Material exploration and engagement

Strategies for investigating how multifunctional materials can be used as design drivers in architecture

Sascha Bohnenberger

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Material exploration and engagement

Strategies for investigating how multifunctional materials can be used as design drivers in architecture

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I hereby declare that the following PhD by Project, except where due acknowledgement has been made, is my own work and has not been submitted previously, in whole or in part, to qualify for any other academic award. The content of this thesis is the result of work that has been carried out since the official commencement date of the approved research programme. Any editorial work, paid or unpaid, carried out by a third party is acknowledged.

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Abstract

Since the early 2000s, primarily research-based projects have focused on the use of new materials such as shape-memory alloys, light-emitting diodes (LED), film-encased photovoltaic cells and thermochromic paints. These materials offer a wide range of outstanding possibilities to the construction industry through their capacity to sense and respond to external environmental stimuli. However, the advent of smart materials—multifunctional materials that are designed by chemists, physicists and biologists - pose challenges for design practices exploring such innovations.

Given the rich potential of these emerging materials and technologies for architecture, I was intrigued to know: what is necessary to introduce these materials in architecture?

In this thesis, I report on design strategies that involve extrinsic and intrinsic material properties. My research strategies included the use of digital design tools, physical computing and haptic-intuitive workflows in order to bypass a lengthy iterative design and analysis process through rapid intuitive feedback. My research demonstrates the necessity of both a digital and physical interaction with previously little- or un-used engineered advanced materials, if the use of those materials is to drive change in the overall material system. This proposition is developed and tested by practice-based research and design explorations.

Centred on the idea of material-driven design processes, my research addresses the work of architects, engineers and materials scientists and locates opportunities for working together within a trans-disciplinary environment. Having direct interaction with materials and their behaviours generates an awareness of the material possibilities that enables architects to engage with engineers and materials scientists. In considering both theoretical and practical implications, my research contributes to the discussion of multifunctional materials as they emerge and their applications within architecture.
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Terms and Keywords

Adaptive architecture

An architecture with the ability to adapt to its environment by either topology changes of the overall shape, local alterations of building components or by regulating its energy consumption autonomously to its occupation and environmental situation.

Augmented composites

Augmented composites are assembled material composites based on multifunctional materials that may incorporate additional traditional materials. They have the advantage to be controlled via digital media and are part of a digital and physical design process to encounter the possibilities of dynamic material systems.

Comfort zone

The comfort zone describes the mental framework of a person that operates only in its own known boundaries. The comfort zone is a constraint behaviour that hinders professionals and researchers to experience new insights from the outside world, which may lead to unforeseen innovative outcomes.

Constraint design models

A model that is defined by rules and limitations. The constraint can be form, function, use of materials or the material properties itself.

Design driver

A design driver enables and supports the design process. For example, materiality, functionality and theoretical theories are all design drivers that help to establish innovative solutions.

Haptic-intuitive engagement

The haptic-intuitive engagement is about physical relationships between the user and the environment. It enables to gather information intuitively through interacting with physical objects and digital environments to inform design decisions.
Material composite

Composite materials that are manufactured and engineered; or natural materials made by combining two or more materials with notably different physical or chemical properties. The material composite itself combines the properties of the individual materials to create a unique behaviour. Wood, for example, is a natural composite. Concrete, also a composite, is one of the most used materials in architecture.

Material system

A combination of materials that can incorporate composite materials and single materials. In a material system, the introduced materials are working together but not necessarily all at once. The different material components can be controlled separately to enhance or react on spatial and environmental conditions.

Material-driven design

Refers to a design process that is either inspired by or following material specificities, such as the properties and behaviour for a design outcome that are informed by the material itself.

Multi-performance criteria decision

Multi-performance criteria decision making process, whether analogue- or digital-driven, made by comparing and weighing multiple criteria—for example, analysing and comparing properties of different material products to negotiate the best suitable product for a design. This process does not necessarily lead to an optimised solution but rather defines a solution space that leads to more informed and better decisions. I refer especially to multi-criteria decision-making processes in this thesis in the realm of structural optimisation and material selection processes.

Multi-functional materials

Multi-functional materials describe the advantage to combine structural and non-structural functionalities, such as sensing, actuation, and memorising.
Rules of thumb

The term ‘rules of thumb’ refers to procedures that allow predicting the action of design decisions by approximations that are described by the rules.

Smart materials

In this thesis, the term ‘smart material’ is used to refer to its original meaning. ‘Smart materials’ and ‘smart structures’ are defining a class of materials and material systems with functional capabilities. They have built-in sensors, actuators and control mechanisms to react to external stimuli in a reversible manner.

Synergy effects

The term ‘synergy effect’ is used in this thesis to describe a bi-directional relationship between the digital and the physical. More specific it refers to the synergies that exist and can be build-up by working with digital and physical models to observe and discover material behaviour to inform a later material driven design process.
Digital Design Tools

**Arduino™**

Arduino is an open-source computational project that develops single-board microcontroller and a programming language compiler. The software environment Arduino is based on the Processing language and is utilised to develop programs that control the microcontroller capabilities.

**Firefly™**

Firefly is a Grasshopper component developed by Andy Payne and Jason Kelly Johnson since 2010. This software tool enables a direct connection between the Arduino hardware and the Grasshopper environment.

**flowL™**

FlowL is a plug-in developed by @[uto] and is, at its core, a vector field visualiser that can generate vector fields by positive and negative charged attractor points.

**Grasshopper®**

Grasshopper is a visual-programming tool developed by David Rutten at Robert McNeel & Associates. Grasshopper is a plug-in that operates within the 3D modeller Rhinoceros. While Grasshopper offers the visual control of generative algorithms and parametric modelling, it is capable of running custom designed programs that extend the functionality. Structural analysis, sound generation and the control of the Arduino microcontroller are just a few tasks that can be added and controlled within the Grasshopper tool.

**Kangaroo™**

Kangaroo is another component for Grasshopper that is developed by Daniel Piker. With Kangaroo, it is possible to simulate physical forces in real-time to study equilibrium states, motion-dependent effects and to apply optimisation algorithms.
Karamba3D™
Karamba is a structural analyses tool that is developed as a Grasshopper component by Clemens Preisinger in collaboration with Bollinger+Grohmann Schneider Engineers. Thus, structural systems can be developed in a digital design environment that is known to many architects.

Processing™
Processing is an open source programming language initiated by Ben Fry and Casey Reas, with an integrated development environment (IDE) and designed especially to support the creation of electronic arts and visual design.

Rhinoceros®
Rhinoceros (Rhinoceros) is a non-uniform rational B-spline (NURBS) 3D modeller developed by Robert McNeel & Associates. It features a scripting language called RhinoScript that is based on the Visual Basic language as well as the scripting language Rhino.

RhinoScript
Rhino’s scripting environment is called RhinoScript and is based on the Visual Basic language. RhinoScript makes it possible to automate operations in Rhino and to read and write Rhino files directly to communicate with other software platforms.

Scan&Solve™
Scan&Solve is a plug-in for Rhino and is able to compute simple structural analyses and simulation. Scan&Solve operates in regard to other structural analysis applications analysing and computing closed solid polysurfaces, the native geometry usually generated within Rhino. With this analysis tool, simulations such as deflection, stress and strain of the geometry are possible.

TouchOSC™
TouchOSC is a software environment for developing control interfaces for mobile devices. The software can send and receive digital messages over a Wi-Fi network and enables the mobile device to act as a remote control.
Material Dictionary

This section describes the discovered materials that I worked with during the research. The materials can be structured as advanced static and advanced active dynamic materials. The first category comprises materials that address particular and well-defined performance criteria. The second category represents smart materials. The discussed materials were chosen to represent the rich palette of novel materials due to their accessibility and affordability. These materials are well known, documented and have been explored in modern science for more than 50 years; nevertheless, within architecture only a few applications and case studies exist.

1. Aerogel

Aerogels are solids formed by removing the liquid from a gel through a drying process called supercritical drying, as visualised in Figure 1. The liquid is removed from the gel by applying high temperature and high pressure. The remaining porous structural skeleton is termed ‘Aerogel’. These gels are known to be the lowest density solids and one of the best solid thermal insulators. Today, this research expands into the field of nanotechnology. New drying techniques allow the production of so-called multi-walled ‘Carbon Nanotube Aerogels’ and ‘Metal Aerogels’. In this thesis, only the silica aerogel product Nanogel© is explored.

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2 Nanogel is a product name of the Cabot Company that is an expert and one of only a few companies in the world that produce Aerogel commercially.
2. Electrical Conductive Materials

Electrical conductivity can be described as the ‘product of two factors, charge density and mobility of the electrons’ of the material structure. This implies that every material is more or less conductive by either consisting of many electrons or by consisting of electrons that have a high velocity to drift, thus having a high mobility. Conductive materials have a wide use, and are used in interactive textile products to create flexible circuits and sensor devices. Materials with high conductivity can be found in a variety of products such as: anti-static foam, conductive fabrics, conductive gels, conductive paints and inks, conductive threads, wool, yarns and Velcro and thin flexible wires.

3. Photoluminescent Particles

This material is a photoluminescent nanoparticle based on strontium aluminate phosphor that has a long afterglow effect. The fine powder was developed at RMIT by a team supervised by Professor David Mainwaring. The powder particles can be embedded in paint and PVC sheeting and spun in fibres that allow the use of the

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powder for a range of different applications. The photoluminescent nanoparticles absorb light and emit this over time. The energy releasing decay can be controlled and changed. An instant re-emission of light is called fluorescence, while the delayed release is the so-called phosphorescent effect (Figure 2).

4. Shape-Memory Alloys

Shape-memory alloys (SMA) are functional materials that have the ability to change their shape without permanent deformation and can ‘remember’ their original geometry. There are several types of SMAs; in general, the most common are based on a combination of nickel and titanium. The shape-memory effect describes a phase change of the internal structure, while the material remains still as a solid. The shape change effect is ‘linked by a temperature of stress induced transformation’ of the alloy. The high-temperature phase (austenite) and the low temperature phase (martensite) define the change of the crystal structure of the SMA (Figure 3).

Figure 3: The state change effect with its several phases. (Image adapted by author Source: Jorma Ryhänen)

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7 Jorma Ryhänen, 'Biocompatibility evaluation of nickel-titanium shape memory metal alloy', (PhD thesis, University of Oulu, Faculty of Medicine, Department of Surgery, 1999)
This gives the alloy the unique properties of shape-memory and elasticity. Today, SMAs can be manufactured as wires, tubes, sheets, thin films and pre-defined shapes for specific applications.

5. Thermochromic Pigments

Leuco Dyes are composite thermochromic pigments that change colour when heat energy is applied. The composite consists of a dye (colorant), the colour developer (acid) and the solvent (Figure 4). If the temperature is below the melting point of the solvent, the colour forming components are in contact. Due to an interaction between the dye and the acid, colour is visible. If the temperature is above the melting point of the solvent, the colour forming components are separated and the colour disappears. Thermochromic dyes indicate ‘cold’ versus ‘hot’ with one simple colour change. The dye can be applied to different materials, such as paper, cotton, ceramics and plastics.\(^8\)

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## List of Interviewees

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<th>No.</th>
<th>Name</th>
<th>Date</th>
<th>Country</th>
<th>Position</th>
<th>Description</th>
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<tr>
<td>1</td>
<td>No. 1</td>
<td>02.09.2010</td>
<td>Germany</td>
<td>Professor</td>
<td>An architect with a research focus on additive fabrication technologies.</td>
</tr>
<tr>
<td>2</td>
<td>No. 2</td>
<td>07.10.2010</td>
<td>USA</td>
<td>Partner</td>
<td>An architect and researcher with a focus on and strong reputation for new material technologies; in particular, design applications for smart materials and nanotechnology.</td>
</tr>
<tr>
<td>3</td>
<td>No. 3</td>
<td>25.01.2011</td>
<td>USA</td>
<td>Partner</td>
<td>An architect of a cross-disciplinary studio with a focus on new technologies and interactive installations.</td>
</tr>
<tr>
<td>4</td>
<td>No. 4</td>
<td>26.01.2011</td>
<td>Germany</td>
<td>Project Manager</td>
<td>An architect of a cross-disciplinary studio with a focus on new materials in architecture.</td>
</tr>
<tr>
<td>5</td>
<td>No. 5</td>
<td>15.05.2011</td>
<td>USA</td>
<td>Materials Scientist</td>
<td>Material researcher with an interest in collaborating with architects and nano-engineers.</td>
</tr>
<tr>
<td>6</td>
<td>No. 6</td>
<td>07.10.2011</td>
<td>USA</td>
<td>Assistant Professor</td>
<td>Architect and researcher with a focus on material systems and fabrication technologies.</td>
</tr>
<tr>
<td>7</td>
<td>No. 7</td>
<td>13.01.2012</td>
<td>Germany</td>
<td>Researcher PhD</td>
<td>Architect and expert of smart material applications in architecture.</td>
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Introduction

Background
Research Motivation
Thesis Premise and Proposition
Research Framework
Structure of the Thesis
Introduction

The active involvement of architects at the material level becomes critical when we as architects begin to investigate new materials as they are developed by chemists and material scientists.9

1.1 Introduction

The implementation of novel materials from different disciplines in architecture has significant potential. According to the architect and researcher Thomas Schröpfer, the investigation of new materials is a challenge in architecture. Therefore, new modes of enquiry to extend the design knowledge may be needed to implement these materials in architecture. My thesis proposes the following hypothesis: exploring material characteristics intuitively, by directly experimenting with the material in combination with parametric and physical computation techniques in the early design process, establishes a new level of knowledge on the topic of novel materials in architecture. Based on new potentials for digital computation and ‘haptic-intuitive’10 interactions with materials, I will demonstrate how to gain the knowledge necessary to be able to design with dynamic materials.

During the research study, I worked in the field of practice at the German structural engineering company Bollinger+Grohmann Ingenieure (B+G) in order to become familiar with the constraints of actual projects dealing with the integration of new materials. Experimenting physically with state-changing materials in workshops relates to the educational aspects that Rice describes. The different approaches that I am utilising to explore material strategies are located in the realm of practice and academia to support the developed thesis.

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9 Thomas Schröpfer, Erwin Viray, and James Carpenter, Material Design: Informing Architecture by Materiality (Basel, Switzerland: Birkhauser Verlag, 2010), 16.

10 The haptic-intuitive engagement is explained in section ‘Terms and Keywords’ on page 14 and will be presented in Chapter 6.
1.2 Background

Historically, the development of new materials has always been an inspiration for innovation in design-oriented disciplines, and architecture in particular. The invention and use of industrial materials, such as steel, glass and concrete in architecture has had a significant influence in regard to changing forms, constructions, typologies and design philosophy.\textsuperscript{11,12}

Today, so-called ‘smart materials’\textsuperscript{13} seem to have as promising an influence on architecture as the materials listed in the previous section. With their ability to change shape, density or colour over time, they offer new potentials for an adaptive architecture. The major advantage of these materials is their ability to respond to the environment in a precise way over time. Aside from the ubiquitous problems of cost and safety regulation issues, the state-changing material’s behaviour is also one of the most challenging constraints to their integration into the design process. Static modelling techniques and analysis tools currently used in architectural design are not appropriate to understand the dependencies among stimuli, material change and architectural quality. Therefore, it remains a challenge to integrate these materials within architecture.

Several requirements have to be fulfilled to be able to work with responsive materials. They need to be understood conceptually by introducing them, for example, both in education and the early design process.\textsuperscript{14} There seems to be also a high demand for new modes of collaboration among materials scientists, engineers and architects as Blaine Brownell argues.\textsuperscript{15}

\vspace{1cm}


\textsuperscript{13} This keyword and related expressions are found in the section: Terms and Keywords on page 14.

\textsuperscript{14} Michelle Addington and Daniel Schodek, \textit{Smart Materials and Technologies in Architecture} (Amsterdam: Elsevier, 2005).

A ‘material exploration’, based on different novel materials, is conducted and the evolving synergies between material thinking and design strategies are discussed in this thesis. In this thesis, I define the material exploration as a method to investigate material properties as a design driver in the early stage design process.

1.3 Research Motivation

During the era of Modernism and the Bauhaus movement, new material thinking was incorporated into the architectural design process. From early in my career, I have been both fascinated and influenced by the ideology of the Bauhaus, which was based on the concept of understanding material properties, performance and behaviour. This conceptual approach to design, inspired by materials and design rationalisation through material investigation, was revived in the late 1990s. It is exemplified through the work of Herzog & de Meuron, Peter Zumthor, Shigeru Ban and others. A combination of computation and design tools leads to the conceptual framework of a new knowledge and understanding of well-established materials. Today, many new materials, often with dynamic properties, have emerged. However, there is a notable slow progress of a material uptake in the building industry. This relates to the study and practice of architecture and construction of buildings and architect and material expert Blain Brownell explains that the building industry has largely focused on a few core materials while ignoring the better part of a lot of the innovative materials and products.

Prior to my PhD research, I investigated different materials, such as weathering steel, glass-fibre reinforced composites and clay. The engagement with the material itself and hands-on experiments were important exploration pathways leading to the proposed design take-up (Figure 1.1).

---


18 Commonly known as ‘Corten steel’, this class of alloys forms a protective layer under the influence of the weather.
Figure 1.1 Example of my diploma work named All-terrain unit for shelter - A.T.U.S; the unit is inspired and design by the IKEA concept. One tool and two people can assemble the lightweight glass-fibre reinforced panels within a view hours. Left Image: Construction Instructions; Right Image: Section, floor plan and elevation of a 4-uni shelter (image source: author)

At that time, I was continually searching for new materials and possible architectural design strategies, and I was especially inspired by the work published on smart materials. The first attempts of J. Mayer H. in 2000, using temperature sensitive colour for interior architecture,19 and the work described by Axel Ritter20 in 2007, greatly influenced my research, further encouraging my interest in materials that are responsive to external environmental stimuli. I am interested in the notion that materials can replace mechanically driven façade systems with comparable properties to human skin.

When I started working at B+G, my interest in materials in the context of design decisions and constraints was further increased. B+G believe that the development of novel structural solutions that optimise the design in terms of costs and structural performance also optimise the design in terms of spatial conditions.21 To achieve this

19 J. Mayer H., THERMO.BENCH (Berlin: Pixelpark, 2000). The project is a pink waiting bench with temperature-sensitive paint that investigated new ways of engagement with visitors and their environment. The result is a sensitive surface that responds and traces human presence.


approach, the office operates and communicates with innovative analysis and design tools on an interdisciplinary level between engineers and architects. These design tools and the integration of the architectural design procedures into the structural design exploration inspired me to investigate digital analysis and design tools within novel materials.

Coming from the environment of a structural engineering company with a focus on innovative solutions in architecture, and my personal interest in new materials, led me to ask: Why is it still unusual for architects to work with multifunctional materials?

I formulated these three distinct questions, which helped me to locate the field of research:

1. **How can we attain and implement intrinsic material properties in architecture?**
2. **What is required in new material system knowledge in architecture?**
3. **How can we design with such complex materials?**

The experience gained at the office and my personal interest inspired me to investigate challenges in modern materiality and new ways of material thinking in architecture. It occurred to me that the on-going development of new materials demands a new intensive workflow and a different set of design protocols than used for conventional construction. Further, it is the aim of my research to access the viability in the prospects of a haptic-intuitive engagement that leads to a better understanding of the chosen materials.

### 1.4 Thesis Premise and Proposition

Since the early 1970s, a demand for dynamic and responsive architecture has become more prevalent. The aim is to have an optimised performance based on the usage of novel materials. These material systems were imagined either to be controlled via an underlying computational logic or to simply react to the environment. With these ideas of a flexible and intelligent architecture, as described by the architects Nicolas
Negroponte, Wolfgang Hilbertz and Mike Davies, a special interest in computational materials and their predictable advantages in architecture were introduced. With new computational sophistication, they seem more applicable than ever before; this evidence can be confirmed by the advent of a rising interest in the last five years. Although many materials are already able to respond to external stimuli and thereby provide a dynamic functionality, they are still not easily exploited within architecture. The physicist and science writer Philip Ball explains this issue historically and claims:

In the past, a change in a material’s properties (its elasticity, say, or its volume) in response to a change in the environment was generally seen as a potential problem, as a thing to be avoided.

Today, with advances in material science, we can observe a trend towards the understanding of dynamic relations between materials, environment and design.

Materials scientist George Jeronimidis, for example, refers to the advances of dynamic biological systems that can alter the material stiffness according to external forces. This act of adapting has recently been made possible by a spatial organisation of material layers, similar to muscle systems. The understanding of the dynamic alteration of a material is helping to develop similar working engineering solutions—for example, for vibration control of a structure. However, currently we still face the challenge to articulate and design responsive architecture and diversity according to environmental stimuli based on the characteristics of smart materials. Michelle Addington and Daniel Schodek argue in their book ‘Smart Materials in Architecture and Design’ that the

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25 The field of material computation research in architecture can be found at the work of Neri Oxman, Norbert Palz, Mette Ramsgard Thomsen, Michael Fox and others.


27 Biomimicry approaches and Biomimesis are the design strategies of learning from nature and adapting the solutions that nature is offering to develop man-made systems that operate in similar manner.

arrival of these new materials requires a new level of understanding of their physical constraints as design strategies.\textsuperscript{29}

The dynamic relation between the action of a material and its external stimuli might be seen as a design space. It might also be seen as the material-driven design concept\textsuperscript{30} extended through the introduction of smart materials. Can we contribute to a new freedom, drive and mood to work? Can we also investigate and design with unknown materials based on the engagement of physical material exploration?

I wanted to investigate whether designing with material properties and the specific constraints that come with this approach would change the perception of materiality in architecture. The architectural solutions are not only materially oriented but are also influenced by the properties of the dynamic materials. The intention is not to advance a purely scientific approach of optimising material properties; rather, it is an approach to develop new ways of understanding material intelligence to enhance design concepts, which might be supported by parametric tools.

To contribute and expand the notion of material-driven design, this thesis focuses on the following three topics:

1. Material thinking
2. Material representation
3. Interdisciplinary communication

These topics are identified as key approaches for architects to engage with novel materials via design tools in which the intrinsic material properties are explicitly included as part of an architectural design exploration. I will expand the topics in the following sections.

\textsuperscript{29} Addington and Schodek, \textit{Smart Materials and Technologies in Architecture}.

\textsuperscript{30} The notion of a material-driven design can be explained as the design process and intention to define the constraints that accompany the material selection. Those constraints are consequences of the properties, the behaviour and the economic and ecological factors and allow the influence of the design process. The resulting design can either be influenced by mechanical properties of a material or its aesthetic properties.
Material Thinking

Michelle Addington describes the differences between architects and material science as a difference in material thinking, and explains:

*Designers and architects think in a more product-orientated way since they are interested in already existing applications rather than being interested in the material behaviour itself.*

Further, she argues that the complexity of smart materials that are reactive increases the difficulties in incorporating them into the design process. Today’s digital tools and technologies are connecting the conceptual sketch with the realisation of a design, and support material-oriented design decisions. During my time in practice, I realised that with the improvement of these tools, we have the ability to create a range of design investigations, therefore discovering constraints and problems in an early decision process.

Through the development and evolution of digital design and fabrication techniques, the relationship between architects and materials is currently expanding. Lisa Iwamoto describes this phenomenon as a wealth for architectural innovation and invention that supports a design revolution in which ‘the architectural project is a form of applied design research’.

Consequently, a new understanding of material properties based on digital design and fabrication tools is emerging. However, the incorporation and understanding of specific material characteristics in the design process remain challenging.

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32 Ibid.


Research institutes—like the Institute for Computational Design (ICD) at Stuttgart that is led by Achim Menges, and the Centre for Information Technology in Architecture (CITA) headed by Mette Ramsgard Thomsen in Copenhagen—are investigating this approach extensively.

Nevertheless, like Addington, Schodek and Brownell suggest a new layer of knowledge in respect to the dynamic features of novel materials has to be investigated to extend the knowledge of possible future construction materials. This thesis will help establish future design protocols as well as necessary changes to design practice. Based on digital computation and haptic-intuitive interactions with materials, material knowledge is shifting from a geometry based to a material-driven design approach. The awareness of the material characteristics can offer new potentials to act as design drivers for architectural ideas that lead not only to a new knowledge of material properties, but also to new design strategies based on the dynamic feedback of the material itself.

**Material Representation**

The representation of materials currently remains static with respect to their functionality, and is one of many concerns when it comes to understand the dynamic relationships between material and environment. Material behaviour can be visualised through parametric design and advanced analysis and simulation tools up to a certain point.

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35 The ICD is investigating computational design and computer-aided manufacturing processes in architecture. The interrelation of computational processes in the fields of design, engineering, planning and construction is of interest and leads to the production of performative material and building systems. ‘ICD Institute for Computational Design Research and Education Profile’, accessed January 6, 2012, http://icd.uni-stuttgart.de/?p=3343.

36 CITA is an institute exploring the emergent intersections between architecture and digital technologies through examining how architecture is influenced by new digital design- and production tools, as well as the digital practices that are informing our societies culturally, socially and technologically. ‘CITA: Center for Information Technology and Architecture’, accessed January 6, 2010, http://cita.karch.dk/.

37 Addington and Schodek, *Smart Materials and Technologies in Architecture*.

38 Brownell, *Material Ecologies in Architecture*.

If we incorporate the potential of engineering software, the results are likely to reveal performance criteria that may influence architectural design decisions.

The dynamic visualisation of data greatly increases the understanding of the scenario of interest and helps communication to the rest of the design team.⁴⁰

A critical analysis of environmental effects and design questions is needed to frame and represent the constraints for a successful implementation of new materials in early design. Robert Aish, for example, describes the design process as ‘making inspired decisions with incomplete information’ and is something that ‘explains the necessity of a counter balance of our intuition’ with a well-developed sense of premeditation. He asks further the question: ‘How can we augment the cognitive processes?’ ⁴¹

With this in mind I asked myself what do we need in order to work with dynamic materials, do need to consider new ways of representation to visualise the effects of a design decision that occurs with the use of these new materials?

My research assesses the opportunity of creating real-time responsive digital and physical techniques based on parametric and physical computational tools. This approach requires the simplification of the material behaviour, which is based on the identification of the material and design constraints that are underlying each project. These approaches may lead to a better understanding of new materials, helping inform design decisions at an early stage.

### Interdisciplinary Communication

The loss of responsibility means that architecture must cope with a variety of disciplines from different backgrounds. Kieran and Timberlake indicate:

By allowing, architecture to become reduced to the current degree and by relinquishing responsibility for assembly, product development, and materials science to specialists,

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⁴¹ Robert Aish, 'From Intuition to Precision', in *eCAADe 23*, 2005, 10–14.
the architect has allowed the means and methods of building to move outside the sphere of architecture.\footnote{Stephen Kieran and James Timberlake, \textit{Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction} (New York: McGraw-Hill, 2004).}

In particular, communication between materials scientists and architects poses two major problems. They have not only a different body of language, but also different foci of interest. Materials scientist Michael F. Ashby and designer Kara Johnson explain:

\begin{quote}
Bridging this gap in information and methods is not simple. The technical terms used by engineers are not the normal language of industrial designers—indeed they may find them meaningless. Industrial designers, on the other hand, express their ideas and describe materials in ways that, to the engineer, sometimes seem bewilderingly vague and qualitative.\footnote{Michael F. Ashby and Kara Johnson, \textit{Materials and Design: The Art and Science of Material Selection in Product Design} (Sted: Elsevier Science & Technology, 2010).}
\end{quote}

However, as architect José Daveiga and materials scientist Paulo Ferreira explained in 2005:

\begin{quote}
The material capabilities now offered by the forefront of materials science will require a new kind of understanding and cooperation between disciplines.\footnote{José Daveiga and Paulo Ferreira, 'Smart and Nano Materials in Architecture', in \textit{ACADIA 05 Smart Architecture}, 2005: 58–67.}
\end{quote}

Closer collaborations between the design and science disciplines will lead to synergies between the two that might create an alternative, sustainable and aesthetically improved environment. Thus, the research takes all three fields—architecture, engineering and material science—into account and is located in the cross section of these fields.

\section*{1.5 Research Framework}

This thesis examines the different possibilities of a ‘material exploration’ strategy, which I observed and analysed within the theoretical framework and practice. I undertook my research within RMIT University’s Spatial Information Architecture Laboratory (SIAL),
in collaboration with B+G. My proposition is developed and tested by a triangulation of research methods. The research methods include: embedded practice-based research at B+G, qualitative data gathering through design experiments, case studies, workshops and a quantitative analysis of the research question based on an online survey, and formulating and demonstrating the research question. Through connecting the practice with the academic field of enquiry, I was able to gain an understanding of material thinking in both worlds. This work formulated the basis of my interest in discovering more on how architects, engineers and scientists are communicating and what is required to introduce new building techniques and materials to architecture. These insights are represented through an observer perspective and example projects will be discussed in detail in Chapter 4.

Figure 1.2 The research field is identified as the cross product of materials science, architecture and engineering (Image Source: Author)

45 According to Wendy Olsen, the mixing of methodologies is a more profound form of triangulation and tends to support interdisciplinary research. Wendy Olsen, 'Triangulation in Social Research: Qualitative and Quantitative Methods Can Really Be Mixed', in Developments in Sociology (Causeway Press, 2004). Triangulation will be explained in more detail in the second chapter, Methodology.

46 The ‘Embedded Research within Architectural Practice Programme’ is a particular programme developed at the Spatial Information Architecture Laboratory (SIAL), at the Royal Melbourne Institute of Technology (RMIT University). It is explained in more detail in Chapter 2: Methodology.
The following section details how my research is structured, by defining the issues of material-driven design via literature, and how the hypothesis is tested using experiments and case studies.

1.6 Structure of the Thesis

To examine the hypothesis—that a new modus operandi of representation will allow us to gain a new level of material thinking and communication through the engagement with smart materials and so be able to challenge and deliver innovative architectural design outcomes—I have structured my thesis in the following manner.

Chapter 2: Approach and Methodology details the embedded practice research programme that I was part of at the German structural engineering company B+G, the practice partner for the research project. I outline the concept of the embedded practice and discuss the importance of the reflection of the practice as the real-world factor of my research investigation. Further, I introduce the research tools, and the quantitative and qualitative data that were collected and analysed. I outline the concepts of experimentation and workshops with novel materials, different software tools and the opportunities for collaboration between material science and architecture. In doing so, I refer to the practice-based case studies combined with the academia-oriented workshops and explain why the collection of quantitative and qualitative data is of high importance.

