shared understanding, whether it be a product concept or a structural geometry. Physical prototypes are, however, particularly in the case of materials research indispensable. Physical prototyping can nevertheless entail challenges especially in cases that involve immature and new materials, which may have a limited availability, and of which knowledge regarding their technical, perceptual, and associative qualities may be limited.

In regards immature materials, Ashby and Johnson (2002) suggest material workshops between designers and scientists, which would facilitate "… direct interaction between those who make and characterize materials and those who design with them" (p. 165). These kinds of workshops could be useful platforms for early stage physical prototyping, which could support the development and awareness of new materials through simple physical experimentations. These workshops could precede the production of physical concept prototypes, such as the panel prototypes in Case III of this thesis. Different kinds of physical prototypes serving different purposes can be thus utilized along the process for the exploration of materials: for familiarizing with a new material, for cultivating a concept and its processes, and for developing a product prototype for manufacturing (Figure 13.4).

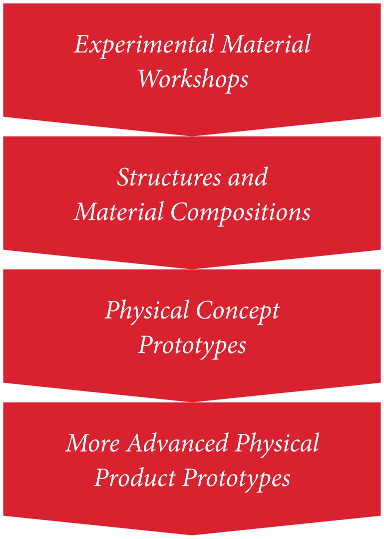


Figure 13.4 Different physical prototypes could be produced in different stages of materials research and development processes.

14 Contextualizing Knowledge Through Design

Design's methods for prototyping can be valuable for contextualizing and confronting scientific knowledge with reality (Stappers, 2007). One key goal of explorative prototypes is thus the contextualization of knowledge. The process aims at evaluating the utilization of knowledge in practice, and thus, how knowledge can be used for the creation of impact.

The case studies described in this thesis essentially also highlight this objective. Case I describes a process where structural analysis and theoretical knowledge from materials science, concerning the composition of nacre, is translated into a new context: a structure that can be 3D printed and that will hopefully inspire useful concepts. The objective is to understand whether such an interpretation of the information derived from the research of nacre could have interesting properties for applications. Case II describes how concepts can provide a "sneak peek" of potential future applications and products made possible through novel materials. Thus concepts depict the potential use of materials in a context, thereby facilitating the evaluation of potential trajectories for materials development. Case III depicts the testing of foam formed pulp in a new context of use: in curvy and colourful acoustic panels. Thereby various characteristics of foam formed pulp were examined, including also perceptual and associative qualities on top of a large amount of technical ones.

Concepts create a context for the materials to be tested in. Concepts thus function as a useful "excuse" or incentive for putting materials to test. New questions and problems emerge as materials are being examined for something specific and concrete. A specific context gives also a reference point for result evaluation.

Knowledge from such explorations can naturally be adapted into other contexts: on top of producing acoustic panels, moulding processes of foam formed pulp could be used for the production of different cushions for example. Naturally, new concepts can again bring challenges of their own to the process, but work would not have to be started form zero.

The contextualization of knowledge from materials research, or from other fields if science, brings forth essential aspects related to the design approach, which were introduced in the theoretical research of this thesis. One essential aspect is the integration of knowledge: for a material to function in a context, it must fulfil all the requirements that the context sets. The explorations in Case III that investigated the moulding, manufacturing, and dyeing of the material, were essential, but still very initial ones. For creating a feasible product out of the panel concept, also various other aspects of the material should be tested and developed, such as properties related to safety and maintenance. The integration of different knowledge is essential also for traditional engineering-oriented problem solving processes. However, on top of technical problem solving, design's integrative approach relates also to the creation of meaning, and to the experiential aspects of products, which are central in terms of design-driven innovation (Verganti, 2009). Hence the spectrum of integration is very broad in design, as it relates to a vast array of properties concerning materials' technical, perceptual, and associative characteristics, which can again be divided into numerous sub-categories. These all affect a material's usability for design, and as they are not all purely technical, engineers and scientists rarely address them. (Ashby et al., 2009; Ashby & Johnson, 2002)