In Chapter 3: Effects of Materials in Architecture, I explore the history of material development and the effects that materials have had on architecture at different stages. I explain the changes in design caused by material exploration and technology improvements. In this chapter, I also indicate how new materials, new design methods and social concepts were introduced in architecture. Starting with the industrial revolution, the chapter describes the emerging world of composite materials in the 1960s and society’s growing quest for a more sustainable world. In the last sections, I explain the current relationship between design strategies, material engagement and fabrication and outline novel materials and their properties. This chapter frames the historical context for my research and explain the importance of materials in architecture as a design driver and driver for innovation.

Within Chapter 4: Architecture and Materials Science Synergies, I emphasise the importance of the historical split between architects, engineers and materials scientists to interpret the differences and commonalities of their languages and design ideas. The chapter
introduces selection tools to find the right materials that are available and present methods of how the disciplines are engaging with materials and communication among each other. The one-on-one interviews that I conducted are complementary to the literature review and provide further evidence that a change and enhancement of our knowledge is necessary if new materials enter the realm of architecture.

Chapter 5: *Observing Material Decisions in Daily Work* examines the daily work in the practice and the early design challenges. The design intentions and the constraints in the building environment—such as smooth surfaces, strong and thin structural elements and ways to maintain or reduce energy consumption—are everyday challenges for architects and engineers. When it comes to optimising the performance of a building, we can try to enhance the mechanical and electrical devices or replace materials with those better for the overall achievement of a project. Architects have a significant repertoire of materials available, especially for the interior of a building.

In my experiences, gained at the practice, the introduction of alien materials or the development of new material concepts poses challenges in order to speed up the design process and ‘make things happen’. On the basis of two project examples in which I was involved, I present problem definitions and solution spaces for analysing and comparing material systems as well as an integrative design approach based on the use of simulation and analysis techniques.

As an architect in an engineering company, I saw significant potential in introducing a third category as part of the design process: the materials scientist or expert to revolutionise the acquaintance with new materials. Therefore, the aim is to indicate the ‘comfort zone problem’ and what we need in order to improve our communication and representation techniques to frame constraints and become familiar with the ‘wicked problems’ of a new design challenge. These questions were addressed in an online survey and the outcome will be presented and discussed. Further, with the help of the online survey, I provide a careful analysis of the triangulated parties: architects,

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47 The comfort zone problem is explained in more detail in the section ‘Terms and Keywords’ on page 14.

48 According to Richard Buchanan, a wicked problem is the task for designers to conceive and plan what does not yet exist before the final result is known. Richard Buchanan, ‘Wicked Problems in Design Thinking’, *Design Issues* 8, no. 2 (1992): 5–21.
engineers and materials scientists. One outcome of the analysis highlights possible solutions that can provide a better understanding of novel material properties.

Chapter 6: *Material Explorations* presents design procedures in order to create a better understanding of novel materials based on the idea of material explorations. *Material Explorations* can be utilised either by a theoretical engagement based on data sheets and precedents like it is usually the case in practice or by a direct engagement with the materials itself. The first strategy was conducted through the case study of the ‘SmArt Architecture’ course at the University of Kassel conducted in 2010 and discusses materials as design drivers. The practical and direct approach seeks easy-to-use representation and design techniques that help to increase the knowledge of novel materials from a design perspective. A design project in collaboration with materials scientist David Mainwaring is explained and helps to locate existing limitations when it comes to a ‘first contact’ with a novel material from the design point of view. The findings of the first experiments lead to the development of design strategies based on parametric modelling and physical computation that were later tested in a series of workshops. The outcomes and the synergies of practice and academic research, and the social and physical engagement with the materials are presented.

Chapter 7: *Discussion and Conclusion* summarises the potential of a novel engagement with intricate materials in architecture and the possibilities offered by gaining a better knowledge based on trans-material design explorations. In the chapter, I align the outcomes of the case studies, the survey and the practice observations with recent activities and projects in the field of a material driven design approach in architecture in respect to multifunctional materials. The results and further investigations and future research proposals are outlined and framed to stimulate the future discussion of novel materials within architecture.
Approach and Methodology

Embedded Practice Researcher Domain

Bollinger+Grohmann Ingenieure as Practice Research Domain

Material Thinking at Bollinger+Grohmann Ingenieure

Material Representation in Practice

Communication in the Office

Practice-Based Research

Interviews

Online Survey

Workshops

Design Explorations
Approach and Methodology

It became apparent that even those architects at the cutting edge of design and technological innovation are generally, by virtue of their size, more engaged in pushing manufacturers to advance their thinking than in doing direct research themselves ...⁴⁹

2.1 Introduction

In the previous chapter, I introduced the three approaches to this investigation: practice-based research, qualitative and quantitative data gathering. The interweaving of these approaches within the project work allows the identification of questions of concern in practice and education, as well as solutions. In the above quote, Paul Finch discusses the ‘common’ way architecture encounters new technologies and materials by involving manufacturers to do the research for architects. In this chapter, I explain the methodological approach that I undertook as architect within academic research to provide a clear understanding of the research design.

In section 2.1, I present the concept of ‘Embedded Research within Architectural Practice’,⁵⁰ followed in Section 2.2 by an introduction to the office where my research was located. In this section, I outline the goals and philosophy of the practice because they have influenced my investigations. Section 2.3 introduces the process of triangulation. I explain its role in developing the conceptual framework and how the areas of practice and university-based research can be drawn together. Further, I will introduce the quantitative and qualitative research tools that I utilised to investigate the research question.

⁴⁹ Paul Finch, 'The Problem of Architectural Research', 2005

⁵⁰ This academic collaboration has been made possible through a postgraduate scholarship from the Australian Postgraduate Award Industry (APAI), according to the Australian Government Australian Research Council the Australian Postdoctoral Fellowships (Industry). They give support under the umbrella of the Linkage Projects scheme, which encourages postdoctoral researchers to engage in industry-oriented research training and enables the researcher to pursue internationally competitive research opportunities in collaboration with industry.
2.2 The Domain of Embedded Practice Research

This research has been undertaken within the ‘Embedded Research within Architectural Practice Programme’ that was established in 2005 at SIAL, RMIT University. The goal of the programme is to help bridge the research gap between universities and practices. The key concerns of the programme are to:

- Investigate routes to design practice innovation in different practice contexts;
- Create a better understanding of the factors that lead to change and innovation in architectural practice;
- Initiate a forum composed of key members of each of the participating practices for dialogue leading to new areas of research and development in the context of the construction sector.

By addressing these topics, the programme investigates linkages between the worlds of practice and academia. Bridges across this gap are of great importance. Garrick and Rhodes have argued that, for a multi-skilled working environment, an education is mandatory to combine the world of academic research and practice. Here, academia offers the potential foundation for experiments and reflections that are usually difficult to implement in a practice-oriented working environment.

Snow described the existing gap between practice and science as follows:

*Pure scientists have by and large been dim-witted about engineers and applied science. They couldn’t get interested. They wouldn’t recognise that many of the problems were as intellectually exacting as pure problems and that many of the solutions were as satisfying and beautiful … We prided ourselves that the science we were doing could not, in any conceivable circumstances, have any practical use.*

I argue that my research has only been possible because an overlap does exist between material science and design-oriented practice but which are usually not immediately

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apparent. The exploration of this productive territory has only been possible through the approach of an embedded practice research.

2.3 Bollinger+Grohmann Ingenieure as Practice Research Domain

The practice in which I have been embedded is B+G. Founded by Klaus Bollinger and Manfred Grohmann in 1985, B+G is a multidisciplinary practice that has established a culture of close collaboration with architects and artists. With five offices based in Europe and Australia, B+G has over 100 employees and covers the disciplines of sustainable design, façade and structural engineering and architecture. B+G describes itself as follows:

*Design and building is teamwork of the architect and engineer. This cooperation already begins with the design. The integral design process leads to an aesthetic solution and is the basis for a high quality economic building. Through an early and comprehensive collaboration, innovative approaches can be developed.*

*Our scope of work includes building structures, façade design and building performance for commercial, retail and exhibition facilities as well as classic civil engineering structures such as bridges, roofs and towers.*

During my time as embedded researcher, I was part of B+G’s performativeBuildingGroup (pBG) at Frankfurt in Main, Germany. The pBG, which has existed since 2009, operates at the interface between architecture and structural design. To support a close collaboration between architects and engineers from design to construction, this division is present at every B+G office and is both task oriented and project based. Currently, the group in Germany consists of six employees. There is a versatile expertise, with focuses on form finding, optimisation of structures and materials, algorithmic geometry generation, developing evolutionary algorithms for structures, linking analysis with synthesis, multi-criteria-design and geometry generation for computer-aided fabrication. Within this group, architects and engineers work together on projects, designing structural systems and researching material applications on a day-to-day basis.

54 [http://www.bollinger-grohmann.de/](http://www.bollinger-grohmann.de/)
Material Thinking at Bollinger+Grohmann Ingenieure

B+G has developed a strong and on-going interest in innovative construction materials and manufacturing techniques to push the boundaries of architecture in new directions. In the office, I observed that materials have been applied to create lightweight structures, such as the ‘Roof for the Zweites Deutsches Fernsehen (ZDF) Televising Garden’ by Albert Speer und Partner (AS&P) in 1997 and architectural landscapes like the ‘École Polytechnique Fédérale de Lausanne (EPFL) Rolex Learning Centre’ by SANAA in 2010 (Figure 2.1).

![Figure 2.1: EPFL Rolex Learning Centre by SANNA. (Photo by: davidpc_ Available under the Attribution- NonCommercial-ShareAlike 2.0 Generic)](image)

Without the awareness of the specific properties of each of the applied materials, these projects would not have been executed in the way they have been. Each material was the driving force behind the architectural design and the structural solution. Further, the investigation of novel materials, like glass-fibre reinforced composites introduced at the ‘D-Tower Project’ by NOX Architects (Figure 2.2), lightweight membrane systems to design façade systems, as seen at the National Library of King Fahad by Gerber Architekten (2004) and ultra-high performance concrete (UHPC), is a field of interest to match the design skills and engineering knowledge of a company.

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In all these projects, B+G has used computational analysis tools and computer-aided manufacturing (CAM)\textsuperscript{56} tools to extend its knowledge of how to effectively deploy material properties. These projects stand as a series of novel engagements with materials applied to architecture and construction.

Material Representation in Practice

The representation of material behaviour according to applied forces on a structural system is one important tool to understand the complex dependencies and reactions of a structural design. One way to solve the numerical analysis and calculation of the displacements at each node and the stresses within each element of a structural system is called finite element (FE) analysis.\textsuperscript{57} This computational method visualises and represents the inherent forces and constraints, the relevant information about displacements, bending moments, stress and other related forces via ‘force diagrams’. The analysis model is calculated and represented by an idealised abstraction of the

\textsuperscript{56} CAM is commonly referred to as the use of computer software to control machine tools and related machinery in the manufacturing of work pieces.

physical reality of a structural system. Physical elements that are not relevant to the aimed structural analysis can be filtered to achieve the degree of abstraction.58

Typically, a simple line/node model represents linear elements such as beams. Walls, slabs and spatial complex surfaces are often represented by single subdivided surfaces. Aside from the FE-analysis information gathered to understand the performance of the structure, detailed annotated plans (connection details, reinforcement drawings or position plans) contain information about the material system (class of concrete or steel, dimensions or reinforcement direction) and help to communicate the material-driven ideas (Figure 2.3). Another technique is the use of false colour plots and spreadsheets to express physical properties such as heat transfer or energy consumption.

![Figure 2.3: Visualization of a bridge structure and adjacent to this the corresponded FEA-model that describes the beams, columns, connection nodes and the intersection of each element. (Image source: Bollinger+Grohmann Ingenieure)](image)

**Communication in the Office**

With each project, the office attempts to establish an early engagement with the involved disciplines. Depending on the stage and complexity of the project, multiple meetings per week, or at least weekly meetings, help to redefine the tasks for each member of the planning team. I experienced that the internal communication process is based on the use of mainly digital tools to document a project completely in 3D. Within

this approach, parametric modelling and 3D structural analysis are key features to provide detailed documents for the construction phase of a project.

The described representation and communication techniques are the common tools used to enter into a dialogue with professionals from other disciplines to discuss and understand the designed structural system and the choice of materials. Gann and Salter argue that engineers and architects have developed a different set of languages, based on the specialisation of each discipline, which hinders knowledge transfer and communication (Figure 2.4).

![Figure 2.4: Descriptive drawing to communicate the different membrane shapes of a façade system with additional information about the warp stress and the load conditions of the membranes. (Image source: Bollinger+Grohmann Ingenieure)](image)

### 2.4 Triangulated Research Method

The field of smart materials in architecture is very versatile and can be approached from various directions such as purely design driven, theoretically or technically. In order to tackle a subject with such depth and breadth, I built the analytical conceptual framework upon triangulation. According to Olsen:

> In social science, triangulation is defined as the mixing of data or methods so that diverse viewpoints or standpoints cast light upon a topic.

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The research methods draw together observation and action in the field of practice, the collection of numerical data based on an online survey and of empirical data based on interviews and workshops. Greene describes the purpose of triangulating from multiple sources and perspectives\textsuperscript{61} with five justifications that were extended later by the educational researcher Katrin Niglas\textsuperscript{62} in more detail.\textsuperscript{63} I refer to triangulation by the following three aspects as the most relevant ones within my research:

- Completeness: a more complete picture if both quantitative and qualitative data can be generated
- Sampling: the aim to facilitate the sampling of respondents or cases
- Confirm and Discover: using qualitative data to articulate a hypothesis and to test it by using quantitative research.

Each of the multiple sources drawn upon and generated by the research represents a specific perspective, and highlights particular aspects of the problem (Figure 2.5).


\textsuperscript{62} Katrin Niglas, 'The Combined Use of Qualitative and Quantitative Methods in Educational Research' (Dissertation on Social Sciences, Tallinn Pedagogical University, 2004).

\textsuperscript{63} Alan Bryman, 'Integrating Quantitative and Qualitative Research: How Is It Done?', \textit{Qualitative Research} 6, no. 1 (February 2006): 97–113.
Figure 2.5 illustrates the Triangulated Research. Qualitative, quantitative and embedded research is conducted separately, and the results inform and reflect on each other to create a holistic research method. (Source: Author)

The quantitative data collection was an important tool that allowed me to become aware of the bigger picture of how different disciplines think of new materials, and I conducted this phase of research through an online survey. The survey on its own can be questioned as an ‘overly generalised interpretation’ as C. C. Ragin states, but in combination with qualitative sources confirmation and discoveries are envisaged. In this way, Fielding and Fielding suggest, the use of triangulation is not intended to lead to additional validity but should help to support the research with a deeper understanding of the problem.

In architectural practice, design and communication knowledge is based on a repertoire of cases. These cases are either personal experiences or model cases and highlight

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quantitative or qualitative discoveries, as described by Rolf Johansson. Thus, the architects Linda Groat and David Wang argue, the triangulation of qualitative and quantitative data is a common method to deliver new insights into architectural practice.

The research has been undertaken within three years, for two of which I was fully embedded in the project work at B+G. The last year of the research was dedicated to experiments and workshops. In the following section, I explain the different research methods in more detail to give the reader a deeper understanding of the different approaches adopted (Figure 2.6).

![Figure 2.6: Research approach and time line throughout the years of candidature. The figure shows the bridging elements between embedded practice and academic research. Every research element is connected and informs the following (image source: author)](image)

**Literature Review**

The literature review is in its essence presented and discussed in the background chapters Chapter 3 (*Material Development and its Effect on Architecture*) and in Chapter 4 (*Architecture and Materials Science Synergies*). Within these chapters, I present the main body of literature related to my work. The primary topics of the literature that I have been reviewed cover the fields of: adaptive architecture, computational design, material history, the relationship between architecture and technology, the architecture–science affiliation and Smart Materials. While this literature formulated the foundation for the

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68 A detailed 'Research Time-line' can be found at the Appendix A6. The purpose of the graphic is to visualise the single research projects and to highlight their correlation among each other in the light of the triangulated research method.
research other areas became more of a focus during my research. Contemporary materials science, digital crafting, material development and design thinking and theory contributed to the core of my research to understand the impacts of materials science to modern society and technology.

A large proportion of the literature is presenting in the areas of digital crafting, physical computing and innovative materials contemporary literature and research from the last 5–15 years. In particular, the research and literature regarding innovative materials in architecture drew attention and became of interest to a bigger audience while the research was conducted.

Practice-Based Research

The project work in which I participated at B+G included competitions, detailing of structures and specification of fabrication processes. I worked on several projects during my research period that were related to the research topic of trans-material design exploration. Two of these projects are detailed in Chapter 5. My tasks within these projects were multifaceted and ranged from developing parametric design tools, providing a better exchange of ideas between architects and engineers, talking to manufacturers and supporting the development of structural solutions.

During the practice, the focus was on identifying gaps in how knowledge of new materials is emerging and what kind of representational tools are needed to communicate and express design concepts that could help in the understanding of the relationship between material, structure and design intentions. In each project, my research helped to develop new knowledge, design strategies, techniques and tools. The work, the results and the findings of my period embedded at B+G are explained in more detail in Chapter 5: Observing Material Decisions in Daily Work.

Interviews

From my experiences within B+G, alongside scanning the professional literature discussing novel material in architecture, I developed a list of questions (see Appendix No. 1). Three core issues—communication and collaboration, innovation and the design process involving new materials and obstacles resulting from new material—were investigated through seven interviews. In Chapter 4: Architecture and Materials Science
Synergies, I draw on these ‘semi-structured’ interviews to discuss the existing problems and challenges in the field of applying new materials in architecture.

The semi-structured interview technique is described by Stefanie Keller and Katharina Conradin as an approach characterised by a lesser level of intrusiveness and is one that encourages two-way communication. The interviewee is encouraged not only to respond to the questions but also to ask questions. Hence, they are more likely to discuss sensitive issues with the interviewer. Often, information obtained during semi-structured interviews provides answers that lead to more detailed questions. Those questions have to be answered according to the insider information gathered from the different participants.

This method is seen to have particular value as an ‘invaluable tool for hypothesis formulation’ and was therefore chosen to provide information to identify further research interests and to frame the research field.

The selected interview partners are all experts in novel material thinking in the fields of architecture and material science. By scanning the list of contemporary architectural practices, architectural research and material science research institutes that engage with novel materials and architecture, six architects and a materials scientist were asked to be part of the interviews.

I developed ten questions that served as a core line of enquiry. The questions were first addressed at the beginning of the interview when asking the interviewee about their position on novel materials and technology, followed by asking and discussing the notion of smart materials in architecture. Further, the design process and the personal relationship between architecture and science was included in the conversation. The focus in the interviews was to discuss personal engagement with novel materials, and to identify and reflect upon obstacles that come with the process of applying those materials.

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69 Interviews of this type are useful for studying perceptions and opinions; they are effective for gaining insight into problems that are not immediately perceptible.


72 The role of the interviewers in their area is described in more detail on page 20.
materials in the design. The answers informed the on-going research and led to an online survey.

**Online Survey**

The aim of the survey was to extend my research by covering a diverse group of people from different countries and backgrounds. The intention was to provide a broader view of the existing approaches and obstacles when applying new materials and technologies in architecture. Questions were formed around areas of design tools, lack of knowledge and the difficulty in communicating. Ten distinct questions were developed in order to understand the identified issues on the subjects of material thinking, material representation techniques and communication. Sixty researchers and professionals from the disciplines of architecture, engineering and materials science from 12 countries were interviewed and asked to join the online survey to contribute to this research. The participants were chosen based on their affiliation to contemporary design, technology and material investigations and varying from institutes and companies such as Deutsche Luft-und Raumfahrt (DLR), the Swiss Federal Laboratories for Materials Science and Technology (EMPA), the Architectural Association (AA), the Harvard Graduate School of Design (GSD), Bollinger+Grohmann Engineers or Decker Yeadon to name a few.

The survey itself was conducted as a structured questionnaire and included both open-ended and closed-ended questions, such as multiple choice, Likert-scale and ordinal questions. The intention of the survey was to map differences between disciplines, how to gain a better understanding of material properties and communication between the different disciplines. The analysis of the survey provided information on how the different disciplines are designing and think of novel materials in their profession. This was important to develop methods for the later established design explorations on the basis of the survey outcomes. The quantitative research element of the thesis provided a deeper insight into the thoughts of architects, engineers and material experts. Each discipline was separately analysed and then later juxtaposed and validated to indicate the importance of the overall given answers per question. Pie charts and bar diagrams were

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73 A comprehensive list and the three detailed interviews can be reviewed at the Appendix chapter.

74 Likert-scale questions are useful to determine respondents’ attitudes or feelings about something.

75 Ordinal questions indicate a ranking and the importance of something.
used for the evaluation of the three groups, and to create the qualitative summary of the answers. My findings are discussed in detail in Chapter 5.

2.5 Personal Testing Ground

To better answer my central research question, I also investigated novel materials outside B+G. This approach was taken in order to become personally involved in designing with novel materials and to work hands-on in an open and flexible design environment. Further, it was the intention to observe, test and reflect on the developed design strategies. In doing so, I gained more insight and detailed information about how materials scientists, material experts and designers are finding new ways to work with new materials and technologies. This engagement was conducted by organising and taking part in several workshops and self-initiated experiments and by collaborating with senior students at the University of Kassel, Germany, and the Architecture Master Class of the Städel School in Frankfurt am Main, Germany. Those research methods are explained in more detail in the following sections.

Repetitive-circular design process

For my further investigations I thought not only to simulate the material behaviour in a digital world, rather we have to work with an overall design scheme that derived out of the notion of a ‘repetitive-circular (heuristic)’ design process. Birger Sevaldson describes this process in five distinct units to deliver a new understanding of computer technologies:

- A laboratory for the development of new techniques
- A prototype which clearly isolates and describes selected techniques
- A test-ground where the prototype is used to test for generic validity
- A feedback system to collect data from the test-ground which feed back into the laboratory
- Documentation and analyses and development of theory

A closer look at the five stages reveals that we can adapt these five points into the representation and integration of novel materials in architectural education and

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practice.\textsuperscript{77} This approach was utilised to structure the workshops and test different design tools.

**Workshops**

As part of my personal experiences with novel materials and technologies in architecture, I joined several workshops over the past three years. In 2010, 2011 and 2012, I took part in workshops initiated by Smartgeometry\textsuperscript{78}, all of which had a strong and positive influence on this research. In 2010 and 2011, my role in these workshops was as a participant; in 2012, I led the workshop. These workshops, as well as the workshop intensive ‘Designing the Dynamic’ at RMIT University [SIAL] in 2011, can be described as flash research\textsuperscript{79} methods. Each workshop scenario was held over a period of four days, with a group size that varied between 8 and 18 participants. The workshops that I attended as participant served as an experimental field to familiarise myself with different manufacturing, design strategies and material systems. By organising the last of the three Smartgeometry workshops, and the ‘Designing the Dynamic’ workshop, I was able to test the developed tools and strategies that may help us to become familiar with novel material systems. I evaluated the results of the explored strategies via discussions with the participants, the developed working prototypes and a conducted survey at the last workshop.

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\textsuperscript{77} In the case of material investigations repetitive-circular design process can be understood as true laboratory similar to a scientist or electro engineer laboratory. This scenario is more suitable for pure research and education institutes but Architects such as Decker & Yeadon or the Group of Cloud 9 are proofing the concept of a new architectural practice with a strong focus on In House research related to every possible topic.


\textsuperscript{78} Smartgeometry is an organisation that was founded in 2001 and is organised by volunteers only. It establishes a platform for exchanging ideas and knowledge between practice, research and academia in architecture. Annual conferences and workshops organised by the open community of the Smartgeometry initiative serve as landscape for exploring digital and physical emerging technologies in architecture;

http://smartgeometry.org/index.php?option=com_content&view=article&id=47&Itemid=63

\textsuperscript{79} Flash research is a concept developed by David Benjamin and Soo-in Yang, the founders of 'The Living'. They describe their research as a D.I.Y. design method, and they involve targeted, intensive explorations of architectural ideas with a maximum budget of approximately $1000 and a limited time of a maximum three months. David Benjamin, 'Open', in *Matter-Material Processes in Architectural Production* (New York: Routledge, 2012), 143–153.
The dense research and working environment at a workshop is similar to a laboratory testing field, with a degree of freedom to explore different materials, design techniques and novel strategies. The environment helps to explore research ideas and to engage with other researchers in a multidisciplinary setting. Within a workshop, you can force yourself out of your comfort zone and take the challenge to investigate previously untouched ground.

**Design Explorations**

The work with novel materials, especially in the building industry, cannot be achieved by only working in design practice or material research oriented academia. Whereas the conducted workshops had the focus of testing and learning design strategies within novel material systems, the design explorations had the intention to investigate personally collaboration and teaching. I engaged on the level of material experimentation and collaboration with materials scientist Professor David Mainwaring from the RMIT University Department of Applied Chemistry. David Mainwaring is a physical chemist whose projects include the development of longer lasting and more efficient ‘phosphorescent materials’. Leanne Zilka, David Mainwaring and I designed a passive light system that was exhibited at the 2010 Luminale in Frankfurt am Main, Germany. This exploration serves as an investigation of the collaboration between science and architecture.

As a part of my investigation, I conducted design studios to observe the students’ experiences with novel materials and how their newly gained knowledge changed their perception and guided the design process further. My personal experiences at the University of Kassel and the Städelschule Architecture Class, focused on the possibilities of novel materials as design drivers to define concepts and innovative solutions with students in the architectural concept phase. Different smart materials were introduced either as theoretical concepts or as true materials that the workshop participants could work with to experience the dynamic properties of those materials. The results and the detailed process of the workshops and the experiments are explained in Chapter 6 of the thesis.

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Smaller prototypes and material explorations were conducted throughout the three years of working with smart materials and are partly described in the thesis. They are explained in detail in the appendix of the thesis to emphasis the different streams that I chose to develop my hypothesis and argument.

### 2.6 Summary, Chapter 2

This chapter has introduced the idea of the triangulated research approach. I have outlined the different research methods, the notions of quantitative and qualitative exploration the concept of conducting workshops and experiments to unravel and evaluate the data of my research. I discussed the concept of being an ‘embedded practitioner’ at B+G. This unique position allowed me to engage with engineers and architects as a researcher in everyday practice, on a day-to-day basis. In this chapter, I have related this context of my research methodology.

The triangulated research approach offered me the unique opportunity to relate the practice experience and the ‘live’ laboratory investigations with theoretical ideas and practical material explorations. I have described the relevance of conducting my PhD research in practice and academia in areas where I had the opportunity to intertwine the topics of novel materials and design.

In the following chapter, I introduce the reviewed literature in regards to material development and its effect in architecture. I elaborate on historical events and material innovations that led to the today’s material culture. I will discuss new streams and present the notion of Smart Materials as the starting point of my research investigation. The literature addresses social, technical, economical and design-related aspects that are concerned with defining materials as a design driver.
Material Development and Its Effect on Architecture

Introduction
The First Material Revolution
The New Age of Materials
The Next Material Revolution
Smart Materials
Case Studies
Material Culture
Summary
Material Development and its Effect on Architecture

Each material has its specific characteristics, which we must understand if we want to use it … This is no less true of steel and concrete [than of wood, brick and stone]. We must remember that everything depends on how we use a material, not on the material itself … We must be as familiar with the functions of our buildings as with our materials. We must learn what a building can be, what it should be, and also what it must not be … And just as we acquaint ourselves with materials, just as we must understand functions …

3.1 Introduction

As Ludwig Mies van der Rohe stated in 1938, an understanding of the specific characteristics of a material is an important factor in the creation of a sufficient, efficient and functional design. Even though he was arguing for a greater knowledge of existing materials such as wood and brick and the new materials of that time, steel and concrete, this statement can be applied to the new functional materials of our age. To develop an understanding of my argument concerning engagement with multifunctional materials in architecture, this chapter will consider material culture and its impact on architecture and design. I will present historical events that influenced architectural design and construction methods based on new awareness of materials.

The chapter consists broadly of three sections. The first section focuses on the history of construction materials and the Industrial Revolution, which is considered the first

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81 From his inaugural address at the Illinois Institute of Technology, Ludwig Mies van der Rohe, 'Illinois Institute of Technology', 1938.

82 I recognise that our material culture has a very long history and some of the earliest materials were composite materials such as wattle and daub composites; Gary D. Shaffer, 'An Archaeomagnetic Study of a Wattle and Daub Building Collapse', *Journal of Field Archaeology* 20, no. 1 (1993): 59–75. However, for my argument in this thesis, I have narrowed the discussion and started with the modern manufactured materials.
material revolution and the key event in increasing momentum in materials development. Next, the modernist movement is discussed. This movement is considered of educational importance in the field of materials studies and the practice of architecture. Finally in this section, I present plastics and glass fibre-reinforced composites, which started to play a leading role in the 1960s and 1970s. My intention is to emphasise that architecture is a material practice; thus, the social and theoretical relationship between material and design is a part of each section.

Within the second section, I present today’s concepts of modern materials with a focus on multifunctional materials. In introducing the principles of the ‘technology transfer strategy’, I discuss the potentials of smart materials from an economic and ecological position. Case studies of existing research projects and working prototypes are discussed from the perspective of future technology that is beginning to take place in architecture.

In the third section, the concept of ‘material thinking’ is introduced and illuminated by the current debate about novel materials as a means to create innovative architecture. The current materials development in all sectors with respect to sustainability questions and adaptive systems is the driving force in the investigation and contributes to the notion of material thinking.

Materials that are designed to become multi-functional are of particular interest. These functional materials, which can be ‘programmed’ and combined to create ‘augmented material components’, make possible interactive communication between the architects and the environment. The dynamic features shift the perception from the material as a surface or merely static element to dynamic materials systems. Examples of this approach will be presented as well as the current debate on material thinking in architecture, from which issues arise that my research will focus on.

3.2 The First Material Revolution

With the advent of the Industrial Revolution, the use and the perception of construction materials changed dramatically. Prior to that, as described by Addington and Schodek, the building process and materials selection had been straightforward and the materials were chosen pragmatically either according to their local availability or their visual
qualities.\textsuperscript{83} There was a limited choice of materials and, to use them, the master builder had to learn about the performance limitations and properties of these materials through experimentation. The skills gained and knowledge derived, ‘often through disastrous trial and error’,\textsuperscript{84} was essential in order to be able to work with the available materials. Weston reports that, over centuries, this experimentation with familiar natural materials resulted in a fundamental knowledge of building skills. This knowledge was first applied to every new material introduced in architecture by emulating familiar models of building.\textsuperscript{85} The Industrial Revolution induced an alteration in the architectural and technological landscape with the introduction of mass production and the development of brick, iron, glass and concrete.\textsuperscript{86}

**The Iron Bridge**

In the minds of many scholars, the turning point in architectural history of the use of modern materials in the construction industry was the formative design and construction of the first iron bridge, the Iron Bridge at Coalbrookdale (1777–1779).\textsuperscript{87} Even though iron had outstanding properties (strong tension and superior compressive strength) and could be prefabricated, the construction techniques for bigger structures had not yet been developed. Instead, the design and construction drew from already-existing methods: the single elements of the bridge were connected in the same manner as timber constructions and the semi-circular arch form was derived from that used in masonry arches (Figure 3.1). Even though the bridge was a lightweight structure compared with stone and wood bridges, it contained a large number of redundant elements.\textsuperscript{88} Moreover, compared with a stone bridge, the iron structure was too light, thus the counter force coming from the stone walls forced the ‘iron arch inwards and

\begin{footnotesize}
\begin{enumerate}
\item Addington and Schoek, *Smart Materials and Technologies in Architecture*, 2.
\item Ibid., 3.
\item Olga Popovic Larsen and Andy Tyas, *Conceptual Structural Design: Bridging the Gap between Architects and Engineers* (London: Thomas Telford, 2003), 43–45.
\item Ibid.
\end{enumerate}
\end{footnotesize}
This example is an indicator of an incomplete awareness of the material’s potential and level of fabrication knowledge at that time.

Nevertheless, the bridge was symbolic for the advantages of cast iron as a construction material and supported society’s acceptance of this new material. David P. Billington illustrates this with respect to engineers in his book, *The Tower and the Bridge: The New Art of Structural Engineering*. Billington argues that for Thomas Telford, the first President of the Institution of Civil Engineers of Great Britain,90 ‘the possibility of beauty must come internally from what the technical and economic constraints suggest, rather than externally from the images and formulations refined over centuries in the architecture of masonry’.91 Quoting the romantic poet Théophile Gautier, Giedion outlines that it was not only engineers who were fascinated by the potential of the new artificial materials:

> Mankind will produce a completely new architecture out of its period exactly at the moment when the new methods created by recently born industry are made use of. The

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application of cast iron allows and enforces the use of many new forms, as can be seen in railway stations, suspension bridges and the arches of conservatories.\textsuperscript{92} With iron, it was now possible to bridge larger distances; one key fact of iron was that it was perceived as a homogeneous material that could be prefabricated in a large number of pieces within a short time. This also allowed for construction costs to be reduced.\textsuperscript{93} A new research program in 2001 analysed the bridge using 3D scanning techniques\textsuperscript{94} and revealed that the bridge components, even though prefabricated, are similar but not identical. Each element was cast slightly differently, showing that the manufacturing technology at this time was not as precise as had been assumed.\textsuperscript{95}

Nevertheless, growing faith in manufactured materials and the available range of new materials started to replace common materials such as wood and stone.\textsuperscript{96} In the following sections, I will present a series of case studies that indicate the material impact in architectural practice and education.

**The Uptake of Early Material Innovations in Architecture**

During this time of change, a series of architects and engineers started to investigate different combinations of materials with iron as the core structural material. The reason was simply to extend the range of materials and to create a wider diversity of material effects. It was in 1867 when the French gardener Joseph Monier explored structurally reinforcing concrete with wire mesh to enhance flowerpots.\textsuperscript{97} While Monier was not totally aware of the mechanical properties—particularly, the tensile strength of reinforced concrete—inventors and businessmen like Thaddeus Hyatt, David Kirkaldy

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\textsuperscript{93} Larsen and Tyas, *Conceptual Structural Design*, 43–45.


\textsuperscript{96} Larsen and Tyas, *Conceptual Structural Design*, 43.

\textsuperscript{97} Peter Collins, *Concrete: The Vision of a New Architecture*. 2nd ed. (Montreal: McGill-Queen’s University Press, 2004), 60.
and G. A. Wayss started to test scientifically the properties of reinforced concrete.  
This rigorous testing, collecting and analysing of data lead to the formation of the ‘Reinforced Concrete Committee’ of the Royal Institute of British Architects in 1906.

The success of the Industrial Revolution was dependent on the inventions of a whole range of materials and technologies such as concrete, brick, iron and steel. These new materials and the developed construction techniques allowed architects and engineers to explore a new lightness and elegance of structure and building. Besides the structural materials steel and concrete, glass increasingly became of use due to advances in manufacturing technology, enabling the production of large-scale glass elements with a maximum length of 1,200 millimetres. This brought a new concept of transparency and lightness to building design, which resulted in one of the first icons of lightweight and mass-produced buildings: the Crystal Palace (1851).

Based upon a new understanding of the structural capacity of materials, taller buildings and stronger structures began to be built. Well-known examples of this development are the Eiffel Tower (1889), the Wainwright Building (1891) and the Ingalls Building (1904), which presented the possibilities of the new materials.

The Spirit of Materials

With the evolution of new materials along the technological improvements of the early nineteenth century, a controversial discussion about the benefits and fears of the technological achievements took place. The mechanisation of the building industry and the socio-technical network, for example, caused a wave of criticism in architecture.

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98 Ibid., 60–62.


103 Weston, Materials, Form and Architecture, 43.
Architects were offended by the skeletal metal and at first rejected the use of modern materials or tried to hide the materials behind a layer of traditional materials such as stone. This anti-industrial mind-set resulted in a climate in which few architects were disposed to explore the potential of new materials. However, even John Ruskin, the critical architectural voice of the Industrial Revolution, acknowledged the innovation of new materials in principle, as long as they were produced by craftspeople and not in an industrial manner. However, Ruskin saw the use of industrially produced materials for purely functional buildings as illustrating the difference between architecture and purpose-oriented engineering. The opposing voice was Eugène-Emmanuel Viollet-le-Duc, who argued that progress in architecture and society was only possible through the progression of industrial materials. Viollet-le-Duc was especially concerned with the misuse of materials and asked for honesty in construction: rather than hiding the material, the material should be considered and chosen by its properties. In his drawings (Figure 3.2), we find evidence for this statement, as he has replaced typical vertical stone elements with iron columns.

Figure 3.2: Drawings by Viollet-le-Duc visualising the use of iron columns. (Source: see footnote no. 109)

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Viollet-le-Duc saw another advantage of industrial materials: the standardisation and prefabrication of building components. He argued for the architect to have a higher level of control to reduce intensive labour work and to produce economical architecture.\textsuperscript{110}

As a result, processes to categorise and standardise building materials were successfully introduced by engineers and manufacturer. This was subsequently identified as a downgrading process of craftspeople. The philosopher Manuel De Landa summarises this argument with reference to the engineer James E. Gordon in his essay ‘Material Complexity’.\textsuperscript{111} According to De Landa, Gordon argues that the introduction of steel eased the development of production chains that required a minimum of know-how and brought about a huge regulation system that limited the use of materials on construction sites.\textsuperscript{112} Further, it was felt that the advent of the Industrial Revolution hindered free spirit and the inspiration of crafting was reduced to the required ordered steps within a factory:

\begin{quote}
The widespread use of steel for so many purposes in the modern world is only partly due to technical causes. Steel, especially mild steel, might euphemistically be described as a material that facilitates the dilution of skills. ... Manufacturing processes can be broken down into many separate stages, each requiring a minimum of skill or intelligence. ... At a higher mental level, the design process becomes a good deal easier and more foolproof by the use of a ductile, isotropic, and practically uniform material with which there is already a great deal of accumulated experience. The design of many components, such as gear wheels, can be reduced to a routine that can be looked up in handbooks.\textsuperscript{113}
\end{quote}

The discussion between the importance of craftsperson-ship, art and industrial manufacturing techniques asked for new educational models by focusing on material

\textsuperscript{110} Viollet-le-Duc, \textit{The Architectural Theory of Viollet-le-Duc}, 176.


\textsuperscript{112} Ibid., 20.

experimentation and direct experience. In the next section I will focus on the Bauhaus movement and in particular the educational instruments that led to materiality in design and architecture.

The Bauhaus School

In response to availability of many new, poorly understood materials, the education system responded by focusing on material experimentation and direct experience. The Bauhaus school for example was one of the prominent models that incorporated the traditional skills of crafting with industrial manufacturing techniques and design skills. The philosophy was the creation of a harmony between the function of an object and its design due to a ‘new formal language that meant to unite industrial production processes with creative craftsmanship and design’. A cornerstone of the educational curriculum of the Bauhaus school was the initiation of a course to expose students to a great variety of materials. The aim was to stimulate the students and to create material awareness through a series of workshops in the first educational year. For example, Johannes Itten’s *Vorkurs* (preliminary course) asked students to experience and demonstrate the character of materials by studying the surface of materials with their eyesight and by touch. Later, the focus of material studies also included the physical properties of the materials. Josef Albers and László Moholy-Nagy, two artists organised after Itten’s *Vorkurs* of the school, proposed an integrated research and design process of material and matter. Albers argued:

*First we seek contact with material … instead of pasting it we will put paper together by sewing, buttoning, riveting typing and pinning it; in other words we fasten it in a multitude way. We will test the possibilities of its tensile and compression-resistant strength. In doing so we do not always create ‘works of art’, but rather experiments; it is not our ambition to fill museums: we are gathering experiences.*

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This was achieved by a systematic encounter with materials, with students designing with one material at the time as it was given to them by Albers.\textsuperscript{119} As an example of a design experiment within this course, students were taught to reduce the material to its extreme to create an optimised well-balanced design. (Figure 3.3)\textsuperscript{120}

To cover the whole potential of materials, Moholy-Nagy concentrated in his part of the Vorkurs on the organisation of space. The students worked with textures of materials to get a sense of the feel of the materials. Later, the students were encouraged to experiment with special compositions and expressions that were possible with different material systems.\textsuperscript{121} In particular, the weaving workshop was a place to nurture the concept of scientific material experimentation and work, for example, with cellophane, artificial silk or chenille\textsuperscript{122} to develop translucent curtain materials. As a student at the Bauhaus school in Dessau, Anni Albers (who later married Josef Albers) developed many functional materials, including a furnishing fabric that absorbed sounds on one side and reflected light on the other.\textsuperscript{123}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure3.png}
\caption{Left Image: Sculptor made of a single cardboard strip; Right Image: Experiment with a metal mesh to construct a dome shell structure. (Source: Horowitz and Danilowitz)\textsuperscript{118}}
\end{figure}

\begin{itemize}
\item \textsuperscript{118} F.A. Horowitz and B. Danilowitz, \textit{Josef Albers: To Open Eyes} (London: Phaidon Press Limited, 2006).
\item \textsuperscript{119} Droste, \textit{Bauhaus, 1919–1933}, 140.
\item \textsuperscript{120} Höfler, ‘Seeing by Doing’ Josef Albers und die Materialisierung des Digitalen’.
\item \textsuperscript{121} Droste, \textit{Bauhaus, 1919–1933}, 140.
\item \textsuperscript{122} According to the Online Oxford Dictionary, ‘chenille’ is a tufty, velvety cord or yarn, used for trimming furniture and is often made into carpets or clothing.
\item \textsuperscript{123} Droste, \textit{Bauhaus, 1919–1933}, 184.
\end{itemize}
3.3 The New Age of Materials

Concurrently to the introduction of this new educational model, the material revolution moved forward to research on synthetic materials such as plastics and aluminium, which were introduced as promising materials into the building industry. In North America, the production of aluminium increased in the 1920s; in 1931, the first extensive use of aluminium as a construction material was made in the Empire State Building. Further examples of the new approaches possible in building as a result of the introduction of aluminium include Buckminster Fuller and his work with aluminium to produce lightweight structures and economical optimised systems, such as the Dymaxion House (1928) and the Dymaxion Car (1933).

World War II changed and expanded the range of available materials. Dietz and Scheick have stated that the introduction of a range of new materials and material products followed the needs of the building industry after World War II, with particular reference to the technological advances in fabrication. The new materials such as Bakelite, polythene and aluminium were developed especially for enhancing the weight–strength ratio reports Gordon. The materials—aluminium and synthetically manufactured products like nylon, clear strong plastic and glass fibre-reinforced composites—became accessible post-war for general applications.

Aluminium Architecture

Before the end of World War II, aluminium was mainly utilised by the military and the emerging aerospace industry to create lightweight planes. As an extremely light and


125 Adriaan Beukers and Ed van Hinte, Lightness: The Inevitable Renaissance of Minimum Energy Structures (Rotterdam: 010 publishers, 1999), 34.


strong metal, it was first utilised for aircraft and replaced the common steel skin. Aluminium was thus becoming an important metal and the architect Peter P. Doordan reports in his book *Design History: An Anthology* that in the United States, for example, the government subsidised the industry’s productive capacity of aluminium to meet the needs of the material. Further, he observed that, with the end of the war, a critical point for the aluminium industry was reached. To sustain the expanded productive capacity, industry executives searched for new markets. Doordan explains that it was not only the economic push towards aluminium that affected engineers and architects, but also the promise of ease of fabrication and the possibility of designing lightweight structures with prefabricated elements.

Architects and engineers’ interest in working with new materials and in creating new applications coincided with the promotion of aluminium by the industry and military. For example, Jean Prouvé’s experience working for the military and familiarity with advanced materials and manufacturing techniques and concepts of prefabrication enabled him to design prefabricated, lightweight buildings that were easy to erect.

In 1951, his prototype of *La Maison Tropicale* was almost entirely made of aluminium (Figure 3.4) and combined ventilated aluminium walls, layered façades and a double-skinned roof, aiming to be used in both hot and humid equatorial locations.


131 Ibid.


134 Garófalo and Hill, 'Fixing the Drape'.
Even though aluminium offered benefits due to its formability, extreme lightness and weather resistance, architects saw also difficulties in applying design strategies based around this material. Mies van der Rohe, for instance, was fascinated by the material’s properties (the physical as well as the aesthetic), but expressed his concern as a designer, stating ‘the danger with aluminium is that you can do with it what you like; that it has no real limitations’. To overcome these concerns and to support the further development with aluminium, the industry in the United States, for example, employed designers who were expected to work with other creative people outside their own comfort zone.

It’s a Plastic World

Significant material research into alternative lightweight and strong materials was conducted during World War II. One outcome was glass fibre-reinforced plastic (GFRP) and the building of the first GFRP radar domes (radomes). The material was advantageous for radomes due to its ability to be transparent to the radar signal. GFRPs are electrically non-conducting materials that also provided strength to cover and protect the radars.

In his thesis ‘The Material Geometry of Fibre-reinforced Polymer Matrix Composites and Architectural Tectonics’, Bettum discusses architecture’s interest in experimenting with fibre-reinforced plastics (FRPs). He identifies three main reasons for this interest

136 Doordan, Design History: An Anthology, 161.
and for the expansion of their use in society during that time: ‘cultural expansion, optimism and the literal conquest of outer space’.38 Further, Bettum provides evidence for the particular interest of architects and engineers to engage with the material:

*Three factors—the materials’ high degree of mouldability, the synergy between the form of the object and its strength with a concomitant potential for weight reduction, and the industrial production of pre-fabricated, modular elements—contributed to the gradual emergence of a particular type of architecture with an affiliated specificity of form.*139

Besides the well-known examples of prototypical plastic houses, such as the Monsanto House of the Future (at Disneyland in Anaheim, California, USA, from 1957 to 1967) and the Futuro House (designed by Matti Suuronen and built in the 1960s and early 1970s), that showcased possible architectural applications on a larger scale, architects started to experiment with the material at a smaller scale. Renzo Piano was one of the first who saw the potential of GFRP’s and his intense studies with the structural engineers Z.S. Makowsky and Peter Rice led to a new understanding of their properties and a new knowledge about how to design with these materials. They developed several mid-scale prototypes such as the Industrial Shed in Genoa (1966) or the Shell Structural System for the Fourteenth Milan Triennial in 1967140 to investigate the core properties of FRPs and GFRPs with a ‘scientific approach to problems that encouraged’141 to build a deeper awareness of the manufacturing and material technology. Later on, 1:1 exhibition pavilions such as the Italian Industry Pavilion (1970) in Osaka and the IBM Travelling Pavilion (1982–1986)142 helped to testify the properties and possibilities of FRPs. These

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139 Ibid., 107.


personal experiences led Piano to later state, as Bettum reports: ‘I feel that the architect has to have a scientific understanding of a material, of its possible transformation, of its behaviour’.  

Somewhat contradicting Piano’s view, Rice, the engineer of the two, indicated when reflecting on this approach that:

*Exploration and innovation are the keys. I have noticed over the years that the most effective use of materials is often achieved when they are being explored and used for the first time. The designer does not feel inhibited by precedent. … In any of these structures, there is a simple honesty which goes straight to the heart of the physical characteristics of the material and expresses them in an uninhibited way.*

FRPs were neglected for architectural purposes from the mid-1970s until the early 1990s. Due to a growing awareness of environmental issues, plastics acquired a negative image of disposability and cheapness. However, research continued, especially in the aerospace and defence sectors. Flexible moulding and composite techniques supported by computer-controlled manufacturing processes helped to re-establish the material in architecture and influenced architectural thinking about continuous surfaces, flexible design and lightweight structures. The success of synthetic materials, including fibre-reinforced composites and polymer compounds, was analysed by Ashby and is visualised in Figure 3.5. The diagram shows clearly the peak in the use of metals and alloys between the 1940s and 1960s and indicates that manufactured materials have largely taken over since then. This development is especially interesting to architects with respect to future building developments to meet the long-term requirements of the price–performance ratio, as Adriaan Beukers and Ed van Hinte state.

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Figure 3.5: This ‘Hill and Valley’ diagram explains the development and importance of materials during the centuries. Starting in 1800, we see that composites, cements, polymers and ceramics were the most prominent once. This changed during the research into stronger materials and Steel and Alloys had the highest importance from 1940 until 1980. Today, a paradigm shift tends again towards the development of polymers, composites and ceramics. (Image adapted by author from Michael F. Ashby in the book Lightness\(^{148}\))

### 3.4 The Next Material Revolution

According to Sascha Peters, we are at the beginning of a new material revolution and ‘the classical mechanized understanding of materiality is giving way to a new materials culture … to achieve a more responsible use of our global resources’.\(^{149}\) Kieran and Timberlake, for example, see the potential of new materials in their ability to reduce weight and add strength to construction while lowering costs and construction time as Filiz Klassen reports.\(^{150}\) Another advantage of tailor-made material systems is that they are becoming multi-functional. Materials with the ability to be light and strong with additional functions such as being able to repel dirt, retro reflect, change colour or filter air bring new

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\(^{148}\) Ibid., 14–15.


opportunities to the design discipline—that is, materials that are adaptable and respond actively according to external stimuli. These materials are shifting the focus from the surface of materials to their functionality.

This new group of materials pose a challenge to design because, Paola Antonelli argues, ‘the mutant character of materials, as expressive as it is functional and structural, generates new forms and a more experimental approach toward design’. According to design strategists Ezio Manzini and Pasquale Cau, these ‘mutant’ or ‘alien’ materials that are unfamiliar to architecture question ‘the traditional divisions of expertise between the chemist (who works with the properties of materials) and the designer (who works with the form of the finished product)’. Further, these materials also address a demand to ask how we are engaging and designing with materials. Functional materials are capable of harvesting energy, storing and controlling energy flow, and are able to reduce the overall mechanical system. Sheila Kennedy describes these capabilities as one of ‘the most significant developments in material culture’ and argues that the ‘shifts from static material properties to dynamic material behaviours’ present the active engagement ‘in the fourth dimension: time’. This fourth design parameter—namely, time—will effectively change the way in which we perceive the material world. Anthropologist Susanne Küchler suggests that those materials will ‘draw our attention to a material world that does not just represent who we are, but which is capable of standing-in for us, substituting for some of our own capacities’.

Nevertheless, from the perspective of sustainable and green architecture, there are criticisms—for example, that the advanced technology needed to create environmental solutions tends to limit the ‘philosophical, psychological and cultural’ ambitions of


Klassen argues that architects and designers are still missing the access to ‘knowledge, ethics, and creativity to transfer these technological innovations’. The addressed issue of the missing access to material know-how and the need for creative environmental solutions suggest further analysis of how to support material selecting processes and to make sense of material properties as design driver.

**Technology Transfer**

Materials development usually takes place outside of architecture and architects engage with new materials through a process of technology transfer. Martin Pawley has promoted this process and the search for innovation and inventiveness as a way of exploring new materials in his essay ‘Technology Transfer’:

> Despite the spectacular output of synthetic materials and new structural technologies that marked the post-war period, their palette remained limited, as did that of their immediate successors … It was precisely because the sons of the pioneers concentrated on formal inventiveness rather than exploring the process of technology transfer that had given them new ways to build, that Modern architecture died of ignorance while new information was exploding all around it.

Sauer describes this process today as a source of novel and technological advances derived from other disciplines, and explains that the leaders in innovative material research are more often found in the aerospace, automobile and military industries than in architecture. In these industries, a material is tested and designed for a specific application. After a successful development process, the material is promoted for secondary usage in other disciplines.

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According to Rashida Ng, despite technology transfer being a process recognised and practised by many architects, the trend of using new materials in architecture has ‘failed to stimulate an era of uninterrupted evolution in the technologies of the built environment’.160 161

There are several possible reasons why architecture may hinder the progress of material innovation. Manzini and Cau refer to the time of development and total understanding of the material as one main factor. He further articulates that only by having a complete understanding of a material’s properties can ‘relations between conditions of the use and the performance that typified the material’ are possible. Here, Manzini and Cau are arguing for an awareness of the material’s properties and designing, with respect to these properties, for the right purpose and not violating the material just for the sake of utilising a fashionable material. In addition, the mere variety of available materials is a problem for Manzini and Cau, who state that in the past:

[T]here were few materials and they were quite distinct one from another, so that each corresponded to a well-defined field of relations. Materials remained constant over time in terms of qualities and properties, and their variations (or the introduction of new materials) were slow enough to allow the adaptations of the system of meanings.163

Because ‘the introduction of unusual materials to architecture is incremental’, Lynn Ermann confidently says that ‘in the near future, technology transfer will find its way’.164 Nevertheless, there is still the argument of an existing strong conservatism in the building industry ‘because of the scale of physical risk and the economic outlay’.165

161 While this argument of Rashida is very provocative and general I identified in detail in Chapter 4 several issues that may lead to this ‘failed uninterrupted evolution’ in the building industry.
162 Manzini and Cau, The Material of Invention, 32.
163 Ibid.
Together, these factors affect when a new material system should be introduced into the market and how it will be perceived.

**Time to Innovation**

Slow market introduction can be explained by the logic of usual time-to-market (TTM) analysis, as described by commerce, in which the time to develop a product is explained. It is an ‘open’ factor and cannot be applied as a general rule. However, depending on the state of the development and whether the newly developed product relies on existing technology, a certain time frame can be indicated. Economist John Braet and design strategist Paul Verhaert demonstrate this by arguing that today in general, the development of new materials and products takes approximately eight to ten years; of a component, four to five years; and of an application, up to two years\(^{167}\).

It is the combination of all these time-dependent developments that accelerate the introduction of new materials and products. Toshiko Mori’s statement that ‘an invention of a new material, and the prior experimentation that ultimately yields this, takes 20 to 30 years before it appears on the market for approved use’\(^{168}\) thus agrees with this. Already understanding this, Frederick J. Kiesler developed a model in 1939 describing the ‘evolution of need’ (Figure 3.6) in 12 decisive steps that coincide with the arguments of Braet, Verhaert and Mori.\(^{169}\)

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The model of Kiesler defines the first six steps as the ones where the actual innovation and takes place. Point 7 indicates a certain resistance that has to be overcome; Points 8–12 refer to production and marketing strategies, which are the most time-consuming ones. These last described points might hold potential for an uptake of new materials by addressing a better accessibility to explore the material in an early stage and include information from the outside world. One explanation for the slow take-up of material is the standardisation of material applications and codification over the past 50 years and that the classifications are insufficient for our time, as Liat Margolis 170 and Addington and Schodek171 explain.

Materials developed during the 1960s for aerospace applications have crossed this border of time into the market and are becoming available today.

Since the early 1990s, particularly in the medicine, military and sports industries,172 high-performance materials have been introduced and further developed. Within these areas,


\[^{171}\] Addington and Schodek, Smart Materials and New Technologies

the materials have been proven valuable and over the past ten years they have become of increasing interest to the design disciplines. For example, exhibitions such as ‘Extreme Textiles: Designing for High Performance’ (exhibited at the Cooper-Hewitt National Design Museum in April 2005) and the ‘Open House: Architecture and Technology for Intelligent Living’ (a traveling exhibition initiated by the Vitra Design Museum in 2007) have showcased.

Current Material Developments

Alongside the increasing interest in architecture to experiment with novel materials emerging from other industry branches, material science is also attempting to encounter new areas in which to implement their developed products. Since the beginning of the new millennium, several reports have been generated by materials science industry and research organisations to analyse the potential of new materials and their market values. The development of new materials and the increasing performance of existing materials are foreshadowed in these reports as being one important economic cornerstone in the future.

In 2001, the Max-Planck Institute for Intelligent Systems organised, in collaboration with materials scientists in Europe and with the European Commission’s Research Area, the European White Book on Fundamental Research in Materials Science. This compendium aims to summarise research in materials science in Europe to highlight future directions and pinpointing research priorities in Europe. The content emphasised that ‘smart

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173 Extreme Textiles displayed textile products and applications that involved the themes of stronger, faster, lighter, safer and smarter. Featuring products of technical textiles, architectural and product design, medicine, aerospace, and the environment, the exhibition showed linked products and ideas from design, industry and science. Matilda McQuaid, Extreme Textiles: Designing for High Performance (New York, NY: Princeton Architectural Press, 2005).


175 International and national research institutes and organisations are analysing the influence and potential of material science as well as the outcome of research to negotiate which sectors have potential to support the economic growth of the country. Important reports include: The Global Technology Revolution reports by the non-profit institution Research and Development (RAND) Corporation, the reports by the UN Millennium Project, the European White Book on Fundamental Research in Material Science (see Footnote 89) and the work published by the Foresight Smart Materials Taskforce.
materials’ will ‘revolutionize the concept of synthetic materials, as well as how we interact with our surroundings’.176 The authors of the document report that smart materials have the potential to ‘respond to external stimuli, adapting to their environment in order to boost performance, extend their useful lifetimes, save energy, or simply adjust conditions to be more comfortable for human beings’.177 Even though the technological forecast and the impact of new materials are questioned by a few,178 most of the reports are optimistic and define areas of potential future collaboration and research strategies.

In another example, the European Technology Platform for Sustainable Chemistry (SuChem),179 created a draft in 2005 that outlined their strategic research agenda with a list of priorities for products that could increase quality of life and suggested that smart materials have the potential to contribute to the sustainability discussion in the building sector. The diagram (see Figure 3.7) identifies ‘Smart Housing’, building and construction as well as efficient lighting and environmental sensor technology as an essential research area that has to be addressed immediately. It also shows that the estimated time for research in these sectors was, at this time, a minimum of 5–10 years before the first research outcomes could contribute. This again is evidence for a slow uptake of material research but also shows the potential for new material products in the building industry.

176 Max-Planck Institute for Intelligent Systems. European White Book on Fundamental Research in Material Science (Stuttgart: Max-Planck Institute for Intelligent Systems, 2001), 12

177 Ibid.

178 Jonathan Huebner argues that the rate of innovation is now rapidly declining and we will see in the future increasingly fewer important innovative solutions (Jonathan Huebner, 'A Possible Declining Trend for Worldwide Innovation', Technological Forecasting and Social Change 72 (2005): 980–6), whereas, in 1998, Thomas Eagar warned that the growth of new materials businesses had not approached the prognostications of ten years prior, but had made improvements in the durability and economy of traditional materials. He went on to argue that this is the quiet revolution. However, he also saw potential if long-term industrial sponsorship was invested and suggested that this will be the foundation of future technological change (Thomas W Eagar, 'The Quiet Revolution in Materials Manufacturing and Production', Journal of Minerals 50, no. 4 (1998): 19–21).

The outcome of this agenda coincides with the 2006 report, *Technology Roadmap for Smart Materials*, which suggests that smart materials are becoming more important in everyday products and the building industry.\(^{180}\)

However, this report also identifies several obstacles that have to be overcome to promote the materials and their qualities. According to the report, some of the key issues are closer collaboration with the design disciplines, the improvement of the TTM process, the establishment of increasing awareness of new markets and the facilitation of better knowledge transfer.\(^{181}\) These topics are addressing directly the disciplines of architecture as a collaborative partner and contributor in the integration of new materials, especially that of ‘smart materials’.

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180 This report was created by industry partners, private research institutions and academics to analyse the potential for smart materials in Great Britain

Addington and Schodek see further potential for smart materials in regards to their ‘transient behaviour and ability to respond to energy stimuli’ to ‘enable selective creation and design of an individual’s sensory experiences’.182 Another argument for the advent of these materials in architecture is the growing awareness of sustainable products and design solutions. Topics like sustainability, regenerative technology and materials, customised mass production, advanced building physics, and a new awareness of the environment due to a possible adaptive architecture are leading the introduction of new materials in architecture. Kieran and Timberlake speculate that ‘characteristic properties have begun to emerge however, in recently developed materials that are the opposite of many conventional materials now in widespread use. ... Dramatic changes in the properties of recently developed materials will ultimately transform architecture...’ Further, they see that ‘beyond [the] infatuation’ with new materials, there is the potential to discover a world of purposeful form, a world in which materials will become design drivers according to their properties.183

Materials that can alter their physical and chemical properties to external stimuli to optimise the mechanical or thermal response are becoming of interest to architects and engineers, as civil engineer Patrick Teuffel reports.184 This class of materials is discussed in detail in the next sections to highlight the possibilities, their limitations and the current use of these materials in architecture.