14.1 Design Connects Scales, Meanings, and Relations

Design can confront and contextualize theoretical knowledge through prototyping, which enables it to contribute to the research and development of materials. Thus design can create information that contributes to research, which science usually translates into a generalizable and reproducible form. However, the knowledge design operates with is highly contextual. Generalizable data is vital in scientific research. The creation, understanding, and utilization of contextually relevant knowledge is, however, likewise important for the generation of impact-rich solutions. The basic reasoning strategies of design, abductive thinking and practical knowledge (comparable with Aristotle's phronesis), are both essentially concerned with contextual knowledge.

Abductive thinking helps to frame complex problems through themes, thus making them more approachable. The framing process essentially provides a context for the problem, through which it is inspected. This is exactly what concept design can be used for in connection with materials science: for developing possible contexts and uses, for which novel materials could be applied. This also makes up the nonlinear approach of design, as potential solutions are constructed to a possible "final form" already at the beginning of a process. An effective way of knowing what should still be developed is to create a solution that cannot yet be produced. Hence concepts provide a context, from which essential questions can be derived.

The connection between contextualization and phronesis is quite obvious: phronesis, as a form of practical knowledge, is exactly concerned, not with timeless and universal truths, but rather with knowledge related to certain occasions. Hereby we can talk about context-related knowledge. This contextual, and at times also tacit knowledge, which is derived through experience, can be associated for example with the practical knowledge of craftsmen, who learned their practice by doing, and who, as a profession, preceded the designers of today (Ashby & Johnson, 2002). From this tradition in crafts stems also the view often present in design, which emphasizes the utilization of materials' intrinsic properties, rather than forcing materials into unnatural forms. This adaptation to the natural properties of materials, as originally learned by carpenters, potters, and smiths, still affects the culture of design today. In challenges related to materials, designers often try to work around the problem, or find a new perspective to the situation by redefining the direction, which causes a creative and adaptive iteration to the process of making. This aspect of design likewise highlights its contextual knowledge, as the direction of work is adapted according to situation and material.

Adaptive learning, as well as the emphasis on context, pushes designers to look for what is essential in a given situation. Therefore, the aim of design, as of phronesis, is to not only create functional means, but to define meaningful ends as well. As Aristotle defined phronesis as essentially different from episteme and techne, it inspires to further consider the deeper differences between designerly and scientific knowledge, and how they can be compared.

It also inspires to consider how the design approach could be further utilized in connection with science. There is still a lot to be learned from explorative prototypes, as the cases in this thesis only present three examples that all relate to very early stages of research processes. How explorative prototypes are used further along the process, and for different tasks of different scale, could be an interesting subject for further investigations.

The development of system maps for different product concepts has for example also been a central objective in the DWoC project, and this has also been approached through a strong design perspective. The objective of these system maps is to depict novel business ecosystems for material applications, which portray the interconnectedness of material flows, value networks, and stakeholders operating in them. These business ecosystem concepts have been very valuable for facilitating collaboration with experts from business model development and foresight. The system maps are examples of broader scale "explorative prototypes", which are not examined in this thesis, but which could be an interesting target for further studies.

For the movement between, and the translation of different scales and perspectives are likewise questions design is concerned with, as it tries to adapt specific data from science to a holistic understanding of context. "How long is the coast of Britain?" asked Benoit Madelbrot (1967), pointing out that the answer depended on the scale of measure. Using the precision of a thousand kilometres gives a vague idea of its length, whereas measuring it with millimetre-level precision gives a hugely longer result closing the indefinable. If looking from too far, important details affecting a system might go unnoticed, but if looking from too close, the big picture of things could become blurry. Therefore, design needs to be able to shift between different scales fluently.

These issues introduce also questions concerning relation and meaning. What is the meaning of a single piece of information in the big picture? The holistic approach of design tries to put information into context, and give it meaning and relation to other things. The meaning and appearance of a colour is highly dependent on the colour it is contrasted with, and a chord in music has fully expressed itself not until it is followed by another. The same analogy applies also to how knowledge is used for sparking innovation. A holistic understanding of the factors and their relations that affect a context is thus essential.