### 3.5 Smart Materials

In 1988, at the US Army Research Office Workshop, the terms ‘smart materials’ and ‘smart structures’ were coined to arrive at a consensus for a standardised terminology. In comparison with conventional materials, smart materials are functional and have been defined as:

\[
A \text{ system or material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a}
\]

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182 Addington and Schodek, *Smart Materials and New Technologies*, 8


predetermined manner and extent, in a short/appropriate time, and reverting to its original state as soon as the stimulus is removed.\textsuperscript{185}

Their classification is based on the relationship between the stimulus and response. This definition of smart materials was extended and detailed by Gandhi and Thompson in 1992. They distinguish smart materials as either active or passive. An \textit{active} smart material is able to alter its own geometry or material properties when external stimuli are applied\textsuperscript{186}. A \textit{passive} smart material is an additional material that enhances an existing material without changing its own properties; fibre optics that can sense but not actuate are examples of passive smart materials.\textsuperscript{187} I have explored both material classes and will elaborate on the combinatory strength of the materials later in Chapter 6.

Further, according to Küchler, the goal of research into smart materials and structures is to animate the inanimate world by providing it with the attributes of living things—the creation of networks of integrated artefacts that work in interrelation to form complex systems of sensate things that (eventually) really learn.\textsuperscript{188}

**Terminology**

I have gathered information that expands on the discussion of the terminology of smart materials in architecture. The German architect Ulrich Königs, for example, speaks of ‘smart’ materials as materials that ‘\textit{have the ability to modify their composition independently by reaction with external and internal influences … they react to necessities resulting from the material structure itself, just as living organisms do}’.\textsuperscript{189} Whereas, for example, one of my interview partners was more precise, preferring to categorise smart materials as plants. He argues that a plant is an organism that is capable of a specific setup of predefined actions and reactions to environmental forces. Although smart and engineered, these materials


\textsuperscript{187} Ibid., 87.

\textsuperscript{188} Küchler, ‘Technological Materiality’.

merely react to a pre-designed behaviour and have no learning capability that would allow them to become intelligent. Interview Partner No. 4 said: ‘At the end the intelligence lies in the user of the material and not in the material itself’.

In contrast, Oosterhuis writes that he does not think of the intelligence of a system as being human intelligence. Rather, he points out the emergent behaviour that is:

> coming up from the complex interactions of less complex actuators. It seems to be possible to apply the same definition of intelligence to the functioning of our brains, traffic systems, people gathering, and to the growth and shrinking of cities. 190

A newer terminology that is being introduced by designers and materials science tends to emphasise more the functionality of these materials. Multifunctional materials describe the advantage of combining structural and non-structural functionality such as sensing, actuation, and memory. 191

In my thesis, I tend to use this newer terminology to express the multi-functionality and combinatorial possibilities of in particular smart materials.

**Classification**

Smart materials can be classified in many ways—for example, they can be ordered according to their behaviour (e.g. ability to change shape or to create energy). Addington and Schodek suggest a multi-layered system: the first layer describes the function of the material and the second layer characterises the results of this function. 192

They give an example for this approach by stating that the material can produce direct effects such as ‘(luminous, thermal and acoustic) or they can produce indirect effects on systems (energy generation, mechanical equipment)’. 193 Although this method of categorisation is helpful in understanding what a material can be used for, the question of how it can be used remains open.

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192 Addington and Schodek, Smart Materials and New Technologies, 29.

193 Ibid.
Thus, a third layer is necessary to address the right material in the right context. During my experiments, I quickly realised that we also have to consider any possible inputs that we need to operate the material. Therefore, to be able to choose an appropriate material, we also have to understand the relationship between the stimulus and the response it generates. Figure 3.7 shows a classification of active smart materials according to this idea. As passive smart materials can be embedded in any material system, they are excluded from this classification.

Selection of a material is based on the external stimuli, which are often a known constraint in the design process or can be determined in the early stages of design. The desired effect of a material system is also a component that is developed at the design stage. Once the available external or preferred triggering force (such as heat or electric current) is known, the appropriate decisions can be made about the desired reaction of the application. For example, the aim is to generate a mechanical force, to be able to replace a hydraulic operating façade mechanism with a lighter system based on smart materials; we can identify four different materials that can be actuated with four different external forces. Depending on the available or best suitable force the range of materials can be reduced for further exploration (Figure 3.7).

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194 The experiments will be explained in detail in Chapter 6, ‘Material Explorations’.
Adaptive System

Smart materials are often considered examples of the core aim of material science, which is to supersede structural materials with functional ones. In other words, the functionality of a smart material establishes a certain intelligence that it can use to adapt its physical properties and mechanical behaviours in response to an externally applied energy. In structural engineering, an adaptive system is thought of as the active control that protects structures failing under changing load conditions such as wind or seismic loads. According to civil engineer James T. P. Yao, the active control system consists of sensors, actuators and a control unit. Depending on the load condition, the system will change the structural system according to the applied energy (Figure 3.8).

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For example, in structural engineering smart materials are considered a technology that can replace the mechanical and sensory parts of an adaptive system to provide a redundant and unfailing structural system like Teuffel presented in 2009 (Figure 3.9).\footnote{198}

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{figure3.9.png}
  \caption{Diagram of a typical adaptive system by Patrick Teuffel based on James T. P. Yao’s concept of structural control (image adapted by author; source: Patrick Teuffel\footnote{197})}
\end{figure}

\begin{figure}[h]
  \centering
  \includegraphics[width=\textwidth]{figure3.10.png}
  \caption{Diagram of an adaptive system that combines and replaces the electrical sensors and actuators with materials with advanced properties (Image adapted by author, source Patrick Teuffel)}
\end{figure}

\footnote{197} Patrick, Teuffel. 'Entwerfen adaptiver Strukturen Lastpfadmanagement zur Optimierung tragender Leichtbaustrukturen', (PhD thesis, University of Stuttgart, 2005)

\footnote{198} Patrick Teuffel, 'Performance Based Building Design Using Smart Materials', in S-ASBE 2009: 3rd CIB International Conference on Smart and Sustainable Built Environments (Delft, 2009).
Applications

Teuffel's argument can be confirmed by the first experiments in aerospace applications, such as the model aircraft with shape-changing wings developed in 1995.199 The research team replaced the traditional mechanical steering mechanisms of the wings with piezoelectric actuators200, which altered the shape of the wings by converting electrical energy into mechanical ones in response to flying conditions201, according to Ball. The advantage of the smart wings was that they continually adapted their shape and position to increase aerodynamic and structural efficiency.

In 2001, Hugh Casey described the recently introduced piezoelectric materials as external damping devices in ski design and proclaimed that those materials are an ‘‘interesting benchmark on the “progress” in ski design and manufacture’’.202 Research conducted in civil engineering is interested in integrating piezoelectric ceramics and fibres into structural systems to monitor structural health and for structural actuation as described by Victor Giurgiutiu.203 Besides the structural actuation and the energy-harvesting properties of piezoelectric elements,204 shape-memory alloys (SMAs) have been used to reduce the weight of robots by replacing the servo motors. Further, deployable structures for space applications that utilise SMAs as actuators are used in the National Aeronautics and Space Administration’s (NASA) Hubble Space Telescope to deploy the solar panels automatically.205 Another example is the Mars

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199 Developed in 1995 by a researcher at the Auburn University in Alabama, US.

200 Piezoelectric materials are able to produce an electric field when external mechanical forces are applied such as pressure or stretch. In reverse they change shape if an electric field applied is applied. Ritter and Mueller, Smart Materials in Architecture, Interior Architecture and Design, 142.

201 Ball, Made to Measure, 118.


Pathfinder Sojourner rover, which has a protection shield that opens or closes the glass plate of the solar cell that runs the rover.\footnote{G. A. Landis and P. P. Jenkins, 'Dust on Mars: Materials Adherence Experiment Results from Mars Pathfinder', in Photovoltaic Specialists Conference, 1997: Conference Record of the Twenty-sixth IEEE, 29 September–3 October 1997, 865–9.}

In architecture, Mike Davis suggested in 1988 the idea that materials ‘can alter their properties or transmit information merely due to electronic or molecular proceedings’, \footnote{Mike Davis, 'A Wall for All Seasons', RIBA Journal 88, no. 2 (1981): 55–57.} that mechanical parts can be dispensed with and the energy flow of a building controlled using the skin of the building itself (Figure 3.10).

![Figure 3.10: Polyvalent wall concept developed by Mike Davis in 1981. Each Layer is just a view micron thick and is designed to perform a certain function such as natural ventilation, natural lighting and thermal control of the interior. (Image source: Ulrich Knaack\textsuperscript{208})](image)

**Limitations**

Smart materials do have their limitations, especially because of their micro-structural composition. Further, the materials are often designed for a specific purpose and only undergo pre-designed actions that are calculated by materials scientists. When using an SMA, it is necessary to be familiar with the forces, displacements, temperature conditions and cycle rates of the material. Usually, these data are provided by the manufacturer and developer once the material is introduced to the market; but, as Marcelo Coelho states, ‘a lot of this literature presents techniques, processes and even terminology which

\footnote{Ulrich Knaack et al., 'Adaptive Façades', in Façades Principles of Construction (Basel: Birkhäuser Verlag AG, 2007), 88.}
Another critical aspect of integrating smart materials into the building environment is the combination of ‘intrinsic and cognitively guided response variations’ and that they are often introduced by a ‘patching’ strategy, as Neri Oxman describes it. The materials end up being a kinetically actuated façade or being embedded on top of an existing structural design. These material systems are assembled out of a combination of smart devices and regular building components, thus might end up requiring too much energy to be operated and controlled globally by a computational system. However, Oxman also sees the potential of these materials and assumes that the next generation of construction materials may support dynamically responsive material compositions.

Nevertheless, the programmed functionality of smart materials offers the potential for a responsive and informed built environment and increases the palette of available materials in the field of architecture.

### 3.6 Case Studies

Smart materials in architecture are a relatively new field of material investigation; the examples presented here showcase the possibilities as well as the upcoming challenges. The case studies are a representative cross-section of projects that deploy smart materials in an architectural context. They are structured into three main sections: ‘Responsive’, ‘Sustainable’ and ‘Experimentation’. The chosen projects cover a major range of materials to acknowledge the variety and complexity of smart materials.

#### Responsive

Responsive architecture is often equated with a change in shape—to provide, for example, sun shading or simply to create a soft and flexible space that responds to environmental stimuli. Smart materials with their shape-changing properties have been of interest over the last decade and have been investigated by several research projects.

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211 Ibid.

212 A comprehensive list of projects working on smart materials can be found in the Appendix A7.
Nowadays, smart materials are more popular in academic research than ever before. The ShapeShift project (2010) developed by Edyta Augustynowicz, Sofia Georgakopoulou, Dino Rossi and Stefanie Sixtand and supervised by Manuel Kretzer from the Computer Aided Architectural Design department at the Eidgenössische Technische Hochschule (ETH) Zürich, investigates dielectric electroactive polymers ‘to create a new possibility of architectural materialization and “organic” kinetics’. In this project, the developed system utilises materials’ properties to ‘become orchestrated for their aesthetic qualities’. The flexible developed skin is understood as an alternative replacement for conventional building skins, moving towards a flexible and sensitive architecture.

Another approach of a flexible responsive material is the use of SMAs, which can change their shape according to applied energy, heat or electricity, similarly to electroactive polymers. One example is the prototype developed by Andrew O. Pane that works with SMAs to create a responsive object. In this case, the SMA works as ‘sensor, processing device, and actuator all-in-one’. Pane has incorporated a tailor-made microcontroller to control light sensors that send an impulse to the panel to open or close it, once the right light conditions are reached (Figure 3.11).

![Figure 3.12](http://fab.cba.mit.edu/classes/MIT/863.10/people/andy.payne/Asst9.html)

*Figure 3.12 shows the developed opening mechanism actuated by SMAs. The temperature changes in the SMA is causing the changes of length in the material, hence the triangulated elements are rotating and opening. Once the temperature is dropping again the elements are being closed due to the relaxing state of the SMAs.*


214 Ibid.

Sustainable

To reduce or harvest energy or to provide alternatives for building functions, usually new technology developments are proposed, which is why smart materials are often regarded today as possible solutions. For instance, Markus Holzbach researches sustainable architecture in the realm of new smart material applications. While studying for his doctorate, Holzbach developed the pavilion ‘Paul’ (Figure 3.12) in 2004 at the Institut für Leichtbau Entwerfen und Konstruieren (ILEK) in Stuttgart, Germany. The experimental structure presents the possible integration of highly insulating ceramics, including storage capacity and phase change materials. The overall wall structure is only 1.4 cm thick but has similar insulation parameters to traditional solid walls.216

Figure 3.13 The pavilion Paul is able to perform different states of illumination. The lighting technology is also an integrated part of the developed ‘smart—skin’ (source: Markus Holzbach; http://www.holzbach-architekten.de/page1/page9/page10/page10.html)

Kennedy & Violich Architecture (KVA) is another example of a cross-disciplinary practice and research company that is involved in novel material applications. To this end, the company founded its own material research team called ‘KVA MATx’. In collaboration with industrial partners, the team investigates new materials for sustainable architecture, such as the Portable Light Project.217 In the project, as Addington describes, several smart materials are used ‘to yield results that are direct, discrete, transient, and local’.218


Experimentation

Decker Yeadon is an architectural practice and research group based in New York that focuses on the implementation of novel materials and technology in architecture. They have established their own laboratory for nanotechnology research and are the first architectural practices to have created ‘buckypaper’, which is based on nanotubes.\(^{219}\) Peter Yeadon states that ‘experimentation in architecture and experimentation in nanotechnology are actually not that far apart’ and that both aim to ‘produce new knowledge and may lead to new capabilities’.\(^{220}\) Decker Yeadon recently proposed a kinetic façade based on the findings of their experiments. The façade comprises ribbons made of electroactive polymer actuators with nanotube electrode coatings. The ribbons are expected to change their shape in response to the sun.\(^{221}\)

They also developed a façade system based on the technique of dielectric elastomer actuators that are situated between a double-layer of glass. The elements are triggered by electric impulses that respond to light measurements and heat control (see Figure 3.13).\(^{222}\)

Figure 3.14 presents the Homeostatic façade system. The façade is thought of dielectric elastomer actuators that are situated between a double-layer of glass. The opening mechanism is actuated by electrical impulses. Left image the closed state, right image: open state of the façade system (courtesy of Decker Yeadon)


\(^{221}\) Ibid.

3.7 Material Culture

Most of the case studies presented here apply smart materials according to their functional properties to realise a performative architecture. The successful integration of state-changing materials to contribute to the discussed problems of an adaptive responsible architecture, the issues of the fourth dimension: time and knowledge exchange have to be considered. The characteristics of these materials—‘that a change in one property may often be accompanied by changes in other properties’—describe the complexity of the design challenge:

*Certain photochromic compounds ... change reversibly in response to light and temperature changes. And inversely it may be the case that several properties change at once after the stimulation by a single influence.*

The technical aspect is not the only one that has to be reviewed as new technology is introduced into architecture. The development of novel materials also questions the use of existing materials and how we perceive our building environment. These concerns are expressed within the discussion of new technology in architecture.

The industrial designer Walter Dorwin Teague expressed this in 1949:

*But the Machine Age in its multitude of inventions has not only included our long repertoire of new materials, it has enormously increased the number and kind of things we can do with materials, old as well as new. It is not surprising that as a result we have fumbled very clumsily with many of our unfamiliar stuffs, while we ran wild in inept uses of those our forefathers understood so well.*

The issue of an integrated knowledge model as well as the question of new aesthetics and performance possibilities are reflected by architects and designers alike. Peter Zumthor, for example, describes his relationship with materiality and the use of materials in his architecture as a discovery of the ‘poetic quality in the context of an architectural object’ and continues by saying that only with a meaningful situation generated

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224 Ibid.

by architecture can a material be poetic, ‘since materials in themselves are not’. While Quentin Hirsinger and Elodie Ternaux state in the book Material World 2: ‘too much choice means no choice’ and ‘the profusion stifles creation,’ Bruce Mau asks, ‘now that we can do anything, what will we do?’

Architectural work cannot only be described by the composition of space; it is also described by the important connection between spatial quality and material qualities. Recently, Thomas Schröpfer, Erwin Viray and James Carpenter argued that if an architect abandons materials, he or she will not be an architect anymore. This statement emphasises that architects have to embrace materials not only as design drivers but also as cultural inspiration for future innovation in architecture.

Call for Change

These multi-functional materials and the discussion of materiality are becoming complex and need to be addressed within other disciplines to gain new insights, inspiration, as well as an awareness of the constraints that come with a possible material implication. Many engineers and architects support this call for knowledge exchange and collaboration between other disciplines and architecture, including Adams Kara Taylor (AKT), Bollinger+Grohmann Ingenieure (B+G) or Kieran Timberlake promote. The investigation of novel materials and the innovative use of those might ‘stem from a personal investigation into material’ and lead to thinking outside of the architect’s described

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233 Schröpfer, Viray, and Carpenter, Material Design, 16.
role, Schröpfer explains. He continues that this action outside the ‘comfort zone’ becomes critical when architects start to investigate new materials developed by chemists and materials scientists. He concludes that ‘as a profession our material palette has been limited by our simple classification system and by a lack of integrated disciplinary exploration’. This lack of integrated disciplinary exploration is also a concern of Kieran and Timberlake, who hope to establish ‘alliances with material scientists and product engineers to use materials they are not using now, purposeful materials and not just collections of neat looking materials’ reports Ermann.

Bergdoll argues that the new materials demand a ‘reciprocal relationship between science and design’ and Klassen states that the expression of true design ‘through autonomous artistic organization and material embellishments no longer seems to provide a convincing goal and that today in contrast, many architects are becoming involved in “alchemy” of construction’, to contribute to the discussion of a more responsive and responsibly built environment. These perspectives from architects and designers who are working with novel materials call for a change in the communication and collaboration between architects and other expert disciplines like material science and engineering. Wiscombe is provocative in promoting change in his essay ‘Emergent Models of Architectural Practice’. Therein, he pictures a scenario where ‘fabrication techniques, engineering dynamics, and materials science’ are being fed forward into the design process to ‘free architectural practice from its tendency toward stratification and provincialism’. He gives the example of a successful story in the architectural office SERVO, which works, as a rule, with professionals other than architects and engineers and asks for fluent and emergent collaboration.

234 Ibid., 33.
237 Klassen, ‘Material Innovations’, 122-135
Along this same line, Kennedy calls for new models of practice that ‘simultaneously consider “doing” and “thinking” to accelerate the implementation of active materials and technologies in architecture’ as a need to ‘engage with active, energy-exchanging materials in design’ for responsive and performance building systems.\(^{239}\) This is the ideal matrix to which my investigation and the applied triangulated research method are intended to lead.

### 3.8 Summary, Chapter 3

In this chapter, I have described some strategic key points: the history of material inventions, the importance of material developments and their impacts on architecture. The connection between new materials and new technologies has been identified as a key driver for architectural innovation, as well as the notion that new materials are accompanied by new design strategies and responsibilities that architecture has to investigate. The sustainability movement was discussed as well as economic factors and these were identified as key drivers in the push towards novel material solutions as a means of the material can become the design driver itself.

One key finding is that through the practical investigation and the hands-on experiences with the materials architects and engineers begin to appreciate the viewpoint of the other as seen in the example of Piano and Rice. This appreciation was made possible by the engagement with innovative material systems and the trial and error experiences and the use of those within design gained from the material experiments conducted by Piano and Rice. Therefore my research will address the question of how to gain design knowledge by experimenting with advanced materials further in Chapter 6.

Most of the presented examples in this chapter involve the use of smart materials either at the experimental stage or still only concepts that try to showcase the potential of new materials.

Besides these defined problems, the call for change in terms of collaboration and knowledge exchange was presented in the last section. This issue needs to be discussed in more detail to highlight the differences of disciplinary levels and the domain of collaboration in the realm of a material culture. In the following chapter, I will juxtapose

\(^{239}\) Kennedy, 'Responsive Materials', 118.
architecture and material science to prove the need for a new model of dialogue to support the experimentation and design of novel materials in architecture.
Architecture and Materials Science Synergies

The Origin of Materials Science
Architecture, Science and Technology
Different World Views
Sources of Material Information
Approaching Materials
Summary
Architecture and Materials Science Synergies

Materials science isn’t what it used to be. ... All the engineering of a device or a structure was concentrated in the way the parts were put together. Now things are different. Many of the advanced materials at the forefront of materials science are functional: they are required to do things, to undergo purposeful change. They play an active part in the way the structure or device works.\footnote{Philip Ball, ‘Smart Materials’ (paper presented at the open day for school teachers, Department of Materials, University of Oxford, Oxford, 2002).}

4.1 Introduction

As described in Chapter 3, materials have a significant influence on the built environment and design culture. Newly available materials with novel mechanical and sensorial properties are contributing to, as Philip Ball describes in his statement above, the emergence of adaptive building components. However, since architecture and science have split into a variety of specialisms, collaboration has become more difficult and possible synergies between architecture and science more limited.

To discuss new materials in architecture and to omit materials science would be impossible; therefore, this chapter explains the origin of materials science and how the two disciplines of architecture and science have developed diverse modalities of material know-how. This background is important to this research, as it will allow better understanding of the complexity that underlies the topics of material thinking, material representation and interdisciplinary communication.

In the following sections, I explain the different worldviews of materials science and architecture to emphasise. Three subcategories (education, scale and modes of representation) are introduced to emphasise this development. I then discuss the current situation by presenting the common methods and tools that architects and scientists use in working with materials. Using precedents and interviews, different levels of material engagement
and material applications are presented. As a result, I raise the question of why there is still a constrained uptake of material technology in architecture.

### 4.2 The Origin of Materials Science

The study of materials did not begin at one fixed point in time, but it can be argued that metallurgy \(^\text{241}\) started a new chapter in material awareness, as the metallurgist and historian of science Cyril Stanley Smith stated. \(^\text{242}\) From the mid-eighteenth century, the focus of knowledge in the building crafts shifted from trade guilds and construction sites to mass production and industry-sponsored scientific laboratories. \(^\text{243}\) Traditionally, the study of materials was established by an intuitive knowledge derived from a series of physical experiments—for example, by mechanically testing the tensile and compression capacities of a material. Later, at the beginning of the twentieth century, mathematic and scientific approaches were introduced, such as X-ray diffraction. \(^\text{244}\) These new approaches distinguished the science and study of materials from engineering disciplines and physicists and chemists began to be interested in materials also. \(^\text{245}\) Until World War II, materials science was the science of static materials and focus was on developing systems that were rigid and strong. The properties of these systems—mainly concrete, steel and glass—were optimised to withhold stronger force impacts and to last longer. The aim was to have as few movements in a system as possible. \(^\text{246}\)

A new concept of uniting the separated disciplines, including solid-state physics, metallurgy, polymer chemistry and inorganic chemistry, was developed to overcome the problem of disconnection.

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\(^{241}\) Metallurgy is the study of the physical and chemical behaviour of metallic elements and alloys.


\(^{244}\) Developed in 1921, ‘X-ray diffraction’ is the technique of measuring the distance between atoms in a crystal in which an X-ray beam is deflected when it passes through the crystal.


This resulted in the founding of the first official materials science institutes in 1959.\textsuperscript{247} With the rapid development of advanced microscopy and the discovery of microstructures within materials, a new understanding of material behaviour and properties was possible. The focus of research switched from the surfaces of materials to their inner structures.\textsuperscript{248} David Turnbull has described materials science as the ‘characterization, understanding, and control of the structure of matter at the ultramolecular level’, and that the understanding of the correlation of this structure to its mechanical, magnetic and electrical properties is the core of materials science.\textsuperscript{249} Since the founding of modern materials science, subcategories in the fields of material physics, material chemistry, material engineering, nanomaterials, crystallography and many others have been located under the umbrella of materials science.

According to the 2003 US National Research Council report,\textsuperscript{250} materials science and engineering are today interdisciplinary by nature and advances in the development of new materials often result from work responding to a specific need of a particular field, such as medicine or aerospace. Today, materials science related to architecture is linked via the engineering disciplines and is part of what is called ‘building science’.\textsuperscript{251} This newer discipline includes research topics such as energy consumption, stability/durability, sustainability and human physiology.

Since building crafts and science have split into a variety of specialisms, collaboration has become difficult due to the educational framework and different ways of thinking. Becoming cognisant of the synergy effects between architecture and materials science is assisting to understand the current relationships between architecture, science and technology.


\textsuperscript{248} Gordon, \textit{The New Science of Strong Materials}.


4.3 Architecture, Science and Technology

Even though architecture and science have evolved into two distinct areas, with science involving more rational thinking and architecture being more oriented towards the humanities, they share common goals. Both disciplines have a certain interest in shaping or ‘reshap[ing] the categories of visual perception’. On this correlation, architectural historians Antoine Picon and Allessandra Ponte state that ‘both contribute to the cultural construction of perception’ and further explain that science and architecture share an ambition to encounter and transform the environment and ‘above all to populate the world with subjects different from one period to another’. Further, William W. Braham and Jonathan A. Hale argue that the evolution of science and technology has had a strong influence on society and architectural thinking ever since.

The Relationship between Architecture and Science

Inspired by the industrial revolution and the revolution of science, architects began to use scientific images and metaphors and referenced architectural theories with science and technology to support their design strategies. For example, the biologist and mathematician Sir D’Arcy Wentworth Thompson’s notion, formulated in 1917, stated that form is the ‘diagram of forces’ influenced engineers and architects. Many adapted the work of Thompson: Le Corbusier interpreted Thompson’s ideas of ‘spiral shapes and complex proportional relationships … produced to his “Modulor” system’, whereas Louis Kahn was inspired by Thompson’s natural observations of algae and the observation

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253 Ibid


that structure and geometry were related. Thus, what is true for architecture is also true for science; Peter Galison explains: ‘Scientists use architecture to fashion and refashion their identity’. Moreover, famous architectural styles or theories are sometimes introduced in science as analogies to support scientific discovery and to establish a ‘picture’ that is accessible to the public. A good example of this is the naming of the carbon-60 molecule as ‘buckminsterfullerene’ (Figure 4.1). The name is a reference to the geodesic dome design of Buckminster Fuller (Figure 4.1) and describes the structure of the molecules. Such examples can allow me to argue that the relationship between architecture and science is two-way: architecture introduces ideas from science to generate new design and science uses architectural principles to communicate ideas.

Figure 4.1 visualises the spatial arrangement of carbon structures and the buckminsterfullerene in juxtaposition with the Montreal Biosphère of the 1967 World Fair Expo 67 in the United States designed by Buckminster Fuller. (Left image source: created by Michael Ströck and licensed for reuse under the Creative Commons License: Attribution-ShareAlike 3.0 Unported; right image source photo by Peter van den Hamer and licensed for reuse under the Creative Commons License: Attribution-ShareAlike 3.0 Unported)

Today, the engagement with science is not only limited to the borrowing of metaphors to express theoretical approaches, but has also expanded the vision of social context and technology in architecture. Architects and structural engineers are employing

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259 Buckminsterfullerene is based on 60 carbon atoms joined together. The discovery of this material has led to a new focus in nanoscience and nanotechnology. Encyclopædia Britannica Online, s.v.

‘evolutionary’ design strategies and genetic algorithms to optimise structures and define shapes.260 In this, architects and engineers have been influenced by Thompson’s theory that ‘any particle of matter, whether it be living or dead, and the changes in form which are apparent in its movements and in its growth, may in all cases be described as due to the action of force’.261 By applying evolutionary form-finding process, design operators can develop, for example, efficient structural solutions or an optimal building envelope for sun exposure. Martin Hemberg, who studied bioengineering, developed the computational design tool Genr8 together with computer scientists and architects in collaboration with the Department of Bioengineering of the Imperial College in London and the Computer Science and Artificial Intelligence Lab of the Massachusetts Institute of Technology (MIT). This tool works with growing algorithms to respond to environmental factors that are computer-generated by creating attractor fields and repellers.262

Professor Mike Xie from the Royal Melbourne Institute of Technology and his team have applied another approach from Thompson’s findings. They have utilised a bidirectional evolutionary structural optimisation (BESO)263 process to manipulate and design lightweight cellular materials, with the aim being to control and design synthetic materials with similar properties such as those that natural cellular materials encompass (Figure 4.2). In particular, the local control of physical, mechanical and thermal properties is promising in order to create lightweight materials with a maximum bulk or


263 The bidirectional evolutionary structural optimisation method allows elements to be removed from the least efficient regions at the same time as elements are added to the most efficient regions. Hence, a variation of optimised structural solutions can be designed by the constraints of loads, supports and material property. O. M. Querin, G. P. Steven and M. Y. Xie, 'Evolutionary Structural Optimisation (ESO) using a Bidirectional Algorithm', Engineering Computations 15, no. 8 (1998): 1031–48.
shear modulus. Today, the BESO approach is also embedded as an optimisation algorithm in design tools for architects.

![Image of microstructures and effective elasticity matrixes](image)

**Figure 4.2:** Microstructures and effective elasticity matrixes of two-dimensional and three-dimensional (3D) material cells with maximum bulk modulus for various volume constraints: (a) 50%, (b) 30%, (c) volume fraction is 30%. (Image source: Huang, Radman and Xie [Reused from Computational Materials Science, Vol.50, no. 6. X. Huang, A. Radman, and Y. M. Xie, Topological design of microstructures of cellular materials for maximum bulk or shear modulus, 2011, with permission from Elsevier](see Footnote 264)).

In this regard, the emergence of new digital design tools supports the re-establishment of links between architecture and contemporary science. Picon describes the opportunity that exists for architecture to be a bridge connecting art and science:

> By convention art is intuitive, personal and expressionistic, whereas science is rational and analytical. Vitruvius values of ‘commodity, firmness and delight’ touch upon the spiritual as well as the rational, upon the intuitive as well as the measurable. Thus in ‘traditional’ interpretation, architecture bridges art and science.

Currently, this bridge seems to be of interest to architects and scientists alike, and a diverse development of research interests concerned with new materials and technologies to re-inform the built environment has emerged.

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265 Design tools such as the add-ons Karamba3D™ or Millipede™ for Grasshopper have implemented the BESO approach.

266 Picon and Ponte, *Architecture and the Sciences*, 311.

Collaborations among architects and scientists—such as the on-going collaborative research by scientist Rachel Armstrong and architect Neil Spiller—architect Jenny E. Sabin and scientist Peter Lloyd Jones—outline the future potential of a shared interest in innovative solutions. Armstrong, a scientist working with architects, investigates how protocells as 'living' and 'intelligent' building blocks could self-assemble and adapt in favour of dynamically optimising their properties to the surroundings. The investigation involves hands-on experiments with the material and the utilisation of digital design tools. This collaboration between science and architecture was also promoted by Interview Partner No. 1, who believes that, with a combined workforce, meaningful architecture and innovation can take place:

I personally see in the future that we have to have more collaborative environments with real distributed responsibilities as for example in the research cluster of Frei Otto, where architects, engineers, mathematicians and others are bound by a budget and a research task and I think this is something where something really sensual is coming out.

Currently, collaborations between architecture and materials science are very limited and often do not pass the stage of research projects or functional prototypes, as the interview partners argue. However, research and design projects help to study ideas from proposed design studios in regards of fabrication and material design.

In the Project ‘Smart Screen’, for instance, architects and materials scientists have been working since 2006 to develop a shape-memory spring system that passively reacts to

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269 LabStudio, is co-founded by Sabin and Lloyd Jones in 2006, is a hybrid research and design network. Disciplines such as architects, mathematicians, materials scientists and cell biologists are collaborating, to extend the use of new materials and design tools. LabStudio, http://labstudio.org/ (accessed on 6th June 2012).


temperature change by driving a shutter system that operates without any additional energy consumption. The project is an on-going investigation since 2006 of how shape memory alloys can be applied to create passively operating sun shading devices with no mechanical and electronic control mechanisms. According to the architects the biggest obstacle is that not every SMA is suitable for this type of application, and more SMAs have to be tested and engineered in order to reach a state of a component that could be integrated in architecture.272

In this project, the collaboration was focused on adjusting and improving an existing material to fit the need of an architectural idea. Interview Partner No. 2 noted:

> For the Smart Screen project, we worked together with material engineers from an institute in Japan, where they manufactured the material to our wishes to be able to change the material regarding the room temperature.

Another example is the architectural office of Kennedy and Violich (KVA) that established its own materials research unit called ‘MATx’. This unit is dedicated to an ‘applied creative production across the fields of electronics, architecture, design and materials science’.273

The outcome of this collaboration leads to novel material applications such as the Portable Light Project. The project incorporates materials science, electronic engineering and design to deliver a simple and low-cost solar textile kit to harvest energy based on novel thin solar films. The aim is to supply light and energy to populated areas that have no direct access to the electrical grid (Figure 4.3).

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Figure 4.3 Portable Lighting Project, based on easy to access materials and the support of a do-it-yourself (DIY) initiative, the energy harvesting concept supports the people with energy efficient, easy to manufacture lighting concepts. (Source: Portable Lighting; http://portablelight.org/mexico06)

Nevertheless, the communication and collaboration between these different disciplines, architecture and science, must be emphasised to improve the use of novel materials. As Armstrong proposes, ‘scientists need to work outside their own areas of expertise’ and have to collaborate ‘with other scientific disciplines and the arts and humanities’ to support the development of new technologies. The design disciplines are also recognising this trend and Lefteri foresees a change of communication and collaboration between design and science disciplines. He proposes that designers will be part of future material development because they bring a new level of knowledge and a different perspective to materials science. Lefteri is referring to the lack of architectural and scientific interdisciplinary work and observing that designers have skills to identify the needs of a market. Further, he expresses that a designer’s approach to material experiments is different from that of a materials scientist, and that this new input coming from designer can lead to new outcomes and applications of a material system. As an example, Lefteri refers to new products that have been developed by designers, such as the conductive ink by Bare Conductive Ltd and the ‘macrokinetic materials’ by Sarat Babu, to match their needs (such as access to an environmentally friendly and inexpensive conductive ink as in the example of Bare Conductive Ltd). Based on this evidence, it can be argued that designers are becoming an active part of the discussion

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276 https://bareconductive.com/

277 http://www.bread.uk.com/core/?p=69
of material innovation that can bridge the gap between science and technical evolution.278

Science and the design disciplines have different world views: Sydney Gregory has described science as an analytic approach, working with a ‘pattern of problem-solving’ to answer questions that exist in nature, and design as a constructive approach, working with a ‘pattern of behaviour’ by inventing things that do not exist yet.279

4.4 Different World Views

According to Addington and Schodek280 and John Fernandez,281 architects and engineers are generally trained to use a ‘material product’ that they choose from a catalogue of applications. This training is linked to the fact that the construction industry is a branch of trade that is centred on standards. The applications are ready to use products, reflecting materials that are tested and certified by regulation authorities. This standardisation, originating from the early days of the industrial revolution, makes it difficult to bring new materials into the architectural design process. That architects prefer to choose an existing, already categorised material product rather than investigating novel materials was confirmed during the conducted interview with Interview Partner No. 4, who explained that architects tend to be inspired by novel technology and materials:

*We look more to the outcome of materials and products but not so much into their design process. I think the new materials to be used in architecture should somehow be available and we rather should not be involved in the process of developing and making novel materials because it is very time consuming. But if they are in the*

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279 S. Gregory, cited in Nigel Cross, 'Design as a Discipline', in Designerly Ways of Knowing (Basel: Birkhäuser, 2007), 95–104; 121.

280 Addington and Schodek, Smart Materials and Technologies in Architecture.

market, it is important to think about what we can do with them and what it is the potential of the various materials.

In contrast, the materials know-how of a materials scientist is concerned with the pure fabrication of materials that are developed for a particular purpose. These materials tend to be developed in abstract and often do not match the immediate needs of others, as Interview Partner No. 5 explained:

We sometimes develop a material or a structure where we might think we know that it is good for but an actual fact is that when we talk to other people, industry partners or other institutes, it does not really go anywhere. They are just not interested.

A similar problem can also occur when an architect or designer has developed an idea for a new material and is looking for potential partners to realise the product. For example, Interview Partner No. 7 stated:

I have had a contact to a German institute and I came with a concrete idea for an application and the problem was that they only wanted to start to work if I or somebody else would pay them for the job and to sign a complex contract. Where besides other conflicts the patents should stay in Germany. So all in all this was unacceptable.

Lawson explains that one of ‘the essential difficulties and fascinations of designing is the need to embrace so many different kinds of thought and knowledge’. In contrast, scientists are able to operate without even knowing what the designer might think about their product. Lawson goes on to say that for ‘designers life is not so simple, they must appreciate the nature of both art and science and in addition they must be able to design’.

Fernandez sees in these differences a potential that can lead in architecture to novel innovative ideas ‘without the knowledge of potential obstacles’ and that it allows the materials scientist ‘to seek out applications for new materials without being discouraged by the idiosyncrasies of construction and architecture’.

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283 Ibid.

284 Fernandez, Material Architecture, 30.
However, while collaborations between, for example, the engineering and chemistry disciplines are not out of the question as Küchler has stated,285 Thomas S. Kuhn, an American philosopher and physicist, argues that while the scientist is isolated from the rest of the world, this isolation is not, and never has been, complete.286 Addington and Schodek try to explain this disjuncture by highlighting the different interests of architects, engineers and scientists:

*So while architects try to wring a unified visual aesthetic from these materials, engineers and computer scientists are looking to build a unified system of the technologies. Their version of the smart home or house of the future is a formless one; the physical aspects of the architecture recede into the background as performance is foregrounded.*

To understand the current situation, these differences will be considered by discussing the contrasting ways architecture and science are taught and their differing scales and representations.

**Education**

The methods used to solve a problem in science and design differ. Lawson describes an experiment in which he asked final year architectural students and postgraduate science students to design a one-storey structure from a set of coloured blocks. The only rule was to optimise either the red or the blue colour. What the optimisation was at the end and what relationship the bricks had to each other was not pre-set. In his analysis of the findings, Lawson explains that the scientists tried a ‘series of designs which used as many different blocks and combinations of blocks as possible as quickly as possible’. They were looking for rules that would lead to allowed combinations of blocks to search for an arrangement to ‘optimize the required colour around the design’. In contrast, the architectural

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287 Addington and Schodek, *Smart Materials and Technologies in Architecture*, 201.
students ‘selected their blocks in order to achieve the appropriately coloured perimeter’. This was a repetitive task ‘until an acceptable solution was discovered’.288

The search for rules like the scientists in Lawson’s experiment applied is an exercise based on objectivity: an evaluative process that utilises instruments and measurements to justify findings. Brooks explains that this approach comprises the possibility that the visual perceptions and technical measurements may be not precise enough, so an experiment will be repeated to ‘achieve the same result through different experimental designs’.289

Thus, the scientist follows a pattern of rules to ensure the truth of his or her hypothesis derived from the applied experiments. In contrast, the designer works visually and descriptively, using drawings and sketches. According to Lawson, the designer has a greater freedom to manipulate and alter her or his ideas conceptually. Ideas can be tested by simply adjusting the sketch ‘and the implications immediately investigated without incurring the time and cost of constructing the final product’.290 As such, the designer is encouraged to undergo ‘experimentation’ that liberates their creativity and leads to a unique solution.291

That scientists are ‘concerned with how things are’ whereas designers are ‘concerned with how things ought to be’ has also been noted by Simon.292 This argument seems still valid today, as Interview Partner No. 6 expressed:

 Architects are qualitatively educated and engineers and scientists are quantitatively educated and that is already one big problem for further communication. ... The value system is not matching! So the question is really does an architect now have to become a little physicist or a chemist? Or is it more a question addressed to the material scientist that he has to become more familiar with the ‘real world’. I assume the truth is somewhere in the middle.

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288 Lawson, How Designers Think: The Design Process Demystified, 43.
291 Ibid.
Lawson’s experiment, Brooks’ description and the response given by the interview partners can be best summarised by the engineer Eugene S. Ferguson, who has stated that ‘visual, non-verbal thought dominates the creative activity’ of technicians and engineers. In contrast, the scientist is ‘more likely to manipulate concepts, mathematical expressions, or hypothetical entities’. However, it is clear that this strategy is not only applied by scientists. Contemporary architects and engineers, for example, described in From Control to Design - Parametric / Algorithmic Architecture, also work in a similar way; for example, in their utilisation of algorithms in defining forms and optimisation of the shapes of elements to rationalise a design.

In this sense, Ferguson’s argument can only be a general statement that highlights the distinct division of the design and science disciplines. In contrast, materials science is difficult to locate because it is not only affiliated with science but also with the engineering disciplines. In the recent formulated education guidelines, Teaching Materials Engineering, from the United Kingdom Centre of Material Education, Peter Goodhew claims that materials science needs to be separated from pure science because although materials scientists work scientifically with modern analyses and testing devices, they also have to know how to choose a material and how a specific material can support the design. Further, they are trained to design the material itself and to alter its properties to achieve higher performance.

In this regard, a clear distinction needs to be made between the purely academic-driven materials scientist—who is concerned with theoretical problems and related to the ‘pure’ science—and the practice-oriented materials scientist, who is more aligned to engineering. Henry Petroski suggests that the distinction between these two branches of materials science is blurred and expresses this by using the terms ‘scientific engineering’ and ‘design engineering’. These are positions or tasks in which the one operates in the

294 Tomoko Sakamoto and Albert Ferré, eds. From Control to Design - Parametric / Algorithmic Architecture (Barcelona: Actar, 2008).
field or with the methods of the other to find a solution to a specific problem or questions that lead to new discoveries or inventions. To overcome this diversity and to bridge the gap between science, engineering and architecture, Brownell argues for the integration of materials science aspects into architectural education. He foresees that in the future, architects will possess a basic understanding in ‘materials science, industrial ecology and advanced building techniques’. In his mind, architects will become ‘students of technology, incorporating innovative techniques and systems to push the boundaries’.

This recent discourse gives me evidence for the need and exigency of a closer framework between materials science and architecture. Further research into this topic seems inevitable to develop new modes of education. In the light of my personal experience I will elaborate on this topic further in Chapter 7: Conclusion and Discussion.

Scale

Architecture, engineering and materials science depends on an understanding of the different scales in which each discipline works (Figure 4.4).

![Figure 4.4: Juxtaposition of science and design driven Approaches. Science is starting at an atomic scale to first understand how thinks work before he proposes a design. The designer, architect imagines first a design proposal and is starting with this initial idea to explore how he might be able to create it. (Image adapted by author; source: Ashby)](image)

Many materials, whether organic or inorganic, have a hierarchical structure on every scale of length—this is a multi-level interdependency that regulates the properties of the material. This relation between structure and property is the key aspect and the main

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299 Michael F. Ashby, 'Teaching Materials and Processes to First and Second Year Students' (Granta Design Ltd., 2007).


112 Architecture and Materials Science Synergies
interest of materials scientists in order to manipulate and control the properties of the materials or even to design new materials with novel material behaviour. Interview Partner No. 5 gives an example and states:

What I am particularly interested in is how to design the structure of materials on micro- and nanometre scales all the way up to the millimetre scale. I am also interested in terms of designing the structure of a material and then making those materials scalable to centimetre or meter for applications.

Even though scale is relative and units more or less describe the relation of one object to another, it is exactly the scalability—the translation of the materials from the small to the big—which is one of the obstacles in materials science. The production of a novel material or a new material component is usually developed in a sterile and controlled laboratory environment. The primary goal of materials science research is not the making of a final product and research facilities are not geared for this; thus, further industry research is needed to develop the material into a feasible product. The manufacturing processes currently used to transform a science-based finding into a commercially available product are often too expensive or under-explored, as Ashby, Ferreira and Schodek argue. My interview Partner No. 5 explains that:

The biggest obstacle to us is that we are very good in making materials by focusing on how to design a structure on a small scale but you know the pieces that you are making tend to be max. five to ten centimetres big. ... But then, it is a problem finding the right company to work with and to help us to scale up the material.

The scalability of materials so as to ensure their usability in construction is not the only problem in terms of design and manufacturing processes; there is also the problem that material properties are most likely not linearly re-scalable. Reiser comments that ‘in architecture, the inherent scalability of a material does not directly correlate to the scalability of material behaviour’. Human bone structure is a good example of interweaving of structures at every scale to create a structurally optimised material.

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The microstructure of human bone consists of ‘hollow fibres composed of concentric lamellae and of pores’, and the lamellae themselves are again built of ‘fibres, and the fibres contain fibrils’. The orientation and the density of the fibres are responsible for the physical properties of the bone; but if scaled to use as a structural material, bone would begin to fail under its own weight.

For the engineer, scale is an important factor in the structural design and material selection process. Leonardo Fernández Troyano illustrates this statement by using the example of designing and constructing a bridge. He gives evidence by comparing two bridges, a small bridge with a 20-metre span and a large one with a 200-metre span. He explains that the main load for the small bridge is often the live load, such as a ‘vehicle that is travelling over the bridge’, rather than the weight of the structure of the bridge itself.

In comparison, the main forces borne by the bridge spanning 200 metres are most likely those of its own weight, ‘which may give rise to secondary effects’.

This is a decisive factor in dimensioning the structural elements and the choice of materials for the design.

Today, the study of material structures and their behaviour on a micro-level has become of interest as a research field in architecture and structural engineering, supporting a possible link to material science and a better understanding of materials. A material’s physical properties have become an ‘active parameter for the design process’ in terms of improving their implications. Moreover, the detailed view of a material assembly informs architecture and architects are recognising the knowledge derived from the micro-scale of material layers. Recent research by both Neri Oxman and Norbert Palz, for example, shows the potential of ‘tuneable’ and ‘designable’ material structures based on the

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304 Lakes, 'Materials with Structural Hierarchy'.
305 Ibid.
micro-level by the utilisation of additive fabrication technology. In this, digital computation and morphogenesis can be seen as an opportunity leading to a ‘shift from geometric-centric to a material-based’ approach and an understanding of the significance of the behaviour of materials in their own complexity to create real-time adaptive solutions.

That scalability and the understanding of the material structure and behaviour ‘has far-reaching implications for architecture’ is recognised by architects today. Reiser sees an advantage in this, arguing that ‘the medium of these implications is the diagram, which provides an abstract model of materiality’.

The experiences that I gained at B+G agree with these points about scale. In the design process of an architect, the scale of a structure is becoming an issue of second or third thought, especially if he or she is working on small-scale projects like pavilions.

**Modes of Representation**

‘Representations’ are abstracted and simplified models to reduce the complexity of the physical world. These are utilised by architects, engineers and materials scientists alike. However, the existing modes of representation vary, and while some of them share the same framework, others are clearly distinct. This section reports on various modes of representations to discuss another aspect of the differences and synergies that exist within the relationship between architecture, engineering and materials science.

Models used to represent the intentions of a desired architecture visually can be in the form of diagrams, drawings, digital abstract or physical models and computer-generated images. With these tools, the architect describes the surface texture, colour, sensual effects, dimensions and other related information. Therefore, a representation is usually a description of a material system rather than of a single material itself. For example, the façade of a building can be described as smooth, rough, flexible or colourful,

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transparent or light. Picon argues that this type of representation is not appropriate for a ‘precise, unequivocal, and unique material reality’ and further states that ‘even the most convincing techniques of representation do not correspond fully to the experience of the built reality’.\textsuperscript{314} This detached reality can be explained by the use of the Cartesian space, which is the preferred mode of operation in architecture.\textsuperscript{315} The advantage of Cartesian space is that every point can be described by its coordinates and that it defines the geometric relationships between shapes and space. Therefore, it ‘implies the physical conception of space’, in which the object and the space in between can be ‘measured, divided, shaped and moved’.\textsuperscript{316}

In contrast, the scientist deals with a level of scale that might not be instantly visually present to him or her; therefore, the scientist has to work with models to represent and communicate their theories and observations.\textsuperscript{317} This can be an up-scaled model\textsuperscript{318} that represents the relation of atoms, protons, electrons and neutrons to describe a periodic element, for instance. Other forms of representation include numerical representations, equations or simple charts and diagrams. The already mentioned periodic table of the elements is a representation model that displays the relationships between the known elements.\textsuperscript{319} Presently, many different tools, including common architectural design tools such as Autodesk® Maya®, are widely used to visualise and construct micro and nano structures. The plug-in cadnano\textsuperscript{320} for example, combines the geometric principles of


\textsuperscript{315} Greg Lynn, \textit{Animate Form} (New York, NY: Princeton Architectural Press, 1999), 10–11.

\textsuperscript{316} Jeremy Till, \textit{Architecture Depends} (Cambridge, MA: MIT Press, 2009), 120.


\textsuperscript{318} For example, the so-called ball and stick model represents the relationship between atoms and visualises the proportional distance between the centres of the atoms. Further, the given colour of the different atoms describes the diversity of those of which a molecule is made. Theodore L. Brown, \textit{Making Truth: Metaphor in Science} (Urbana, IL: University of Illinois Press, 2003).


\textsuperscript{320} \url{http://cadnano.org/}
nano structures with finite element analysis, providing information about stability and assembly processes. 321

The representational tools of an engineer are similar to those used by materials scientists. Due to their historical engagement with materials from structural points of view, over time, engineers have developed a repertoire of representation techniques that help to define and analyse a structure as well as to mediate the performance of the structural system. For example, Hooke’s law 322 and Young’s modulus 323 are two common representation tools used to describe the structural behaviour of elastic and brittle materials such as steel, carbon fibre, glass, rubber, membranes and soil. 324 To visualise the relationship between the load and the deformation of a material, a commonly used representation tool is the stress—strain curve diagram (Figure 4.5). 325 This diagram is used to display attributes such as stiffness, brittleness or yield strength.

Figure 4.5 Stress—strain curves of different materials (not to scale) From left to right: brittle ceramics fail suddenly and unpredictable once the loads exceed the material capability, plastics reveal a certain resistance of


322 Hooke’s law describes the linear proportional relationship between the extension of a spring and the applied load. The law is an approximation of the reality of the material’s behaviour. Gordon, *The New Science of Strong Materials*.

323 Thomas Young developed Young’s modulus, which is based on Hooke’s law. Young’s modulus describes the elastic flexibility of a material that is dependent on stress and strain. The flexibility of a material depends upon both the Young’s modulus and its geometrical shape. Ibid.


325 The relationship between stress and strain is used to measure and display the energy absorption characteristics of a material under an applied load. Fernandez, *Material Architecture Emergent Material for Innovative Buildings and Ecological Construction*, 90–91.
deformation under increasing load conditions before they deform even further and metals show a continuous deformation under increasing loads until total failure (image adapted by author; source: see footnote no. 317)

Besides using this visual representation of material behaviour, the overall structural behaviour is represented in an abstract mode, either by the discussed force–flow diagrams and computational methods in Chapter 2,\textsuperscript{326} or in numerical representations to test conceptual ideas. Rice once said that the perception of a drawing is misleading the physical reality and commented on the environmental forces like wind or temperature effects that a drawing cannot express.\textsuperscript{327}

The discussed modes of representation are design tools to work with and make sense of material properties on an abstracted level. Diagrams and drawings help architects to communicate their vision, while engineers and materials scientists can design material systems via diagrams and schematics.

In that respect, a closer look into representation techniques and tools might give evidence how to assist a better communication.

### 4.5 Sources of Material Information

Work with novel materials may pose a challenge due to their unknown intrinsic\textsuperscript{328} and extrinsic\textsuperscript{329} properties that lead to unexpected and new behaviours. Existing research and design tools that support material-driven decisions in architecture can help to bridge the explained gap between materials science and architecture. This section looks at material sources and applications and explores the particular challenge of material selection that ties together architecture- and science-oriented approaches.

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\textsuperscript{326} See ‘Material Representation in Practice’ in Chapter 2.


\textsuperscript{328} Intrinsic properties are related to the atomic structure of the material and include mechanical, physical, thermal and optical properties.

\textsuperscript{329} Extrinsic material properties are not related to the atomic structure; instead, they are related often to the context of the material. They include economic, environmental and societal properties.
Today’s material diversity is a significant challenge for all involved in working with materials. In 1997, Ball estimated that there were between 40,000 and 80,000 materials to choose from when fabricating an artefact. Now, 15 years later, this number has probably doubled. There are numerous material books on subjects ranging from materials science and product design to architecture and structural engineering, which describe the correct use of a material in its correct context. So-called material collections inspire the reader and make the topic of materials accessible to a broad audience. There are three types of material books:

1. *Coffee table*. These are meant to be an inspirational and metaphorical source for designers of every discipline. Even though some authors would argue that their books are like catalogues that every architect should have to access every day, the materials displayed are frequently out of context and show only a few architectural applications.

2. *Academic/Science*. In a broad sense, these books are manuals for engineering studies, describing how to use the materials in the right context. They provide a profound knowledge of material properties and are often equipped with data sheets on the typical properties of materials. These details concerning the material properties, combined with case studies from engineering-related disciplines, help to guide readers through the material production and selection process.

3. *Arts and crafts*. These books examine the use of materials by considering examples and providing guidelines. They mainly address the ‘do it yourself’ (DIY) community and everyone who is interested in working and experimenting with unusual materials. These books, such as *Fashioning Technology: A DIY Intro to...*

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331 The MatWeb online database (www.matweb.com) already provides technical datasheets for over 88,000 materials.


Smart Crafting by Syuzi Pakhchyan, help readers to understand the material in relation to the environment and, more importantly, show exactly how to work with the material. These books tend to work with small-scale examples due to the nature of fashion and product design. Smaller scale projects also encourage the reader to reproduce the presented work since the aim is to demonstrate that everyone can be a creative and innovative person within his or her own four walls.

Databases

Material property databases, which offer online access, exist for every relevant sector in engineering and provide the technical data necessary for calculating the behaviour of the material under certain load cases and other force- and energy-related impacts. A new approach to both the classification of materials and to increasing the use of materials in other disciplines is the use of developed software tools and online databases. Here, a re-contextualisation of the definition of materials is approached to cross-link design factors and physical and chemical properties to increase the use of materials in other disciplines and to drive innovation. As additional attributes can be searched for, the choice of a material becomes another dimension of design decision-making.

These selection tools help the architect and the designer to decide which material best supports the design intention. Designers can choose a material according to their chemical and physical properties such as density, durability, weight and strength. Aesthetic and design-relevant properties are also included in such selection, such as the description of the surface topology of a material or the smell and light transmission

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334 Pakhchyan’s work contributes to research on the intersection of culture with technology through the investigation and design of technological systems and novel material applications. Syuzi Pakhchyan, Fashioning Technology: A DIY Intro to Smart Crafting (Sebastopol, CA: Make:Books, 2008).

335 Some of the databases used most often are Engineering ToolBox (www.engineeringtoolbox.com), and MatWeb (www.matweb.com).


Some of the selection tools available even provide detailed analyses of the life cycle and ecological footprint of a material.\textsuperscript{339} In structural and mechanical engineering, for instance, these databases provide a pre-set material list that can be incorporated with existing analysis tools. The online material catalogues and databases provide the necessary data with which to calculate the deflection of a material under loads according to the material’s properties. These tools are becoming accepted in design practice\textsuperscript{340} and are also used to stimulate and educate students to use novel materials in the realm of architecture.\textsuperscript{341} The acceptance of those sources seems a necessary step, since material education has been traditionally examined through the filter of the construction trades, especially in architecture.\textsuperscript{342} Material databases in combination with digital design tools not only extend knowledge of existing materials but also highlight relationships between different materials and design tasks. Further, the Young’s modulus of materials can be compared with their costs per volume to define the best valuable material for a structure (Figure 4.6), for instance,\textsuperscript{343} or the softness of a material can be compared with its warmness (Figure 4.7) to verify the tactile attributes that we have in mind.

\textsuperscript{338} Liat Margolis, 'Encoding Digital and Analogue Taxonavigation'.

\textsuperscript{339} CES Selector is a PC software application, developed by Michael Ashby and the Granta software company. The software is developed to support material selection based on multi-objective process by graphical analysis of materials data.


\textsuperscript{342} Oxman, 'Structuring Materiality'.

Figure 4.6: Multi-criteria selection map: density versus price. (Source: courtesy of Michel F. Ashby and Granta Design Limited)

Figure 4.7: Multi-criteria selection map: warmth versus softness. (Source: courtesy of Michel F. Ashby and Granta Design Limited)
However, Schodek and Addington describe these selection tools as being mysterious to the engineer or scientist:

> It appears to be no common thread present in this descriptive system, yet it has been very useful to the fashion designer. The thread that is present is not a science-based understanding of the materials described; rather the approach touches on the information needed by the working fashion designer in selecting and using materials.\(^{344}\)

Another trend that supports the designer’s choice and stimulates imagination has been physical databases and material collections, which have become popular since the late 1990s. By storing and collecting a huge variety of materials, architects, designers, manufacturers and clients can visit and experience the real qualities of a material. Companies like Material ConneXion\(^{®}\),\(^{345}\) Materia\(^{346}\) and m@tériO\(^{347}\) help to shape a new understanding of material selection by offering the option of selecting a material according to its tactile properties and ecological data, such as glossiness, translucency, structure, UV resistance, renewability, odour and chemical resistance.\(^{348}\) The Finnish architect Juhani Pallasmaa argues similarly that visual experience cannot be the only parameter through which to select items and understand the material world. He describes the everyday experiences of architects as a significant multi-sensory approach that measure space and scale by the ‘eye, ear, nose, skin, tongue, skeleton and muscle’.\(^{349}\)

While these material libraries provide design disciplines with insight into alien materials, Ed Thomas argues that there is the danger that ‘boutique materials’\(^{350}\) will be displayed. He proposes that instead of spending time looking for fancy materials, the materials


\(^{346}\) Materia (homepage on the Internet, Amsterdam: Materia; n.d.), http://materia.nl.

\(^{347}\) m@tériO (homepage on the Internet, Paris: m@tériO; n.d.), http://www.materio.com/.

\(^{348}\) Margolis, ‘Encoding Digital and Analogue Taxonavigation’.


\(^{350}\) Ed Thomas is the global apparel materials design director at Nike Inc. Quoted by Chris Lefteri, in *The Importance of New Materials.*
should be questioned and made sense of. First of all, the materials have to be understood; then someone can think of what might they offer.

Materials not only influence the architect in terms of choosing the ‘right’ material, but can also act as design drivers. The internal logic of materials can stimulate the creation of geometric compositions or the control of a material to reach an optimised material system, which can play an important role in the design process.

4.6 Approaching Materials

As Ashby and Johnson have described and illustrated in discussing the role of science in design processes, materials science can have a strong influence on design. In particular, they refer to the stimulation of design through imagination that comes with new materials. Examples of this include when a material produces an emotional response via its visual appearance or a tactile experience, or offers the creation of a new formal aesthetic through a fluent geometric expression. With new structural, functional and sensorial features, materials, alongside new fabrication and manufacturing techniques, are influencing design processes and outcomes.

Figure 4.8: The role of science in design innovation (Image adapted by author; source: Ashby and Johnson)

In general, we can differentiate two approaches to material exploration and design: the bottom-up and top-down processes. Ashby and Johnson make the distinction between

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352 Ibid., 11.
bottom-up and top-down approaches to explain the differing design procedures of science and design. In materials science, there is at first the functionality of the atomic structure of interest and the scientist operates at the nano- or micro-level to change the material structure. In contrast, architects tend to design first at the macro-scale—the overall shape—then searches for suitable materials after setting the design. However, this outline is a generalisation of the design process, especially in architecture, in which there is a rising interest in interdisciplinary design that seeks to collaborate fluently in the early design phase with engineers, contractors and fabricators, as Branko Kolarevic argues. Today, physical material experimentation, in combination with design exploration through digital simulation, is a strategy that supports the understanding of materials systems. Under the umbrella of the emergence and evolutionary strategy of biological systems, aggregate performance models of materials and geometry are supporting the understanding of material properties to be integrated in the design process. The focus on only a ‘geometric representation of form is not sufficient when considering material properties and their physical interaction with the environment’. The desire to work with a material’s properties and the physical environment leads architects to apply design strategies that are driven by material properties and behaviour – ‘a material-driven design process’ as I experienced it personally in practice, in the SIAL environment and through the responses of the interview partners.