The scientific community today faces new challenges, as it needs to concern itself increasingly with the contextualization of knowledge (Nowotny et al., 2001), which is exactly what design is concerned with. The scientific approach has its roots in what Aristotle calls episteme, a form of knowledge that is teachable and timeless. The Cartesian revolution cemented this episteme-like formal logic as a central way for the production of knowledge, setting up the scientific approach, as we know it today, as the key element in the process. (Toulmin, 2001) However in reality, there are various kinds of knowledge that are equally relevant for the production of impact. The deep understanding of phenomena provided by scientific research is indispensable, but the understanding of highly contextual factors may need a different kind of approach as support. The ability of design to change or create contexts through concept design and abductive thinking, or flexibly adapt to contextual factors through practical knowledge, have become recently valuable also in the realm of scientific research, as the science community is increasingly expected to produce impact in society. Along the lines of use-inspired basic research (Stokes, 1997), and Mode 2 research (Gibbons et al., 1994), which reflect a view on research that aim at societal impact, design can be a valuable partner through contextual understanding, and through a holistic and integrative view on innovation. Especially the collaboration between industrial design practice and materials science can thus provide fruitful results, as both essentially deal with the material world, but through diverse complementary perspectives.

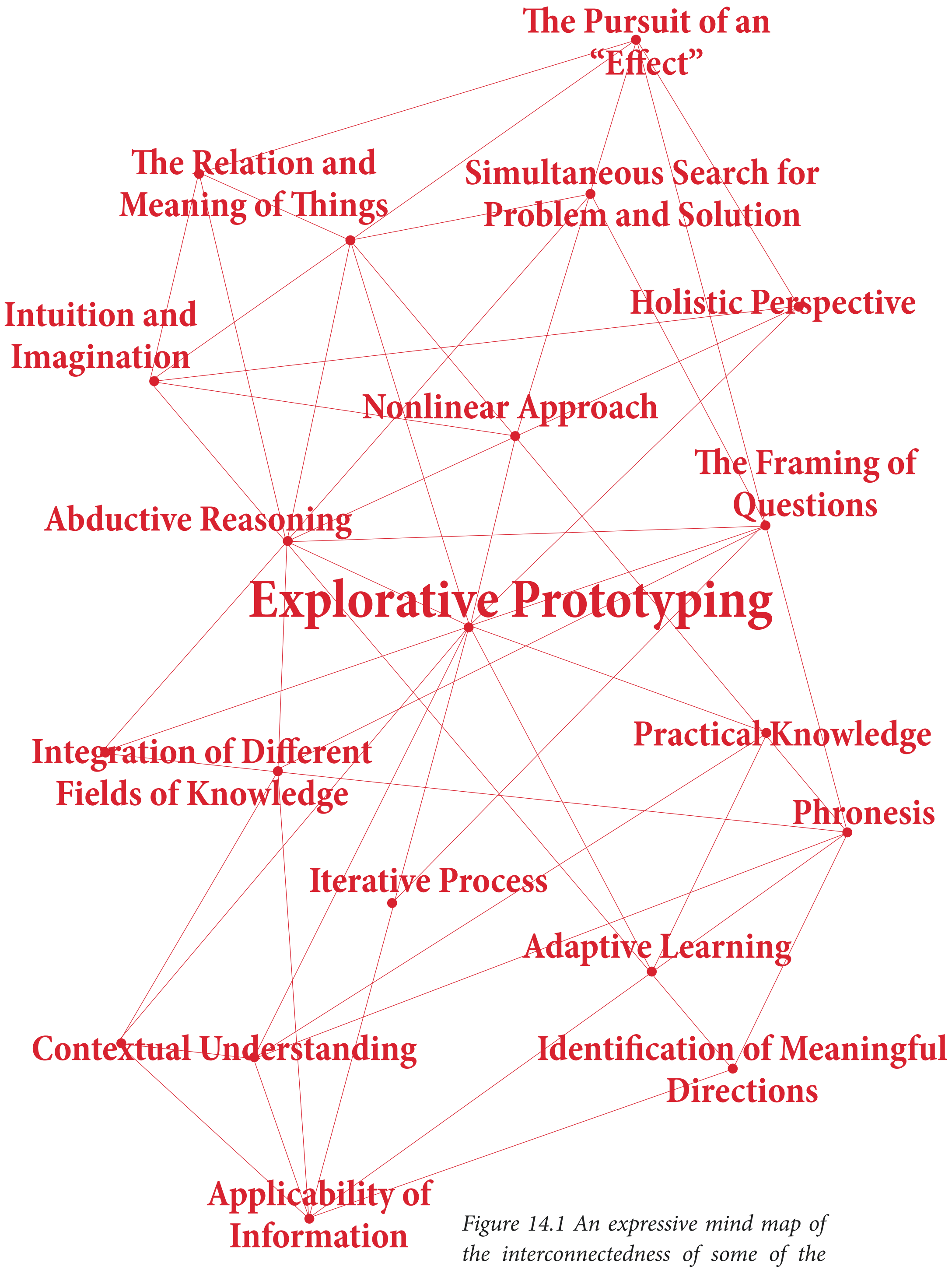


Figure 14.1 An expressive mind map of the interconnectedness of some of the topics related to explorative prototyping.

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Appendix

List of Interviews

Raimo Nikkanen	Professor, Industrial Design, Aalto University	April 15, 2013, Helsinki
Olli Ikkala	Academy Professor, Molecular Materials, Aalto University	June 11, 2013, Espoo