The same is true for the integration of novel materials; De Landa states that a ‘challenge will be to inject new life into infrastructure by embedding into its constitutive materials some of the negative feedback that already animates servomechanisms’. Further, both De Landa and Königs argue that new dynamic materials offer not only the potential for the increased

performance of a design but also can lead to design proposals ‘changed by something that comes from within the materials’\textsuperscript{359} as well as influencing, via the transferred knowledge of the material properties, new design challenges to be addressed.\textsuperscript{360}

A closer look at the different approaches that the two disciplines of architecture and materials science are applying will increase an understanding of the relationship between them.

**Science Approach**

The material-driven design process in materials science is based on the atomic structure of the material. The manipulation of this structure leads to changes in the material’s properties and behaviours in a larger scale material system. This relation termed a ‘multi-scale process’; it describes the different length scales, their properties and how they work together.\textsuperscript{361,362}

Nanotechnology, one modern materials science field, applies both processes. In their book *Nanomaterials, Nanotechnologies and Design: An Introduction for Engineers and Architects*, Ashby, Ferreira and Schodek explain that the starting point from which to design a new material is often the atomic level and from there onwards the material can be built up to form larger structures.\textsuperscript{363} This approach seems to be a preferred design process, as noted by Interview Partner No. 5:

\begin{quote}
We specialise in bottom-up methods; we really like to try to bring in ideas from nanoscience and from microstructure evolution to really make materials designed from the bottom up, and the self-assemble from bottom up.
\end{quote}

\begin{footnotes}
\footnotetext[359]{Manuel DeLanda, 'Material Complexity', 14–21.}
\footnotetext[360]{Ulrich Königs, 'Adaptive und selbstorganisierende Systeme in der Architektur'}
\footnotetext[363]{Ashby, Ferreira and Schodek, *Nanomaterials, Nanotechnologies and Design*, 7.}
\end{footnotes}
The advantage of this approach is a ‘controlled self-assembly process’ based on the internal information of the molecules that bond to form a nano-structure. Typically in materials science, a combination of physical experiments and digital analysis tools provide evidence to predict how to improve properties. Therefore, the formulation of a theory, digital and physical simulations, as well as experiments, inform each other to provide a body of knowledge for the systematic development of new materials.

Physical experimentation is the tool of choice for engineers and materials scientists to use to either verify their theories or collect a dataset that describes more precisely the material property to define a standard. However, experiments can also have an educational use that can help to explain the material properties. The materials scientist Mark A. Miodownik illustrates this using the example of cutting ice:

... using simply a wafer of aluminium nitride, [which] provides a nonmathematical sensual way to discuss the thermal conductivity of materials. In other words, the sheer extraordinariness of some materials demands explanation of the science that underpins them.

Besides physical testing, materials science relies on digital computing technology. Similar to the engineering disciplines, materials scientists utilise finite element analyses (FEA), computational fluid dynamic and topic-specific material processing tools. In materials science, the aim of a simulation is a detailed, realistic and reliable model. The simulation of material properties is a particularly important method to advance the understanding and prediction of materials from the atomic to macro scales. According to Richard Catlow, these computational models provide ‘general insights and an understanding of the simulated system’, ‘assist the interpretation of experimental data’ and can aid in obtaining ‘numerical data on important parameters, which may be either difficult to measure or entirely

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364 Ibid.


368 Such as molecular dynamic computation, cellular automata and X-ray scattering.

369 De Borst, ‘Challenges in Computational Materials Science’.
Further, simulation tools are being utilized to test ‘various environmental forces and impacts’ to accelerate the categorization of a material, to verify its performance and to apply changes according to the results to create a ‘better’ material. Inaccessible to experiment. An example is the propagation of cracks in concrete elements. This is a highly computationally intensive simulation process that tries to predict and calculate the right ‘shape’ of a crack in concrete. In terms of dynamic responsive materials, FEA and computational fluid dynamics are applied to simulate the super-elastic behaviour of, for instance, shape-memory alloys (SMA) under thermal impact. The advantage of these methods is the integration of datasets derived from physical experiments to inform and increase the digital simulation. However, what these methods have in common is that they are not easy to use and lack a dynamic modelling process due to the high computational complexity. This drawback is recognized in materials science as a constraint that hinders fluent collaboration with industry partners that expect solutions in a short timeframe.

Design Approach

Marek Kolodziejczyk\textsuperscript{376} and the early hanging models of Antoni Gaudí, architects like Lars Spuybroek\textsuperscript{377} defined new models of material representation and contributed to another level of material thinking in architecture. These studies of material behaviour and properties can be utilised to ‘find’ the right form of a structure for an optimal force flow, as the first hanging-chain models of Gaudí and the later tensile models of Otto display.

As in the material experiments of materials science, these models work with actual physical parameters. Nonetheless, the chain models, for example, are only form-finding tools that give evidence of the gravity loads of the model. As a result, these models only work with an abstracted material system and do not mirror the true material performance of a specific material; thus, they need to be interpreted properly to match reality.\textsuperscript{378} For example, Gaudí combined his form-finding technique with results from physical compression tests of the stones that he used. His findings were later translated into equivalent weights to match the small-scale reality of his chain model.\textsuperscript{379}

Overall, studies of material models are valuable tools for gaining familiarity with material properties so that they can be integrated into the design process. Ashby and Johnson argue that this strategy is especially true when it comes to materials with which the architect is not familiar.\textsuperscript{380} Often, the material description lacks information about specific environmental effects that the architect wants to address. Coinciding with Ashby and Johnson’s argument, this proposition was affirmed by the interviews undertaken in the present research as Interview Partner No. 2 exemplifies:

\textit{We research materials in general and then we try to find architectural applications for them. We look at their capabilities and their performances. It is more bottom-up rather than top-down research.}


\textsuperscript{380} Ashby and Johnson, \textit{Materials and Design: The Art and Science of Material Selection in Product Design}. 

\textit{Architecture and Materials Science Synergies} 129
Interview Partner No. 6 explained that work with small-scale projects that correlates with novel design ideas is a tool to investigate the properties of a material. He suggested introducing pavilions to gain the necessary practical building experience:

Small-scale projects like pavilions can help to understand the material properties and to show clients and manufacturers the potentials. My colleagues are using the pavilion as an experimental laboratory and a case study to introduce new ideas and techniques and after the analysis of the results of the pavilion they try to apply the new gained ideas into their real projects.

Alongside physical interaction with materials, gained knowledge about the material’s capabilities and limitations, the ‘transposition of the performance of physical materials into a computational realm’ is today a tool to enhance design parameters.

Since the 1990s, the simulation of spatial properties, especially the relationship between an object and forces, has been used as a design concept. In his book *Animate Form*, Greg Lynn describes this approach as a ‘co-presence of motion and force’ that shapes form by introducing a design space that is a ‘medium of motion and force’.

Software allows for the manipulation and creation of form under force parameters similar to those in the real world. An object can be morphed, deformed or ‘emerge’ through the introduction of environmental parameters. The Bubble BMW Pavilion (Frankfurt am Main, 1999) by German architect Bernhard Franken is an early example of this approach. In *Transparent Kunststoffe: Entwurf und Technologie*, Simone Jeska describes the process as two ‘water drops’ that were simulated in the digital space by the internal pressure and surface tension. The collided drops created one shape that was later translated into the built form.

With regard to material-driven design, this approach has its limitations due to limited control mechanisms and computational power. Further, as this approach does not take into account real material conditions, the method can only be a conceptualised form-finding tool.

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Today, with the rapid on-going development of computation protocols and hardware, this approach may again be a potential solution for engaging and experimenting intuitively with material properties at an early design phase.

Prominent examples are the real-time physics simulation tool Kangaroo, developed by Daniel Piker for Grasshopper, and the various physical game-engine libraries for the programming language Processing. Piker describes his software as a bridge between physical modelling and virtual modelling. On his blog Space Symmetry Structure, Piker explains the use of virtual materials, which have no real world analogue. He argues that we can invent new custom materials to maintain a wider range of possible geometric properties that he calls ‘pseudo-physical materials—virtual materials’. The limitation with this approach is that a physics game engine is still working with an approximation of the real behaviour. However, from my observations and design studies, I can confirm that this approximation leads to an initial understanding of dynamic material behaviour.

The increasing interest in a material computation design process to not only simulate but also design with material properties supports the development of analytical design tools.

The growing palette of stand-alone or bespoke software tools developed can testify to this. With such tools, the virtual form generation is based on real physical events. Material properties can be assigned to an object and the force conditions can be applied. Based on the optimal force flow, for example, the overall height, shape and size of profiles as well as even the choice of material can be evaluated almost in real-time. The decision-making process via form finding, structural optimisation or other environmental impacts can lead to a better understanding of a material’s properties. Case studies using the structural analysis tool Karamba3D testify to this.

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385 The real-time CADenary tool v2 (Axel Kilian and John Oehsendorf, 'Particle-Spring System for Structural Form Finding', Journal of the International Association for Shell and Spatial Structures, 2005; the SMART tools (SMART Group of Happold, 'Welcome to the SMART Solutions Network', SMART Solutions Network: Simple Innovative Solutions to Complex Engineering Problems [website on the Internet, n.d.], http://www.smart-solutions-network.com/); and the Topostruct and Millipede tools (Panagiotis Michalatos and Sawako Kajima, [website on the Internet, n.d.], www.sawapan.eu) are some of the tools available besides the sophisticated analysis tools that mostly work with force-related algorithms to optimise and design with material constraints.
4.7 Summary, Chapter 4

This chapter has identified some of the key issues slowing down the integration of novel materials into architecture. The origin of materials science and the characteristics of materials scientists were explained as background to the current situation of the juxtaposition of architects, engineers and materials scientists. To emphasise the differences but also to outline possible synergies, the different worldviews of these disciplines were discussed, such as the focus of materials science on micro-scale problems and the macro-scale focus of architects. The specialisation of the disciplines has resulted in not only different working methods but also differences in how each discipline perceives the others.

Further, obstacles that were presented by the introduction of novel material and technology approaches have been discussed. In looking into the relationship between material selection tools and possible collaborations, it was revealed that the different approaches to materials’ specifications limit one discipline’s ability to understand the goals of another. A key aspect is that architects are only exposed to a limited range of materials if they apply the presented selection tools; therefore, they will not come into contact with new materials. Moreover, as Pallasmaa has argued, the selection tools cannot incorporate the personal sensual expectations or experiences that an architect gathers their everyday life.

Besides these material selection processes, this chapter has outlined some design and analysis procedures in science and architecture. Both apply digital tools to design for and with materials and utilise strategies familiar to both, such as evolutionary optimisation tools, offering space for speculation about how materials science and architecture might collaborate in future. In addition to the digital design component, physical experimentation is becoming an important approach in understanding material behaviour that is present in the contemporary framework of both materials science and architecture. The direct experimentation with materials to measure and understand the capabilities of materials is not new to the design and science disciplines as I discussed in Section 4.5 (Approaching Materials). However, the emergence of digital fabrication and design techniques supports the material thinking process. Especially for architecture, a combined digital and physical investigation of a materials property is again a focus today due to digital tools that allow for a flexible usage of values that describe the material in terms of its design parameters.
With the origin of the materials science discipline, an additional layer of specialisation has been introduced into the construction industry. Hence, a new level of language has been introduced, which thus has the potential to hinder communication. The diversity of science and its relationship with architecture may be considered one obstacle to the successful integration of new materials into architecture.

Another aspect of the presented overview about the materials science and design disciplines is the acknowledgement that both disciplines are in a process of recognising the other as an important partner for innovative design solutions. Usually, materials science has had an informal approach to affect design; this seems to be in flux and materials science might become an active partner for architecture.

As an integral part of the applied triangulated research method, the experiences gained in practice will help to understand how materials in practice are perceived by the professions. Further, I will test some of the introduced digital and analogue decision-making and design tools to validate these instruments. These approaches are reported in the following chapter, Chapter 5.
Observing Material Decisions in Daily Work

Introduction

The Case Studies

Case Study 1: Diagonale—The Deichman Library

Case Study 2: Hermès Wood Pavilions

Qualitative Data for a Deeper Knowledge

Summary
Observing Material Decisions in Daily Work

The process of making is no longer entirely linear. Producers engage in design, and designers engage in production. Production becomes part of the design process by working with assemblers from the outset, designers picture how things are made, their sequence of assembly, and their joining systems. Materials scientists are drawn into direct conversation and problem-solving with engineers and even with designers. The intelligence of all relevant disciplines is used as a collective source of inspiration and constraint.386

5.1 Introduction

In the previous chapter, I outlined the worldviews of three parties—architects, engineers and materials scientists—and discussed the effects of novel materials that might appear in architecture. Kieran and Timberlake emphasise387 that architecture, engineering and materials science may interact in the design and manufacturing processes. Thus, my investigation at B+G focused on engaging with advanced engineered material systems, the material decision and the design process.

During that time, I was part of the pBG group and worked with structural and building physics engineers, as well as with the clients—mainly architects—that B+G works for and with. In this chapter, I report on my experiences with embedded research in B+G to support the correlation of my triangulated research methodology

387 Ibid.
Personal Engagement

I was involved in more than 20 projects during my first two years at the German branch of B+G, with tasks ranging from parametric design to material research and communicating design solutions with architects.

Two of those projects serve as case studies and present the current work with advanced engineered materials that are known to the industry but are either applied in a new way or considered a risk factor due to their stage of development and missing regulations and classifications.

In this chapter, I explore the constraints and possibilities of the emerging projects, which have been limited in their explanations due to the sensibility and restricted publication of the internal knowledge of the involved parties. This limitation is often intrinsic to the involvement in the context of real commercial projects.

Quantitative Analysis of Possible Interfaces

In light of the case studies, my direct involvement in the day-to-day work and the lessons I have learned over one-and-a-half years, I conducted an online survey to complement the interviews and the working experience. The survey focuses on advanced active material systems, and architects, engineers and materials scientists answered questions about material strategies and engagement in the context of their profession. The results are visualised and evaluated graphically and presented in the section Survey Outcome. They represent a cross-section of interfaces and demonstrate a bifurcation of the disciplines in the disciplines.

5.2 The Case Studies

From the first day of my PhD research, I was a full member of the pBG team, and I worked on projects and competitions. The projects presented in this thesis were chosen because they were shaped by specific material properties. The limited number of case studies also highlights the slow uptake and limited use of novel materials in today’s architectural practice.
The first case study introduces aerogel\textsuperscript{388} as a highly efficient and lightweight material with additional properties to diffuse light. A multi-performance criteria\textsuperscript{389} selection approach was conducted as a decision tool, and the material’s qualities influenced the local design criteria of the façade system.

The second case study reports on the design and manufacturing processes based on the internal material structure of laminated timber studs. Understanding the material’s properties provided a design driver to construct free-form interior space dividers.

The projects presented incorporate novel material strategies as static solutions to contribute to the overall performance of the design proposal. This restriction is common to the construction industry because a kinetic or active system is still seen as complex and problematic (see Chapter 4). In the presented case studies, I refer to the common problems and solutions regarding the integration of novel material strategies and examine how the choice of material influences the overall design process.

\textsuperscript{388} For a detailed description of aerogel I refer to the Material Library section aerogel on page 16.

\textsuperscript{389} The term ‘multi-performance criteria’ is explained in detail in the section, Terms and Keywords, on page 14.
5.3 Case Study 1: Diagonale—The Deichman Library

Project Description

This project started in 2009 after a competition was won by the collaboration of two Norwegian architectural companies: Lund Hagem Arkitekter and Atelier Oslo. The scope of the competition was to design a new building for the existing municipal public library: the ‘Deichman Library’ in Oslo (see Figure 5.1). The library was designed as an open space, with approximately 18,000 m² for a mixed library use.

After the architects won the competition with the German structural engineer Florian Kosche, who is based in Oslo, the two offices approached B+G to be a collaborative partner to undertake the structural design of the building and provide a feasible façade concept. I was involved in both areas—the structural design of the building and the façade design, and especially the material research for the façade.

The following sections focus on the research related to the façade system and materials. The work covers the period until the end of the so-called skizzenprojekt—the preliminary design and design phase. During that time, the project team of the architectural consortium and the façade team at B+G researched different material systems of the façade. The project is still in development and is expected to be finished in 2014.

The Façade

The façade aims to diffuse the sunlight and provide natural lighting conditions suitable for a library. From the beginning, the architects developed the idea of an open library with special media zones, with the façade to be structured in transparent and translucent zones to accommodate the different functions of the library. The overall façade area of
the building, excluding the roof and the cantilever areas, is 7150 m$^2$, with 1950 m$^2$ (27 per cent) of clear window elements and 5170 m$^2$ of translucent elements (see Figure 5.2). The building has five façade faces, due to its multifaceted form. To fulfil the government energy requirements and to meet the design strategy of a translucent but highly sustainable building, the architects planned to introduce ‘aerogel’ as a translucent insulation material. Having proposed this novel material early in the competition, the architects had begun their initial research.

Aerogel

My role in the project team of B+G was to research aerogel in order to contribute to the knowledge and development of the material for the office and the project.

The silica gel-based material can be manufactured and combined with several other materials to create material products that are feasible for applications outside the aerospace program. To use this material as a building product – especially as a translucent façade system—a few existing material systems and manufactures were localised. The ‘solid’ aerogel is also manufactured as a sponge-like filling, due to the brittle behaviour of the material. In this form, the material can either be blown in between existing wall structures for insulation or injected into a hollow sectional substrate. This can be a polycarbonate plate with an aerogel filling or the internal space between two or more glass panels (see Figure 5.3). Those constraints limit the use of

390 Textile sheets, gels and the monolithic ‘solids’ are the most common products.

391 Research projects are currently developing a range of products that will be available soon using the material for insulation applications. Insulation wool, fleece, bricks with aerogel and blow-in insulation based on aerogels have been researched and developed. ‘Aerogel—from Aerospace to Apparel’, *Spinoff*, May 2011, http://spinoff.nasa.gov/spinoff2001/ch5.html;
aerogel, especially in the building sector, to any product that is based on straight elements. Nevertheless, the properties of the aerogel material system offer an innovative alternative in regard to lightweight, translucent insulation materials. The decision making process and the design constraints for this material solution will be discussed in the next section.

Figure 5.3: A close-up of aerogel infused in a polycarbonate plate. (Image source: Atelier Oslo)

Constraints

The architects described their intentions in a report conforming to the regulations of the Ministry of the Environment of Norway in the context of a long-term sustainable building. The technical façade concept for the skizzenprojekt asked for a solution composed of materials with translucent and transparent surfaces. The operation under regular building codes even when all involved parties, architects, engineers and the client are committed to introduce innovative materials is becoming a challenge.

The objectives for the façade called for a material mix able to reach an overall high thermal performance of approximately 0.50 W/m²K 392 and a minimisation of


392 The U-value (W/m²K) describes the heat transfer coefficient, which indicates the amount of heat flowing per second through a m² of a component at a temperature difference of 1 Kelvin above the subsequent layers of the atmosphere. The smaller the thermal conductivity of the material, the better the insulation of the system.

Jose Luis Moro et al., Baukonstruktion- Vom Prinzip Zum Detail Band 1 Grundlagen (Berlin: Springer, 2008), 311.
approximately 15 per cent solar heat gain for the façade with the highest solar exposure.\textsuperscript{393}

The technical properties varied depending on the material system used and the manufacturer chosen. Moreover, the constraints of energy consumption and the sustainability factor of the façade construction itself—as well as the façade’s visual appearance—were important considerations for the architects. The structural system also depended on the material choice due to the overall weight of the façade solution, which was the main parameter for the design of the structural proposal. The use of translucent and transparent façade areas was also established to take advantage of the library’s natural lighting conditions. This meant that the solar heat gain had to be minimised while achieving a suitable level of visual acuity. The second requirement was that the so-called glare conditions\textsuperscript{394} would be minimised in order to provide, for example, good reading conditions. This is usually compensated with additional façade elements—either exterior sun-control components or the placement of adjacent surfaces to control the brightness levels.\textsuperscript{395}

An extensive product search of existing material systems was necessary to identify the most cost-, manufacturing- and building-effective product to provide the best solution for the Deichman Project. Therefore, a decision matrix was developed to guide the decision-making process. The objective of the matrix relied on data collected from different manufacturers and their provided product specification sheets.

**The Pugh Matrix**

The Pugh matrix (decision matrix) is a method that prioritises and evaluates design concepts versus alternative concepts; it is a multi-criteria decision analysis (Figure 5.5).\textsuperscript{396} A set of original data, in this case the aerogel benchmarks, was used, and the alternative products were scored against the relevant data. The rating of each product was evaluated using a positive, negative or neutral score. The different scores for each...

\textsuperscript{393} The solar heat gain (g-value) indicates the percentage of the light energy that passes through glass and other transparent or translucent surfaces. A lower value represents less solar gain.

Moro et al., Baukonstruktion- Vom Prinzip Zum Detail Band 1 Grundlagen.

\textsuperscript{394} The glare effect is reached when the brightness ratios of surfaces exceed visual comfort conditions.

\textsuperscript{395} Nick Baker and K. Steemers, Daylight Design of Buildings: a Handbook for Architects and Engineers (London: James & James, 1999), 72.
product were then combined and the results represented with a symbol or numerical value (Figure 5.4).397

<table>
<thead>
<tr>
<th>System</th>
<th>Light Transmission</th>
<th>Thickness</th>
<th>Visual Appearance</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>++</td>
<td>-</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

Figure 5.4 shows a simplified Pugh Matrix to demonstrate the use of symbols and numeric values. (Image source: author)

This method has been used by other design and engineering disciplines as a decision making tool in early-stage development, for instance, in the aerospace industry or the car manufacturing industry (see Figure 5.5).398

Figure 5.5 represents the decision-making process as described by John Gershenson.399 (Image source: author)


399 John K. Gershenson, 'Pugh Evaluation Nasa ESMD Capstone Design' (National Aeronautics and Space Administration, n.d.)
The selection and rating criteria for the decision-making process for the choice of material were based on the U-value, g-value, light transmission, fire protection and soundproofing factors. During the research of the different products available, it became clear that the constructability, thickness, dimensions and weight of the elements also had to be considered. By providing a feasible structural solution and to design a possible combination of two different material systems, the dimensions of each material system were important parameters. Additional criteria such as the quality requirements, overall costs, embodied energy and associated emissions were considered in order to cover the entire spectrum of influencing factors that guide the decision-making process. Alongside the pure technical data that could be gathered from data sheets and provided by the manufacturer, the visual appearance was an important factor that could not be judged only by data.

In order to evaluate the appearance, I visualised the architects’ general system based on a Rhinoceros (Rhino) 3D model that they provided. This model needed additional information such as the detailed construction solutions and pre-estimated thicknesses of the structure. The different solutions varied in the thickness of the slab design and the support points for façade elements, which influences the appearance of the façade drastically. The provided model served as a reference point to compare each of the different solutions. The visualisation covered aspects of possible structural components such as an external structural system or an interior structure for the façade elements. The translucent and transparent material was also rendered with the intention to support the decision-making process.

Figures 5.6 through 5.8 show the interior and exterior structural solutions, as well as the different materials and sizes that were researched.
Figure 5.6: Façade with transparent glass elements. The transom + mullions construction is directly connected to the slab system of the library and creates a visual horizontal separation of the elements and highlights the slab area due to an additional needed insulation. A larger grid system is possible due to the size of the glass elements. Left image: interior perspective; Right image: exterior perspective. (Image source: Bollinger+Grohmann Ingenieure)

Slab area with additional insulation due to existing thermal bridge

Figure 5.7: Façade with transparent/translucent elements. Aerogel filling between polycarbonate plates with transparent glass elements. The polycarbonate plates have the advantage of a big element size, and therefore offer the freedom to shape the plates. Only the glass elements have the restrictions in size; therefore, an irregular grid system is the result. Left image: interior perspective; Right image: exterior perspective. (Image source: Bollinger+Grohmann Ingenieure)

Slab is thinner due to an external structural solution.

Free form polycarbonate elements
In addition to the overall appearance of the material system for the façade, a close-up visualisation of the possible connection points was rendered to emphasise the different construction solutions provided by different material systems (see Figure 5.9 and Figure 5.10).
Two different matrix systems were developed: the first matrix helped with the decision regarding which transparent solution to use, and the second matrix was used to evaluate the translucent options. The matrix incorporated standard systems such as double, triple and quad glazing, as well as other ‘high-tech’ glass solutions such as quad glazing with heat mirror films or light-scattering glazing systems. To provide equal comparability, only the material system itself was analysed, and the joints, hinges or connection points of the future façade were not taken into account.400

The teams of B+G and the architects decided to weight the systems to the U-value, cost, g-value and visual appearance because these data elements appeared to be the most valued for the project.

Outcome of the Matrix

With the help of the matrix, five transparent and seven translucent material systems were explored. The results of the decision matrix showed that, in relation to the evaluated criteria, double-glazing with two films and a krypton gas filling was the best option for the transparent façade elements. They have a very good U-value of 0.30 W/m²K and a g-value of 36 per cent, which was higher than the average value for all of the material systems compared. However, there was a downside to their specification: the fabrication process limited the krypton gas-filling element to a size of 1 m x 2 m. From a structural point of view, the matrix showed that this particular solution was the lightest.

400 Specifically, the energy data, U-value and g-value will increase for the overall façade due to additional structural elements that were not evaluated because of the issue of rising complexity of the systems that were analysed.
The translucent material decision matrix indicated that the aerogel material in four of the seven systems was ranked in the first third, but it was not the best solution for this particular case. Even though it had the best insulation properties, with a U-value of 0.30 W/m²K and a g-value of a minimum of 15 per cent, it was very thick (>60 mm) and thus, not as compatible with the transparent glass system. The increased thickness would lead to a façade profile that would be asymmetrical with complex connection points. The outcome of the matrix suggested double-glazing with two films and krypton filling plus an additional layer of screen print or translucent PVB film (see Figure 5.14).

The creation of the matrix was time-consuming due to the necessary extensive material system research, but in the end it offered a tailor-made solution finding strategy.
Figure 5.11 Decision Matrix; top: transparent material system, bottom: translucent material system. The Quad Glazing System had the highest rating for the transparent solution. The Quad Glazing with 2 films and krypton filling received the highest rating for the translucent system. (Image source: Bollinger+Grohmann Ingenieure)
Other material research methods like the selection tools described in Chapter 4 are restricted to only the inbuilt search criteria and do not offer the freedom to explore specifically a novel material system in such a depth. The decision-making process was processed as interdependency between mostly the architects and the engineers. The material developer as well as the material system manufacturer was consulted frequently only for answering project related specific questions.

**Further Design Process**

The decision matrix helps to identify possible solutions to a multi-criteria design problem, but it is not a tool to guide the design process itself. Once the material list has been limited, there is still room for the human factor in the final decision and room to choose a version from the proposed list of materials that is not as good. In addition, once the material system is chosen, there remains a decision regarding where, and how many of, the elements must be placed to reach the optimal light/energy ratio that both accommodates the library’s functions and serves as a sustainable public building.

At B+G, the building physics engineers calculated the thermal conductivity based on 2D sections of the chosen material systems (see Figure 5.12 and Figure 5.13).

![Figure 5.12: Transom and Mullion Façade System with the heat transfer analysis of the face profile cross-section. (Image source: Bollinger+Grohmann Ingenieure)](image)

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601 In the section 4.4.2 Databases I explain the different selection tools with a focus on the available online databases and the developed software package CES Selector by Michael F. Ashby and Granta Design.
The University of Oslo conducted external light studies based on a physical model, and an external consultant in a climatic engineering company analysed the lighting and energy performance for each floor with a digital computer model. The consulting climatic engineers conducted calculations of the annual daylight factors. They analysed two different material systems that were the preferred options of the architects based on the outcome of the multi-criteria selection process.

Project Summary

In this project, it became clear that the combined ideas of architecture, structural engineering, façade and climate engineering, the use of different material systems and the confronting demanding building regulations led to an interdisciplinary approach to the design of this complex façade, even in the schematic design phase.

The insights gained from the material research under real conditions demonstrated that the introduction of innovative material systems for an innovative design proposal is dependant of many factors. It is not only the pure material properties that have to be considered but also every aspect in regards to the final material product, such as the size of the available panels, alternatives existing solutions with similar properties and the impacts for a feasible structural solution. These influences could only be studied by analysing the dependencies among the energy analysis, the calculation of average U-values, and the ranges in operating temperatures, light transmission and the multiple uses of the library, which made the façade very complex.
The matrix decision tool allowed us to negotiate between varieties of material solutions with a high degree of freedom and made it clear that the aerogel material systems were very efficient but problematic in terms of the constructability of non-standard building designs. The decision matrix was also helpful for the purposes of arguing and representing the different material concepts in an easy to read and intelligible manner, such that every discipline involved could contribute to the deeper understanding of the complexity of the façade.

It became clear that the task of working with novel material systems is a task that involves a multidisciplinary team in order to identify all the necessary cornerstones to pinpoint the constraints and possibilities that the material system has to offer. Furthermore, novel material systems require often additional testing in close collaboration with the manufacturer to gain practical experience and confidence. This project gave insights about the discrepancies of established material products and that often, the palette of available products coming from a product manufacturer is set and gives no space for further adaptation or development inspired by architects and engineers. Material component manufacturers tend to rate an arbitrary development for non-standard architecture as high-risk and are concerned of the limited use and the exclusivity to authorship of the developed system. These inhibiting elements seem to be the common situation when attempting to introduce new materials to an actual building project and coincide with the findings of Chapter 3 and the responses of the interview partners in Chapter 4.
5.4 Case Study 2: Hermès Wood Pavilions

Project Description

The RDAI agency, a French architectural company that is responsible for most of the flagship stores of the French fashion label Hermès, was contracted to design a new retail space in Paris. The main interior of the new shop comprises three pavilions with free-form shapes that vary in form and dimensions (height 8–9 m, diameter 8–12 m; see Figure 5.14). A staircase that guides the customer towards the retail area is a fourth object that is designed in the same language as the other three shaped objects in the space. The architects designed the so-called *bulles* as a kind of wooden wicker basket structure to support the philosophy of Hermès as a sustainable fashion label with a high-quality handcrafts approach.

![Figure 5.14: Visualisation of the Pavilions (image source: Bollinger+Grohmann Ingenieure)](image)

After the initial design proposal, the architects contacted structural engineers in the B+G Paris office to deliver a feasible construction for the self-supporting *bulles*. To deliver the project on time, the project team of B+G approached the German timber construction company Holzbau Amann GmbH early in the project as a fabricator and wood specialist for free-form wood structures. I was involved in the first stage of supporting the architect’s design with possible geometry definitions that could be fabricated and manufactured.

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French expression for ‘bubble’.

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152 Observing Material Decisions in Daily Work
Wood

For this project, it was necessary to research the different options to create double-curved wooden elements. Wood comprises cells or fibres, and the wood properties depend on the geometrical orientation and assembly of these fibres. Wood is generally more suitable for tension forces rather than compression due to its fibre composition. The benefit of working with wood is that it is a sustainable material that can be manipulated and shaped by modern digital fabrication techniques such as joining, laminating, carving, bending and cutting. However, if wood is being cut, it can lose its strength if it is cut across the grain direction; therefore, the number of fibres that are severed in a particular direction must be considered in order to prevent loss of stability.

Design Constraints

The three pavilions had to meet the high level of craft and precision appropriate to the fashion label and had to be realised within one year. The free-form shapes combined with the wicker basket appearance led to geometrical and structural challenges such as the capacity to self-support and a method of production for double-curved wooden elements. The objective for the pavilions was to create single wooden studs as long as possible that defined the overall double-curved shape of each pavilion. This aim was derived from the structural and visual criteria that were defined during the first discussions with the architects. The architects and Hermès considered the material integrity of the wood a high priority in order to present the fashion label in the best possible way. Therefore, the connection points of the overlapping timber elements had to be minimised. For this project, the central task was to define the optimal bending and twisting behaviour of the wood and to use the specific structural properties of the timber in the design.

405 Gordon and Ball, The New Science of Strong Materials, Or, Why You Don’t Fall Through the Floor, 137–141.
Observing Material Decisions in Daily Work

Geometry Development

Understanding the dependencies of the overall geometry and local behaviour of wood was a crucial aspect that supported the design process of the architects as well as the team at B+G. The project started with a given 3D model—a volume—of the pavilions that was provided by the architects. The volume was the basis for the 3D modelling of the wood laths. At first, the ‘real’ wood laths were created by simply projecting the axial lines of each element to the surface of each volume. Three axes—X, Y and Z—described a coordinate system that was relative to each individual lath in order to understand and locate the bending and torsion effect of each wood lath separately. The X-axis was defined as the torsion axis of the lath, whereas the Y- and Z-axes defined the bending in either the strong or weak axes of the lath (see Figure 5.15).

The projection process created a uniform distribution of the elements but resulted in elements that were twisted and bent around the three axes. Starting from that discovery, several options were tested and the 3D volumes given by the architects were re-modelled to eliminate the unevenness of the volume that resulted from the manual modelling process.

Therefore, in the second approach, the volumes of the pavilions were divided into two parts, as shown in Figure 5.16. The created horizontal curves were divided equally, and the resulting division points were used as the basis to place cutting planes through these points.

![Figure 5.15: Definition of the local coordinate system for each lath. (Image source: Bollinger+Grohmann Ingenieure)](image)

![Figure 5.16: Torsion and bending of the projected wireframe lines on the guide surface (image source: Bollinger+Grohmann Ingenieure)](image)
The created intersection lines of the planes and the volume were single-curved lines. A section profile was defined, and the dimensions were chosen to meet the aesthetic criteria of the architects. The section profile was extruded along the created section curves and was always oriented towards the centre of the volume of each pavilion. The resulting volume of each lath could then be analysed in relation to the bending and twisting of each lath. The solid elements were bent around the y- and z-axes, but without torsion around the x-axis (Figure 5.17 and Figure 5.18).

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Figure 5.17: Distribution of rule-based guiding points to create the cutting section and intersections. (Image source: Bollinger+Grohmann Ingenieure)

Figure 5.18: Final principle of developable wood laths with no torsion around the x-axis. (Image source: Bollinger+Grohmann Ingenieure)
Fabrication

Later in the detailing phase, the project team in the Paris office created a parametric model that incorporated the findings of the design research. This was used to design and analyse a series of variations of the pavilions. The overall geometrical shape of the pavilions was pre-set by the architects, but the parametric model incorporated parameters such as the slats’ curvature tolerance and intersection angles, the intersection area and slats’ dimensions, braiding density, alignment and torsion tolerance (see Figure 5.19).

For the laths to lie perfectly on top of each other at the connection points, the rectangular section needed to be twisted. This resulted in an additional script that controlled the curvatures and the maximum allowable torsion or twist of the laths. Each lath was calculated as a laminated composite comprising three single laths to create the necessary stability derived from the structural analyses for the global structural behaviour of the pavilions (Figure 5.20).
For ease in the production process, the B+G project team developed a system in close collaboration with Holzbau Amann to cut each element of the composite laths from flat wooden plates. Each lath was cut and trimmed in relation to its final geometry. When a glued wooden element was bent, it would result in internal shear forces that would displace each segment slightly (see Figure 5.21).

The final wooden elements consisted of three single-cut elements that were 14 mm thick and 60 mm wide. The slats had to be slightly bent and fixed in the correct

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Ibid.
geometry manually. After placing and aligning the laminates, they were glued and held together with bar clamps to produce the composite carrier.

![Image](image-source: Bollinger+Grohmann Ingenieure)

Each *bulle* was pre-assembled in the factory hall of the timber company in order to maintain the bending and twisting process in a controlled environment (see Figure 5.22). At the end, the final structures were dismantled and rebuilt on-site at the fashion store (Figure 5.23).

![Image](image-source: Bollinger+Grohmann Ingenieure)
Project Summary

In this project, close communication between the different members of the project team was possible from the outset. One key factor for this early collaboration was the common understanding to work first of all with the properties of timber and secondly establish exchangeable data files for a fluent communication.

The Hermès Pavilions made it clear that by establishing a discourse with the fabricator early on a multi-disciplinary and collaborative design approach can result in a better understanding of a material and its properties. The collaborative work around the translation of the properties of the material into the parametric design and optimisation process was directed by the nature of the material itself. The maximum bending of the wood, the wood grain direction and the fabrication process of the wood laths were formulated and informed by the introduction of rule-based geometries. The developed constraints that informed the geometry and the remodelling of the 3D volumes resulted from the new gained knowledge of wood as a flexible construction material.

A ‘horizontal level of communication’, where each involved party had the same knowledge and level of language to discuss the construction and design issues, was established during the project phase. According to Klaas de Rycke, the project manager and director at B+G Paris, this was only possible by integrating the parametric model and the derived understanding of the material and fabrication methods in the early design process.408

This understanding of the material was the common thread that connected the involved parties and partners. Furthermore, the parametric model revealed to me the further potential as a representation and communication tool to facilitate the assimilation of new materials in the design process.

Summary of Project Work

The two case studies are a cross-section of the projects in which I was involved, and they represent methods of material-driven design concepts in the office of B+G.\textsuperscript{409} In the presented projects and especially in competitions in which I was involved, the material was believed to have the potential to drive new design possibilities. The materials may have been very light and contributed to sustainability factors such as energy saving or passive light control, or they may have had promising structural capabilities and contributed in terms of reducing costs or supporting the aesthetical concept of the architect. What the two projects have in common is the concept of a material driven design approach that can unlock new paradigms in design. The material driven design approach will be further explored in the next chapter (Chapter 6).

It became clear that the plethora of material systems that can be accessed in the building industry is increasing and makes it difficult to decide what kind of material is suitable for a project. In the case of aerogel, the evaluation and comparison of products are even more confusing because the material itself is only available as a part of a ‘composite’ made out of either glass or plastic elements filled with aerogel. The developed material products only encapsulate aerogel; in the building industry, the material research has only begun, while the palette of material systems is at present covering straight-rectangular shapes only.

From the perspective of an architect placed in an engineering environment, I realised that the task to obtain information that would help assess a product for a project is a complex one. Not only do the design criteria and maybe the typical building requirements have to be considered, but the complexity of the task increases exponentially if all the criteria have to be optimised.

However, in the Deichman project for example, the properties and potentials of the material were not clearly known. During the discovery of the true material characteristics, the design changed according to new knowledge gained or it was replaced with another material system that was more suitable for the project’s scope.

\textsuperscript{409}This exploration cannot be generalised to any other office and is limited to the experience gained in the particular projects that I was involved in. However, the projects and the work showcase the daily problems of novel material strategies and material systems.
The applied multi-criteria decision process can be described as analogue. The collected data were not directly exploited as digital inputs to drive and analyse a virtual model, for example. Digital tools that can help to inform multi-criteria design decisions by simulating the ‘real world’ include 3D modelling, scripting and analysis software. For example, in the Hermès project, a script\textsuperscript{410} developed the geometry based on the twisting and bending behaviour of wood by following a set of pre-defined rules such as restraining the twisting of the laths. The geometry development, combined with the structural analysis, provided a reasonable simulation of the later-constructed pavilion.

In each of these projects, the architects and engineers engaged with the material on a theoretical level only and considered the possibilities of the material by referring to collected data sheets, facts from suppliers and through close collaboration with specialists such as those described in the Hermès project.

The case studies also showed the difficulties that designers face in real-life projects when new materials are introduced that are not yet standard in the construction industry. New materials such as the aerogel insulation, which is currently only available as a standardised system and has no examples of long-time usage, posed questions in terms of durability, maintenance and constructability, as the Oslo project showcased. It identified the very obvious impediments to uptake of innovative materials. In both cases, the material had a significant effect on the design process for sustainability, structural or aesthetic reasons.

5.5 Qualitative Data for a Deeper Knowledge

Introduction

While I was working for the company, I became aware that, to understand the everyday problems that occur when working with novel materials, I could only observe the perspective of the engineer and a partial perspective of the architect. In order to explore further possibilities for a material-driven design, the aim was to include the materials science perspective in order to position the research between disciplines that are involved in a material practice. My aim for the online survey was to include insights

\textsuperscript{410} RhinoScript was used to drive the geometry.
from architectural and engineering practices, as well as small individual practices,\textsuperscript{411} companies and research institutes,\textsuperscript{412} and from the materials science industry and its research institutions.\textsuperscript{413}

The goal was to determine and evaluate differences and commonalities among the professions working with particularly novel materials with \textit{advanced dynamic engineered materials} (smart materials), as the knowledge gained in practice was limited to \textit{advanced passive engineered materials}. My experiences at B+G, the interviews conducted and the knowledge gained during the first one-and-a-half years enabled me to formulate 10 questions with 65 possible answers.

The questions addressed each discipline in the same manner, focusing on smart materials and early engagement with the materials, including collaboration, design tools and obstacle definitions. These questions focused on the visual expression of ideas and visual design strategies. This field was identified via conducted interviews; my personal experiences and theoretical research as a possible common ground for exchanging ideas (see Chapter 4).\textsuperscript{414}

The aim of the survey was to extend my research by covering a diverse group of people from different countries and backgrounds in order to provide a broader view of the existing approaches and obstacles when using new materials and technologies in architecture. Questions were formed around areas of design tools, lack of knowledge and difficulty in communicating. Ten distinct questions were developed in order to understand the identified issues related to the subjects of material thinking, material representation techniques and communication.

\footnotesize{
\begin{itemize}
  \item \textsuperscript{411} For security and privacy reasons, the individuals cannot be named.
  \item \textsuperscript{412} The survey includes responses from companies such as B+G Ingenieure, Expedition Engineers, Schleich Bergermann Ingenieure, Grimshaw Architects, Radical Craft, Snohetta, ETH Zurich, the MIT and the AA.
  \item \textsuperscript{413} The materials science side included institutes and research departments such as the Wyss Institute for Bio-inspired Engineering, RMIT University, the Advanced Manufacturing Cooperative Research Centre Ltd and DLR Multifunktionswerkstoffe.
  \item \textsuperscript{414} In Section 4.5, I discussed the different levels of engagement between architects, engineers and materials scientists in relation to discovering, designing and working with materials.
\end{itemize}
}
The preparation of the questionnaire and the structure of the survey drew on handbooks and web-based information sources.¹⁴¹⁵

**Survey Design**

To become familiar with the relevant questions and to structure the survey, I first interviewed colleagues at B+G and consulted a social science researcher at RMIT University. Before distributing the questionnaire, I studied the group of potential participants and tried to select a diverse range of architects, structural engineers and materials scientists. Therefore, the questionnaire does not start with a personal question regarding the participant’s biography; rather, it focuses on collaboration, design strategies and material integration into the domains of the participants.

The average experience in the field of practice was 11.5 years, which indicates an appropriate level of experience to answer the questions. The least experienced person had three years of experience and the most experienced had 41 years.

In total, 177 people were invited from 16 countries, and 62 responded to the survey. Fifty-five surveys were 100 per cent completed and seven respondents completed 50 per cent of the survey, which is a survey completion rate of 31 per cent. The first four questions were answered by all participants, which resulted in a response rate of 35 per cent. The response rates for web-based and e-mail surveys ranged from 0 to 85.3 per cent, according to Leong and Austin.¹⁴⁶ Several web-based sources report that online surveys that address a public source may receive an average response rate of up to 20 per cent.¹⁴⁷ Different papers that address social research in the field of tooling web-based surveys reported an average response rate of 25–30 per cent.¹⁴⁸¹⁴⁹

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¹⁴¹⁵ The online survey was designed with the help of the online tool SurveyMonkey, which is an online platform for creating tailor-made surveys and for storing and analysing the collected data.


¹⁴⁷ http://www.practicalsurveys.com/respondents/typicalresponserates.php


The aim of the survey was to collect and compare information from three different groups. The aim was not to collect 100 per cent correct responses, as the disciplines are broad and vary from one another, and respondents may not have collaborated with the other disciplines. One of the goals was to identify possible trends and indicators for opportunities for collaboration and knowledge exchange.

The survey was conducted as a structured questionnaire and included open- and closed-ended questions, eight quantitative questions and two qualitative questions. Four questions were based on a matrix survey with multiple-choice answers and a ranking system. The participants were asked to rate the priority of the topic to their profession. Each of the answers could be cross-referenced to obtain answers that could be analysed across the disciplines.

Four questions were based on multiple-choice Likert-scale matrices, where the number of given answers was the key factor for the rating. The questions indicated the respondents’ attitudes or feelings about the topics being questioned.

The last two questions were open questions that could be answered individually. These questions were qualitative in nature and were helpful to obtain a better understanding of the types of smart materials that have been used, how they define a smart material and the decision process involved in working with a particular material.

**Analysis and Presentation of Quantitative Outcomes**

According to the rating systems of the survey, the priorities of the answers were translated into a point system in order to compare the total and average of the given answers due to the irregular numbers of responses.

For the numerical analysis of the given answers, I introduced the following translation from a personal perspective to a point system:

<table>
<thead>
<tr>
<th>Very important</th>
<th>Important</th>
<th>OK</th>
<th>I do not know</th>
<th>Not so important</th>
<th>Unimportant</th>
<th>Average Answers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 point</td>
<td>0.75 points</td>
<td>0.5 points</td>
<td>0.33 points</td>
<td>0.25 points</td>
<td>0</td>
<td>1+0.75+0.5+0.33+0.25</td>
</tr>
</tbody>
</table>

*Figure 5.24: Translation of rating system into points. (Image source: author)*
The 10 questions that I asked were as follows:

Choose according to your own practice the frequency of collaboration of the listed disciplines.

Rate the importance of collaboration according to your design development with the different disciplines.

What type of media is most effective to make you understand the design ideas of others in order to support their work with your expertise?

What kind of design tools are you using at your practice to integrate innovative ideas in the design development?

How important are these design tools in your practice in the context of:

- Design collaboration
- Design optimization
- a linear design approach
- a nonlinear design approach
- Sustainability
- Material representation
- Fabrication constraints
- Construction development
- Integrating New technologies in fabrication processes
- Integrating New technologies in digital design processes
- Cost optimisation
- Gaining a new market edge
- Communication
- Aesthetical aspects
- Material behaviour

How important are new materials to your practice in the context of:

- Design collaboration
- Design optimization
- Sustainability
- Fabrication constraints
- Integrating New technologies in construction
- Integrating New technologies in design processes
- Cost optimisation
- Gaining a new market edge
- Communication
- Aesthetical aspects
- Material behaviour
- Flexible use
- Being Innovative
- Constructability
Observing Material Decisions in Daily Work

What is the most interesting and innovative ‘smart’ material that you have worked with recently, and why?

What makes you decide which material you will use for your idea and when does that usually happen?

What are the obstacles for applying results from material research in everyday practice?

What are your sources of inspiration for introducing new materials to your design ideas?

After a year of collecting data from the survey and reaching the goal of obtaining responses from 60 or more participants, I summarised the outcome by discipline in order to represent each group separately. For the single representation of each group, I chose line diagrams, which were also utilised to juxtapose and compare the responses of each given participant within the discipline. Bar charts present the ordinary outcomes of the questionnaire and the sum of the given responses for each question.

![Figure 5.25: Response rating of each participated group (image: author)](image)

To accumulate the different response rates (presented in Figure 5.25), the three groups were analysed separately to obtain the total and average of the given answers. At the end, the responses of the participants were divided into three groups—architects, structural engineers and materials scientists—to equally reflect on the answers and to define the correlations and differences in the groups’ worldviews.

The differences in the response rates may result from the specific field of novel materials in architecture. While materials scientists research new materials, they have limited contact with the construction industry (see Chapter 4).
I intended to include a broad range of experienced professions in the survey to analyse the different priorities and common activities related to design issues and material research. The addressed participants represent an accumulation of the affiliated professions that work closely in the field of material innovation and practice in order to obtain a global perspective rather than a local perspective.

One aspect of analysing the design and collaboration methods among the disciplines relates to data derived from the quantitative analysis. The data can be mapped and visualised in different ways (see the following sections); however, there is insufficient data to provide reasons for barriers to collaboration and insufficient design methods that link across disciplines during an early design stage.

The collected information is based on numerical data that illustrate differences between distinct disciplines but do not explain why these differences exist and how they might be overcome. Therefore, the presented data were cross-linked with working experiences, interviews, case studies and literature; the results of the survey can be seen as accurate and valuable only as a component of the triangulated research method.

The following section details the results of each surveyed group separately and then discusses the accumulated answers to highlight the differences and correlations among the disciplines.

This exploration helped me to articulate my research question in more detail, define my hypothesis and sharpen the argument of this thesis. The responses and experiences gained at B+G led to a discussion of the augmented and dynamic modelling and simulation of advanced engineered dynamic materials (see Chapter 6).

**Survey Outcome: Architects’ Response**

The group of architects addressed was intensively involved in the realm of material-driven design in architecture. They shared an interest in working intensively with materials to support their design decisions. This section discusses cross-referenced topics and the single outcomes of the given answers of the architects using line graphs to help identify the rating of each topic.
Choose according to your own practice the frequency of collaboration of the listed disciplines.

Rate the importance of collaboration according to your design development with the different disciplines.

Figure 5.26 shows the results of the cross-referenced questions to emphasise the real and the pictured collaboration. (Image: author)

Figure 5.26 compares actual collaboration with the intent or need for collaboration. In comparison, the actual and preferred collaboration of architects deviated most at the material science side. The results show that material science was the third most valued party for collaboration when developing a design proposal. Overall, the average rating of the importance of the different disciplines as partners for collaboration was 15 per cent higher than reflected in the assessment of collaboration in the actual work.

The outcome of the cross-referenced questions provides evidence that materials science is of great interest to architects, but there is little collaboration. This suggests that architects that already have an interest in novel material approaches might be open to collaboration and closer work with materials scientists.

Figure 5.27: Results of the question: What type of media is most effective to make you understand the design ideas of others in order to support their work with your expertise? (Image: author)
Of the most effective media for understanding the work of others, 3D physical models, received the highest ranking from the architects, and the 3D virtual model was ranked second for the efficient representation of ideas. Overall, each of the suggested visual media was highly rated, and only the 2D simulation and the graphs and charts were considered least suitable as a tool for communication (see Figure 5.27). This may be because the work of an architect is closely related to the built environment and he or she understands complex behaviours and relations by representation techniques that mirror the reality and dependency of an object’s space.

Figure 5.28 visualises the responds in regard of the question: What kind of design tools are you using at your practice to integrate innovative ideas in the design development? (Image: author)

Figure 5.28 shows that all architects utilise 3D modelling software as a means of developing their design and integrating innovative ideas. They consider the typical engineering and scientific tools, such as structural analysis software or multi physics analysis tools, to be the least influential in relation to innovative processes. Animation software that simulates physical interdependencies is rated below the typical architectural design tools.

Overall, the possible pre-set answers were visual in nature and tried to cover the typical visual design and development tools in relation to architecture, as my intention was to frame the answers towards a design-oriented approach.
Observing Material Decisions in Daily Work

Figure 5.29 visualises the cross-referenced questions to compare the importance of new design tools and new materials and visualise the bifurcation between design tool and material. (Image: author)

Figure 5.29 shows the importance of the preferred design tools mentioned in the previous question and the importance of new materials in order to correlate the answers given. According to the architects, new materials are an important aspect in relation to sustainability topics, and the architects appear to be interested in working with new materials in the context of new material behaviour. Compared to design tools, sustainability and material behaviour have the highest deviation in relation to the importance of new materials.

This suggests that the available design tools are either not appropriate to incorporate into the material behaviour as the design driver, or that design tools are not as significant when working with material behaviour. Conversely, the graph identifies that design tools and new materials are considered equally important for the integration of new technologies into digital design.
Survey Outcome: Civil Engineers’ Response

The civil engineers had the second-highest response rate, but they also had the highest inconsistency in responding to all of the questions. Therefore, the data for questions 5, 6 and 10 are limited in their comparability; however, as individual questions analysed in comparison to the overall answers, they will provide a valid outcome.

Figure 5.30 visualises the results of the cross-referenced questions to emphasis the real and the pictured collaboration. (Image: author)

Figure 5.30 shows that, in comparison, the actual and preferred collaboration of engineers’ deviates most for collaboration with materials scientists and material consultancy. The results show that materials scientists and material consultancy are the fourth and sixth most valued as collaborative partners. Collaboration with materials scientists is of high importance to engineers and is rated higher than collaboration with designers, even though designers are slightly higher in actual collaboration.
Figure 5.31 visualises the responses regarding the question: What is your preferred medium to understand the work of others. (Image: author)

Figure 5.31 presents the preferred method of understanding the ideas of others in order to contribute to their work. The graph shows that engineers identify 3D simulations and 3D virtual models as the most appropriate media to understand the work of others, while 2D simulation is of little relevance to them.

<table>
<thead>
<tr>
<th>Medium</th>
<th>% of Engineers</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D physical models</td>
<td>75%</td>
</tr>
<tr>
<td>3D virtual models</td>
<td>70%</td>
</tr>
<tr>
<td>2D simulations</td>
<td>65%</td>
</tr>
<tr>
<td>sketches</td>
<td>60%</td>
</tr>
<tr>
<td>drawings</td>
<td>55%</td>
</tr>
<tr>
<td>calculation results</td>
<td>50%</td>
</tr>
<tr>
<td>diagrams</td>
<td>45%</td>
</tr>
<tr>
<td>graphs/charts</td>
<td>40%</td>
</tr>
</tbody>
</table>

Figure 5.32: Most effective design tools for implementing innovative ideas. (Image: author)

Figure 5.32 highlights that the most effective design tools for structural engineers are structural analysis tools followed by 3D modelling environments. It also emphasises that other engineering software related to materials science, such as multi-physics analysis...
and computational fluid dynamic analysis software, are not very important for developing and implementing innovative ideas.

Figure 5.33 shows the cross-referenced questions to compare the importance of new design tools and new materials and visualise the bifurcation between design tool and material. (Image: author)

In relation to design tools and the importance of new materials (see Figure 5.33), the engineers’ responses are coherent in almost every topic. New materials are not identified as a means for collaboration in the design phase, but they are of high interest in relation to material behaviour.

The preferred design tools identified in the previous question are considered very important for a collaboration process in the design phase and for working with, and understanding, material behaviour.

**Survey Outcome: Materials Science Response**

The materials scientists had the lowest response rate of 28 per cent. Due to the nature of materials science being situated in research facilities and material testing institutes,
contact with the architectural practice seems limited. This observation stems not only from the survey outcome but was also clearly identified by my interview partners and by the literature that covers this topic. Nevertheless, the same sets of questions were addressed to compare the groups and to locate similarities and differences.

Figure 5.34 shows the results of the cross-referenced questions to emphasise the real and the pictured collaboration. (Image: author)

Figure 5.34 shows that materials scientists mainly collaborate within their own domain. The other possible fields of collaboration range between 20 and 40 per cent. The value placed on collaboration with other disciplines for design is also shown, where the importance of collaboration is 13 per cent higher than the actual rate of collaboration.

The higher-rated importance of collaboration with other disciplines such as architects and engineers may lead to the conclusion that there is a need for closer collaboration among the disciplines from the perspective of materials scientists.

---

Sketches, diagrams and graphs are the best media of communication for the materials science discipline in relation to understanding the work of others (see Figure 5.35). In contrast, 3D representations and visualisations are not as important to materials scientists as representations predicated on numerical information.

Thus, the overall response to the question of which media are best for implementing innovative ideas indicates that 3D CAD software and modelling are of high importance to materials scientists. The typical analysis tools—structural, multi physics and computational fluid dynamics analysis—are less influential as design drivers for materials scientists, as shown in Figure 5.36.
The materials scientists’ responses to the question relating to the importance of new materials and design tools match the ratings for these two in almost every point and deviate on average by only 6 per cent (see Figure 5.37). The highest differences relate to gaining a market edge, sustainability, cost optimisation and integration of new technologies in design processes. As these are the topics most closely connected to the business of design practice, it indicates that materials scientists are probably focused on the direct design of new materials and see less significance in the work with design tools outside of modelling material behaviour, design optimisation, fabrication and using the tools for communication and collaboration. A further observation is that 2D CAD software seems to become an out-dated or irrelevant technology for implementing innovative ideas.
Observing Material Decisions in Daily Work

Figure 5.37 shows the cross-referenced questions to compare the importance of new design tools and new materials and visualise the bifurcation between design tool and material. (Image: author)

Comparing the Total Responses

I randomly selected four questions from those analysed above to conduct a comparison of the disciplines. The single-discipline data provide an overview of the worldviews and interests of the different professions; however, to correlate the professions, a comparison of the given answers will provide an understanding of the commonalities and differences. Therefore, I superimposed the line graphs to present the datasets for each profession within one graph.

The rating of the three compared groups may be obvious at first due to the specialisation of the profession and, whenever a topic tends to be more related to one particular group, the ranking is particularly high. However, when analysed in more detail, the line graphs exhibit a trend in how other disciplines are related to the same topic. For the question of the frequency of collaboration of the disciplines, all three groups probably work within their domain. The materials scientists are almost isolated within their profession. The architects’ responses to the question were weighted to the
typical construction-related design disciplines, while the disciplines involved in direct material research are less included in the work of architects. Structural engineers and architects share the same engagement rate in relation to materials science (Figure 5.38).

Architects rated the frequency of collaboration with structural engineers at an average of 58 per cent, but structural engineers rated the collaboration frequency with architects at 85 per cent. This result may lead to the assumption that engineers collaborate more frequently with architects than architects collaborate with engineers.

As shown in Figure 5.39, architects favour working with tools that explain and visualise the 3D domain; however, the trend of all three professions highlights the work with 3D virtual models and simulations. Sketches are used as a medium for communicating and translating ideas by 60 per cent of all participants.

This leads to the conclusion that sketches are a fast method used to describe and visualise concepts and ideas along with virtual environments and simulations, and they can be utilised to communicate across the different disciplines.
When questioned about the importance of new materials in relation to the different subcategories, all three groups considered the material behaviour the highest priority, as shown in Figure 5.40. Architects view new materials as an important factor in their
design practice and rated the different categories at 73 per cent of importance, whereas the materials scientists rated them at 55 per cent and the engineers rated them at 44 per cent. This led to the conclusion that architects see the potential of new materials for most of the topics, while engineers may not expect a significant influence on their practice. It also may give evidence that architects have an increasing interest in new materials and material technologies, which reflects the statements made in Chapter 3.

The last question addressed the issues that occur when material research is introduced and how to apply the research outcome in everyday practices. Identifying obstacles was an important aspect of narrowing the research field of this thesis.

For architects and materials scientists, the two main obstacles for applying results from material research in everyday practice are a lack of financial resources and a lack of knowledge (Figure 5.41). The high peaks in the lack of knowledge topic for materials scientists and architects suggests that, from the perspective of materials science, there might be a need for a better knowledge transfer to communicate and understand materials and their potential uses in order to apply them correctly. This argument can be supported by qualitative answers that were additionally provided by some participants:

An architect stated that:

true materials R&D is not part of the tradition of architecture. When the conventional architecture firm undertakes “new materials research”, it usually involves...
searching for new products made of novel materials. This does not involve any involvement in materials research and development. Even contemporary architectural fabrication involves simply cutting, casting, or shaping stock materials that are purchased ... that is not materials R&D.

Another argued that the work with novel materials and the integration of the ‘realistic dynamic behaviour into conventional modelling and simulation tools is usually somewhere between difficult and nearly impossible. This creates uncertainty and adds to perceived risk’. He further stated that: When nobody knows then nobody knows and nobody wants to be the first to not know and get it wrong’.

In contrast, engineers suggest that the lack of knowledge is not an issue, but that time and financial resources hinder the uptake of material innovations. This response may derive from the fact that the material used by an engineer tends to be proofed and categorised by authorities. After the categorisation, the material’s properties are given to the engineer; with this dataset, he or she is usually equipped with the necessary knowledge to apply the material.

Another point of deviation between the professions is collaboration. Materials science considers the collaboration with architects and engineers as an obstacle. This seems to be true since architects and engineers give this topic in regards to the frequency of collaborating with materials science a low rating. This indicates that materials science may be a specialised profession that has less contact with other disciplines than, for example, the practice of architecture. Concurrently this trend coincides with the high peak of collaboration in Figure 5.38 for the materials scientist topic and the average low frequency of collaborating with other disciplines.