Sabine Seymour	Director at Fashionable Technology Lab, Parsons, CEO at Moondial Ltd.	July 2, 2013, Espoo
Juha Lipiäinen	CEO at Active Life Oy	July 26, 2013, Espoo
Juan Hinestroza	Associate Professor of Fiber Science, Cornell University	July 30, 2013, Espoo
Marco Steinberg	Strategic Designer, Founder at Snowcone and Haystack	August 9, 2013, Helsinki
Olli Ikkala	Academy Professor, Molecular Materials, Aalto University	August 12, 2013, Espoo
Harri Toivonen	Project Associate at IdeaLab CERN	August 15, 2013, Espoo
Elina Kiiski Kataja	Foresight Specialist, Sitra	August 19, 2013, Helsinki

Tiina Härkäsalmi	Research Fellow, Sustainable Design, Aalto University	September 10, 2013, Helsinki
Elina Hiltunen	Futurist, What's Next Consulting	September, 12, 2013, Espoo
Ilpo Koskinen	Professor, Department of Design, Aalto University	September 18, 2013, Helsinki
Olli Ikkala	Academy Professor, Molecular Materials, Aalto University	September 30, 2013, Espoo
Kari Hiltunen	Senior Manager at Nokia, now Microsoft	October 10, 2013, Espoo
Panu Sainio	Chief Engineer at Vehicle Engineering, Aalto University	October 15, 2013, Espoo
André Gröschel and Juhana Sorvari	Researchers, Molecular Materials, Aalto University	November 19, 2013, Espoo
Amanda Österlin La Mont et al. (Group Discussion)	MA Students in Creative Sustainability, Aalto University	December 4, 2013, Helsinki
Timo Brander	Laboratory Engineer, Aeronautical Engineering, Aalto University	December 13, 2013, Espoo
Timo Kiesi	Assistant, Materials Engineering, Aalto University	December 13, 2013, Espoo

André Gröschel	Researcher, Molecular Materials, Aalto University	December 13, 2013, Espoo
Jan Lindahl	Orthopedist, Töölö Hospital	January 20, 2014, Helsinki
Jukka Ahonen and Janne Hautsalo	Specialists in Construction and Room Acoustics	January 23, 2014, Helsinki
André Gröschel and Juhana Sorvari	Researchers, Molecular Materials, Aalto University	February 3, 2014, Espoo
Tiina Härkäsalmi	Research Fellow, Sustainable Design, Aalto University	February 21, 2014, Helsinki
Jani Lehmonen	Research Scientist, VTT	February, 24, 2014, Helsinki
Jukka Ketoja	Principal Scientist, VTT	May 12, 2014, Espoo