Further, some of the additional responses to questions 7 and 8 are discussed below. One participant answered that he is ‘researching abstract materials’, and another stated that ‘in our case, the development of the materials is the idea itself (usually), as materials scientists—but sometimes we work on structural ideas for which the materials are not that critical to how it works’.

These statements give clear evidence that materials science is more concerned with questions related to their own profession and that they almost work only in their own context related disciplines.
Cross-Referencing the Average Responses

I have now explored the quantitative data related to each question and profession, as well as presented the superimposed responses to four selected questions. In this section, I compare and cross-reference certain related questions and topics by utilising bar graphs to visualise certain aspects of the data that led to the observation that the preferred set of design tools tends to be a static approach, which is applied to make sense of material behaviour.

By comparing the actual use of design tools with the prospects and possibilities of new materials, the juxtaposition tries to define methods of engaging with materials that have multifunctional abilities. I focus on this particular class of materials in the next section and the following chapter: *Exploring Materials*. As described earlier these materials have promising effects for architectural applications and are strongly promoted by materials science. In order to understand the potential of multifunctional materials in relation to the common design strategies in architectural practice, I aim to analyse the synergy effects between new materials and computational design in the light of material driven design processes.

![Figure 5.42: Total average of responses according to the most applied software tools in the domain of the participants. (Image: author)](image)

With a total response score of 74 per cent, the three groups collectively indicated that 3D modelling software is the preferred tool, followed closely by programming and 3D CAD software for developing and integrating innovative ideas in design development (Figure 5.42). The graph also shows that the tools that represent or work with physical interactions, such as animation software or computational fluid dynamic tools, received the lowest ranking, with the exception of structural analysis software.
In contrast to Figure 5.42, Figure 5.43 rates design tools as very important in the context of material behaviour. This suggests that 3D modelling tools, alongside programming and structural analysis, may be utilised to work with, or represent, material behaviour. This seems to be the common practice, as discussed in Chapter 4. In my experiences working with structural engineers and materials scientist David Mainwaring, I realised that finite-element analysis is a strong tool for understanding and analysing not only an overall structural system, but also single-material properties.
Figure 5.44 indicates the total average response of all participants in regards to the importance of novel materials in their domain. (Image: author)

Figure 5.44 shows that new materials are closely linked to novel material behaviour, which is of high interest to more than 75 per cent of the surveyed group. It also shows that cost optimisation is considered very low in relation to the introduction of new materials.

In Figure 5.45, architects, engineers and materials scientists rated 3D simulations, virtual models and physical models as important methods for understanding others’ ideas, while 2D simulations are the least favoured method.

Figure 5.45 shows the overall average of the preferred technology to understand the work of others. (Image: author)
Quantitative Response

While the qualitative analysis provided insights into the use of tools and possible communication issues, the quantitative results provided information regarding the types of materials that interest participants and why are they useful.

Eight architects responded to the question ‘What is the most interesting and innovative “smart” material that you have worked with recently, and why?’ They stated that polymers and material compounds are the most interesting because of the possibility of combining different material properties within one compound. In addition, those material systems are very lightweight and can be ‘programmed’ to reach a certain design goal. Shape-memory alloys and bi-metals were among the most innovative materials and were quoted by four architects.

In contrast, engineers preferred to investigate new types of concrete, such as ultra-high-performance concrete and pre-cast concrete systems. Three participants named sustainable materials with imbedded functionality such as thermochromic materials.

Overall, the responses of the architects and engineers covered the traditional construction materials such as wood and brick, as well as advanced engineered materials with dynamic functionality, such as shape-memory alloys.

Materials scientists found the classes of alloys and fibre composites to be the most interesting and mentioned them six times.

The reason for investigating materials is mainly driven by an increasing awareness for a sustainable design and economic factors to reduce costs for all three groups of participants. According to most of the answers provided, the investigation may take place before a project is initiated, it may be driven by personal curiosity to learn about the material, or it may take place early in the design stage.

Overall, most of the named materials can be classified as advanced engineered materials, which are starting to interest engineers and architects. Materials scientists are clearly on the forefront and are investigating nano-materials and materials that are currently only in the laboratory. However, they show the same interests and reasons for applying new materials—primarily sustainability.
Summary of Online Survey

The survey design gave me new insights into how to ask questions and how to structure a survey. The survey is not complete in terms of the number of participating experts, and the list of the questions could be extended. Further, a short biography of the experts could be included, and more space could be provided for the personal thoughts of the participants.

The aim of the survey was to collect data in order to become familiar with the field of smart materials in the construction industry from the perspective of an architect. I am aware that, to truly justify the outcome, I would need to run the survey again to compare the results. In this case, the results of the survey have been combined with my practical experiences and my personal encounters with advanced dynamic engineered materials that are viable to the research and me.

The results of the survey are complementary to the issues outlined in Chapters 3 and 4 regarding the common design tools that are used today. One important finding of the online survey was that digital simulation and analysis applications are common tools used by architects, engineers and materials scientists when working with novel materials. Digital tools also serve as communication devices for explaining and understanding ideas. It is not surprising that over 70 per cent of all participants prefer to work with 3D modelling software and use the created 3D models as a basis for exchanging ideas, as the outcome will probably be an actual built object. Most of the approaches described by the participants are static analyses and modelling techniques that give the user no freedom to experience motion and time dependant effects.

In relation to the advanced engineered dynamic materials, the use of static analyses and modelling techniques appears to be an inappropriate approach if one wants to design and explore interactive systems that are responsive to external stimuli in the early design phases. Virtual and physical models and 3D simulations are the preferred methods to help understand the work of others; therefore, a combination of both virtual and physical modelling and experimenting with dynamic materials might assist in understanding the design constraints and possibilities regarding the use of those materials.
5.6 Summary, Chapter 5

The findings presented in this chapter are related to the issue of introducing material strategies in the early design phase. My motivation was to present the current state of the industry by reporting on projects that I was involved in as part of the design team of the B+G Ingenieure office in Frankfurt. From 2009 to 2011, I was involved in projects that varied in size, type and material selection, which provided an insight into, and an experience of, a ‘live’ interaction with real projects, including the daily obstacles of deadlines, cost, trust and other project-related topics. The involvement of the materials science side in the projects was sporadic and mostly limited to the exchange of data sheets and the delivery of small-scale samples. This seems to be the typical role of the materials specialist in a design project as I observed it in practice and the conducted interviews.

My investigations into the working methods of multifunctional materials encompassed the notions of digital tooling and understanding material strategies.

The purpose of my investigation was to study how materials can lead to unique design decisions, specifically regarding material behaviour and physical properties. In the case of the Oslo project, I gathered information of how materials start to affect design decisions and how this activity can be approached and supported by tailor made decision matrixes. The Hermès Project, on the other hand, made it clear that an early material awareness can enhance the design process with regard to material specific design decisions.

My embedded practice role led to engaging with architects, engineers, material specialists and fabricators. The interaction with professions of different disciplines made me aware of the tools and strategies that are applied in practice, where one key is to understand the material parameters to define design constraints. The results of the survey accommodate the same findings but point out that the accessible tools may be not appropriate enough to explore the full potential of a material driven design process.

Regarding advanced material systems with state-changing and time-dependent conditions, the difficulties in utilising the specific properties of physical material systems as design drivers are becoming a challenge.

The conducted survey let to an awareness of how architects and designers, civil engineers and materials scientists are working with new materials in a global context, as
well as the obstacles, a lack of communication and the different world views, as the literature review already signalled. In addition to the design techniques, the survey also asked how these groups make sense within cross-disciplinary collaboration and communication. The respondents were asked to consider design processes that support different ways of engaging with materials and with other professions and their knowledge bases. The findings led to the awareness that novel multifunctional materials increase the challenge of using the material properties as a design driver.

The survey’s analysed data was an important source of inspiration for focusing on design strategies that combine physical and digital models in order to promote awareness of material properties. With new materials, this strategy appeared to be a particularly promising path to explore.

As an outcome of the presented research projects, the practice and the online survey, I have focused my further research projects on dynamic material representations to draw attention to material properties as design constraints and to collaborate or communicate material strategies with others involved in architectural design and project work.

The observations and the findings presented in this chapter derived from a direct engagement in practice and the conducted survey. Only by a triangulation of practice—as I proposed in my methodology, social studies and the literature review—was I able to redefine my question of material driven design processes, which I will further address in the next chapter. I will discuss design explorations that addressed collaborations more consciously sited within the realm of material properties as a means to explore new modes of material driven design processes.
Investigating Methods for Materials Explorations

Introduction

Four Modes of Material Exploration

Theoretical Design Drivers

Design Project 1 - SmArt Architecture

Digital Simulation

Design Project 2 - The Lantern Project

Material Sensing and Visualisation

Design Project 3 - Performative Skins

Design Project 4 - Material Behaviour

Augmented Composites

Design Project 5 - Pasta in Bed

Design Project 6 - Microsynergetics

Chapter Summary
Investigating Methods for Materials Explorations

The very nature of responsive environments, involving functioning through interfaces that facilitate interaction, is a form of mediation between inner world self and the outside world, and it presupposes some kind of event that is not wholly pre-programmed. Input from the real world received via sensors is essential, as are output devices in the form of actuators (mechanisms that transform an electrical input signal into motion), displays and other sensory phenomena to engage with users.\(^2\)

6.1 Introduction

In Chapter 5, I described the findings of my experiences at B+G, as well as the results of the online survey, which led to a discovery of some common gaps in the knowledge of applying novel materials.

How can architectural and engineering practices become more familiar with highly innovative and bespoke materials in order to utilise them in the design process?

In order to refine the research question and in accordance of the described triangulated research design in Chapter 2,\(^3\) this chapter details the different methods of engaging with materials that were used during the research. The design projects were employed to test different stages of direct engagement with novel materials that emerged from the results of the online survey and that were drawn from the practical experiences presented in Chapter 5. The experiments were conducted based on physical and digital enquiries that address both material properties and spatial conditions.


\(^{3}\) The triangulation is based on a cross-link of theory, practice and personal explorations as described in Chapter 2 on page 49.
With the assistance of workshops and design cases, this chapter explores the notions of different design methods that support design with intrinsic material properties and the uptake of novel materials in architecture.

### 6.2 Four Modes of Material Exploration

My personal experiences at B+G and the reviewed literature suggest that to design with and understand materials, someone can approach different strategies to explore properties and behaviour. I highlighted earlier in Section 4.6 (‘Approaching Materials’) that science and design professions are working in a similar manner to understand material properties and the interdependencies towards their external environment. Three modes of exploration that are recognised in academia and practice can be summarised as ‘theoretical’, ‘virtual’ and ‘physical encounters’. These modes were discussed in ‘Approaching Materials’ and are likewise familiar to science and design disciplines. I decided to investigate these modes to unravel the advantages and disadvantages of each strategy. A fourth mode of material exploration is the ‘joint exploration’, which combines the digital and the physical modes. Each one of these themes explores a different strategy to become familiar with multifunctional materials.

#### Theoretical Design Drivers

Theoretical engagement with materials and technologies is a common design task for architects and the most common mode of practice, which was confirmed by personal experience discussed in Chapters 3 and 4. Multifunctional materials pose a challenge for architects, as they need to understand the material’s properties as a driver in the design process. Thus, I conducted a ‘SmArt Architecture’ course at the University of Kassel to analyse how students are exposed to advanced engineered materials as design drivers on a theoretical level. The results of this investigation are described in Section 6.3.1.

#### Virtual Simulation

Currently, work with materials in the architecture and engineering fields is primarily driven by the use of static design tools that represent only a freeze frame—that is, a snapshot of a motion picture—of the analyses (see Chapters 4 and 5). The materials are

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424 The section can be found in Chapter 4 at page 127.

425 Fernandez, 'From Kaolin to Kevlar Emerging Materials for Inventing New Architecture'.
virtually tested under forces and the results are presented in false colour plots, deflection diagrams or in an Excel spreadsheet. This approach to digital analysis and material constraints using common engineering tools is discussed in the second project, called ‘The Frankfurt Lanterns’.

**Physical Computing**

A characteristic of a purely digital design enquiry is that, due to a multi-objective design space, the design process is complex and limited in terms of control of design inputs and the predictability of the design outcomes.\(^426\),\(^427\) For early design phases, evidence from research projects and current practices in this area suggest that interactive systems could be introduced to partly overcome this problem.\(^428\),\(^429\) By combining digital and physical models, another layer of environmental influence can be studied to support the material thinking processes within the fourth dimension of time. This is a key aspect to understand the behaviour of multifunctional materials, as I highlighted with the arguments of Kennedy and Ritter. \(^430\)

**Joint Exploration**

By combining digital and physical models, another layer of environmental influence can be studied to support the material thinking processes within the fourth dimension of time.\(^431\)

The limitations experienced in the physical outcomes and analysis of the project ‘The Frankfurt Lanterns’ led to a process of material discovery with real-time feedback based on custom-designed sensors and parametric design tools. This method is discussed in the third and fourth design projects, ‘Performative Skin’ and ‘Designing the Dynamics’.

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\(^{427}\) Picon, 'Architecture and the Virtual: Towards a New Materiality.'


\(^{429}\) Fisher, 'Engineering Integration Real-Time Approaches to Performative Computational Design.'

\(^{430}\) The fourth dimension as a design driver and aspect to understand multifunctional materials is discussed in the third Chapter in sections: The Next Materials Revolution on page 75 and Material Culture on page 94.

which focus on representing material properties and establishing a better understanding of the material. A design application was not part of the agenda. This area of research combines prototype designs that present spatial architectural ideas with the introduction of advanced engineered materials and bespoke sensors in a real-time feedback scenario. The intention is to close the gap between theoretical and practical engagement with novel materials using the developed techniques and combining physical and digital tools.

The projects ‘Pasta in Bed’ and ‘Microsynergetics’ focus on the design of bespoke material systems that comprise smart materials. The concept follows the premise of physical and computational experimentation with the material itself. Research over the past five years has shown that new material systems comprising common materials can be designed with the help of digital simulation combined with hands-on experience.


6.3 Theoretical design drivers

Introduction

In addition to the practical experiences I gained while working at B+G and my limited access to advanced engineered dynamic materials, I decided to investigate the potential of those materials as innovative design drivers. As a result of the prior analysis of the possibilities of working with novel materials, a design course was developed for undergraduate students at the University of Kassel. An issue that I identified during my personal experiences in practice and by scanning the discussed literature is that design strategies and technology must be viewed as one overall source of innovation.

Fernández argues that this issue can be successfully resolved if a shift takes place in how materials are approached by establishing an understanding of how materials are effectively be applied in an architectural context.433

In the first case study, I focus on the idea of integrating the knowledge of the principle material strategies of advanced materials in order to support innovative design strategies.

In addition to the tools that support the selection process of new materials as discussed in Chapter 4 and tested at Case Study 1 and Case Study 2, certain design skills are required in order to recognise the potential of a material. Examples include the concepts of the fourth dimension: time and a basic knowledge of the interdependencies between stimuli and responds mechanisms of great value. A basic knowledge is needed to extend the design skills and to understand a material’s potential to work with multifunctional materials.

Further, Manuel de Landa and Koenigs state that new dynamic materials not only offer the potential for increased design performance, but can also lead to design proposals that are ‘changed by something that comes from within the materials’.434 In addition, they can be


434 De Landa, ‘Material Complexity.’, 14–21
influenced via the transferred knowledge of the material properties to address new design challenges.\textsuperscript{435}

I asked the question ‘Can we utilise material properties and be inspired by their novel material behaviours to design architecture?’ during the ‘SmArt Architecture’ course at the University of Kassel.

\section*{6.3.1 Design Project 1 - SmArt Architecture}

\subsection*{Introduction}

This course was conducted during the winter semester of 2010–2011. I asked bachelor students of architecture to work on a theoretical level with materials such as shape memory alloys, photo luminescent materials, phase change materials, piezo-electric materials and thermochromic materials.

I chose these materials because they have been used in an architectural context, and the materials are not in a basic research state. The materials are already available and thus are well documented. Manufacturers could be researched and the properties and material behaviours could be studied and presented prior to the design tasks.

The course was divided into two parts. The first part was a research task in which the students became familiar with novel materials. Each student researched one material of interest and presented the research to the group after two weeks. The research covered the history of the material, its principle functionality and its precedents in architecture. The aim of this part of the course was to create a material library for the students and to obtain an overview of the materials that are currently available.

In the second part of the course, the students were asked to design three architectural elements: an interactive screen, an adaptive pavilion and an interactive façade. They were allowed to use any media to express their ideas and to investigate the potential of smart materials.

\textsuperscript{435} Königs, ‘Adaptive und selbstorganisierende Systeme in der Architektur.’
Design Task

The first design task required the students to design and develop an information screen that responds to its environment. Precedents such as the Aegis Hyposurface by dECOI\(^{436}\) and the Institut du Monde Arabe by Jean Nouvel\(^{437}\) served as an introduction to the topic. A similar interactive and adaptable structure that communicates with its surroundings was required to be developed with smart materials exploiting their special properties. The aim of the first task was for students to become familiar with smart materials as a replacement for mechanical systems and to view smart materials as the design drivers for their concepts. As a constraint, each student was permitted to restrict the work to one smart material of his or her choice.

The second task asked the students to develop the idea of the information screen and to design a pavilion using the same material they used in the previous task in addition to one new material. The reuse of one material aimed to help the students broaden their knowledge of the chosen material and to become more familiar with its intrinsic properties. The scope of the design sketch was an adaptive environment, a structure or a space that allocates different environmental stimuli and tries to optimise the performance of the space according to the stimuli and the needs of the inhabitants.

The third design sketch was for an adaptive façade system. The façade might feature shading devices, media screens or other functions that could be fulfilled by smart materials. From this point, the students could use the entire pallet of the researched materials.

The design tasks therefore offered freedom with only a few constraints, including the use of smart materials and the introduced topics of an information screen, an adaptive pavilion and the design of an interactive façade system.

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\(^{436}\) The Aegis Hyposurface is a digitally controlled kinetic skin that responds to electronic stimuli resulting from signals such as movement, acoustic changes and light. Kolarevic, *Architecture in the Digital Age: Design and Manufacturing*.

The focus of the design studies included the intrinsic properties of the dynamic materials, the overall state change of the shape-changing alloys, the colour and lighting changes, and the energy-harvesting properties.

The students were given two weeks for each design task. The limited time frame was chosen in order to ensure that the tasks were purely design-driven.

**Studio-Based Projects**

The information screens designed by the students followed several different scenarios regarding the screens’ functionality. The purpose of the screens ranged from museum displays to abstract visualisations of ecological and environmental changes. Overall, most of the work related to the idea of how to establish a direct conversation with the user by tracing their body heat or proximity. The students’ work focused on novel ways of a user–space–information relationship generated by the gathered information.

One example of this approach is the design of a screen that is based on thermochromic heat-sensitive glass layers. Each colour was imagined to have a specific sensing and reacting range according to temperature changes in its surroundings. For example, if a person’s body temperature changed, the screen colour would change to indicate the person’s presence (see Figure 6.1). Further, the glass could fade into different colours depending on the number of people standing close to it. Thus, the student Thirachai Dheravatnvong developed a screen for a club that could not only display information about how many people were in the club, but it also worked as an entertainment device to give visitors information regarding ‘how good the party is’, as shown in Figure 6.2.

![Figure 6.1: Stages change colour according to group size. (Image source: Thirachai Dheravatnvong)](image-url)
The second design task—the pavilion—required more in-depth designs and technical solutions. Caroline Sherwood, for example, investigated passively and actively controlled smart materials.

The main components were activated shape memory alloys that reacted to the traced movements of visitors to the pavilions. Caroline Sherwood introduced a theme called World Discovery Containers, which was based on a travelling exhibition. Within the containers, visitors could experience and interact with the city, the countryside or the oriental market (see Figure 6.3). Each container was equipped with piezoelectric pressure sensors and shape memory alloys that triggered openings and ‘artificial grass’ (see Figure 6.4).
The artificial grass was programmed to provide a sensory experience of walking through grass into the city. Visitors to the pavilion walk barefoot and actuate the grass via pressure sensors, causing the grass to become alive and grow while the visitor is strolling through the exhibition.

The last design task—the adaptive façade—offered the students the potential to integrate their new knowledge and experiment with new ideas. For example, Thirachai Dheravatnvong examined how to control façade elements using shape memory alloys. Inspired by the sunflower and the opening mechanism of its petals, he adapted the system and developed a façade pattern that could be controlled with light and motion sensors (see Figure 6.5 and Figure 6.6).

Figure 6.4: Detail of the push-sensor setup and the smart material composite that represents animated grass. (Image source: Caroline Sherwood)

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Figure 6.5: Single-panel unit with solar cell inlay (left) and substructure of façade with panels (right). (Image source: Thirachai Dheravatnvong)

Figure 6.6: Façade concept with individual operating panels. (Image source: Thirachai Dheravatnvong)
The panels operated by the SMAs are temperature-sensitive and change shape according to temperature differences. Light-triangulated panels were designed to be opened and closed with the minimum energy that a mechanically equipped system would consume. The embedded solar cells collect energy for the panels’ operating system and store the energy to control panel movements the next day.

**Studio Summary**

The students’ showcased design intentions outlined the creative and innovative potential that derives from their introduction to novel material approaches. These new smart materials invited the students to develop dynamic systems using alternative material solutions. State-changing materials with dynamic properties are existing tools that helped the students to explore dynamic relationships and new design concepts. In particular, thermochromic inks, shape memory alloys and electronic devices such as capacitive sensors and actuators were the favourite elements for the students’ to work with.

The design outcomes often lacked in viability of student designs to the construction of the developed concepts, but the course’s intention was to introduce a new layer of materials. A detailed solution was not the aim, nor was it possible within the constrained time frame. The strength of the dynamic material properties gave the students a new understanding of the potentials of a material-driven design approach. That is, by initially investigating a material’s properties and functions, a design may appear to be driven by the opportunities offered by the material’s behaviour.

The theoretical engagement with new materials limited the students due to a lack of direct engagement with the materials. The researched datasheets and case studies promoted the materials’ functions and helped to stimulate the design process. While theoretical engagement supports freedom of design, it did not allow a detailed encounter with materials until the idea becomes a working prototype.

To work with prototypes that represent either a small scale-version or a section of a design is a common procedure in architecture and design when it comes to a decision making process that will influence the final design and construction decision.438 This

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strategy is usually applied by creating a mock-up—for example, to evaluate the different surfaces of a façade or in testing connection points or loading conditions for non-standard structures. Unfortunately, most of the time a mock-up is commissioned when the design is close to being finalised, and the prototype is not utilised as a tool for modifying or changing a design radical. The missing link in architectural practice to a direct contact with materials is as emphasised by Pallasmaa, Cross and Thomas Chastain.

As a result of the studio outcome and my personal experiences at B+G, I will further investigate the technology and construction requirements that are necessary to work with multifunctional materials. An in-depth investigation, with more time devoted to researching efficient design tools, might help to understand materials’ effects.


440 Juhani Pallasmaa, The Thinking Hand: Existential and Embodied Wisdom in Architecture, AD Primers (Chichester, West Sussex: John Wiley & Sons Ltd., 2009), 69.


6.4 Digital Simulation

Introduction

The virtual simulation of material properties and complex material behaviour is part of architecture's research focus (see Chapter 4). Today, simulation is viewed as a tool to reduce labour and time-consuming experimentation. Structural analysis and simulation is an established tool in architectural practice for early design methods.

Simulations are exploited as tools to develop and refine designs before the actual construction of physical models and prototypes. Digital simulation is also at the forefront of investigating buildings’ environmental effects. Architects are interested in exploiting energy consumption, overall energy footprints, sun effects and wind imperfections as design strategies.

However, these simulation approaches often consider force-related properties only. Loads can be represented with spring-systems, vector calculations or FEanalysis tools (see Chapter 4). With the introduction of advanced engineered materials, more than one set of forces (e.g. loads) must be taken into account to simulate the specific material property set-up. In particular, forces that do not play an obvious role in the design stage may have a crucial effect on the design’s outcome. The integration of material properties into the simulation is usually limited in the design process to a form generation, which is often representation-based upon geometric constraints in computations that simulate the material’s behaviour.

Weinstock and Stathopoulos describe the prototype simulation as challenging because the process often ‘requires multiple iterative dynamic simulations prior to the production of a physical rapid prototype’. In the next project, I focus on utilising accessible simulation tools for architects to investigate their capacity as a material simulation and design method.

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6.4.1 Design Project 2 - The Frankfurt Lanterns

Introduction

The ‘Frankfurt Lanterns’ project derived from a previous design studio led by Leane Zilka (RMIT Architecture School), Jenny Underwood (RMIT Fashion and Textiles School) and Professor David Mainwaring (RMIT–Science School). David Mainwaring and his collaborators recently developed a promising long-lasting photoluminescent powder as a potential passive lighting source for the urban environment.

The aim of a new efficient lighting culture in urban planning is described by John Culmer Bell as a ‘low-pollution continuum of well-directed moderate luminous intensity’. He argues that a city in the near future will ‘attempt to minimise its environmental impact, to achieve a relatively low carbon footprint and seek to promote and legislate for prudence in energy management’, which seems to be a new paradigm of urban lighting.

A design proposal for the ‘Light-Biennale Luminale’ 2010, in Frankfurt am Main, Germany, was conceived to explore the effects of longer-afterglow photoluminescent materials (LaPM) that have the potential to passively light urban infrastructures, buildings, public open spaces and even interiors.

In the Lantern Project, I addressed the question of how we can utilise commercially available design tools to develop design principles for smart materials based on phosphorescent materials. Functionally responsive materials add a significant


Ibid.

The Luminale—The Biennale of Lighting Culture—is an open platform for concepts and innovations in lighting design. It covers the topics of energy efficiency, new technologies and materials, and urban qualities. Artists and light designers have the opportunity to present and discuss their work in the context of the urban landscape of Frankfurt am Main. It is an international festival of lighting that takes place every two years in Frankfurt am Main and the entire Rhine-Main region.

This research began with commercially available products that could be easily introduced in the daily workflow in practice rather than work with custom-made software products that might be difficult to integrate.
requirement to the design and verification process. I wanted to evaluate analysis strategies that are commonly used in architectural practices and use them as a set of design tools for early engagement with phosphorescent materials. Further, this project was my first direct collaboration with a materials scientist, and the collaboration procedures between the architecture and materials science fields were of interest. This project in particular was also the initiator for the survey study to get a broader sense of a possible crossing point amongst the fields of materials science, technology and architecture.

Material Exploration and Design Constraints

Along with the advantages of using LaPMs, there are also constraints and restrictions that must be taken into account in the design process. In the Lantern Project, the LaPM requires an explicit analysis of the glowing effect over a certain period in terms of direct and indirect sun exposure. The material needs to be ‘charged’ by the energy of the ultraviolet (UV) light, which is part of the sun’s light spectrum. The material’s phosphorescent glowing effect is a decaying response to the activation of the material’s nanoparticles in the sunlight. Once the UV light activates the phosphorescent particles, they start to glow in a similar manner to fluorescent colours; however, rather than stopping to glow if the light turns off in that particular case, phosphorescent particles maintain their lighting properties over a longer period. This period and the strength of the glowing depend on the intensity and time scale of the exposed UV light. This process of light exposure is referred to as ‘charging the material’, which is similar to charging a battery (see Figure 6.7).

![Figure 6.7: Function of the green-emitting LaPM. An experimental ceramic with induced particles glows when the surrounding lights become darker. (Image: Applied Sciences Laboratory RMIT)](image)

450 Photoluminescent nanoparticles absorb light and emit this over time. The absorbing process is called ‘charging’. The energy-releasing decay can be controlled and changed. An instant re-emission of light is called fluorescence, while a delayed release is the so-called phosphorescent effect.
The material is under development and is being optimised to be as long-lasting and intense as possible. Consequently, this emerging or prototypical state poses a challenge for every new design.

Further, alongside the material constraints, the project took five months to develop and assess the material, to gain knowledge of how to apply the material onto different substrates, design the installation, produce it in Australia and ship it to Frankfurt, Germany.

An initial testing phase of different materials was conducted to find a suitable substrate for the photoluminescent nano-powder. At first, several metal sheets with different patterns were analysed. Here, the glowing pigments were integrated within a weather-resistant paint and applied manually to the various substrates. This approach proved to be ineffective because the colour pigments could not be uniformly dispensed. However, the different patterns could be analysed in relation to their exact consistently conditions. The pattern in the central panel of Figure 6.8 shows the optimal result in terms of colour continuity.

A different approach was developed due to the difficulty of applying the pigment uniformly across the metal surfaces and the weight of the metal sheets. The powder of the glowing particles could be directly integrated into a polymer film and laminated onto translucent plastic cylinders (see Figure 6.9).
Simulation

Evaluating the glowing effect in a real environment beyond the laboratory context was a crucial aspect of the project. The intensity and colour of the glowing effect was determined by the mixture of nanoparticles, which are usually tested in the laboratory under steady state conditions. In this case, light emissions were tested with a fluorescence spectrometer that measured emissions at different wavelengths in a nanometre (nm) spectrum. The measurements provided a scientific description of the glowing effect, but the commonly available analysis software for architects only provides the design criteria of light based on lux or lumen. Thus, a digital simulation of the glowing effect in predicting the real scenario with the true glowing effect becomes a challenge.

I started to simulate and analyse the afterglow characteristics within the environmental analyses software Autodesk® Ecotect® Analysis and the light simulation tool

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452 The lux (symbol: lx) is the SI unit of illuminance and luminous emittance, measuring luminous flux per unit area and illumination of a surface.

453 The measurement of the glowing effect of a light source is based on a low-level energy release of the electronic state change of the particles and is measured in millicandela per square metre.

454 Autodesk Ecotect is an environment analyses and design software for architects that has a direct connection to Radiance.
The simulation was based on empirical inputs of colour and illumination intensity in lux that derived from previous experiments of comparisons with the prototype. The material characteristics were aligned in an iteration process to match the glowing effect of the light source. The results were compared to samples of the material to match the glowing effect (see Figure 6.10 and Figure 6.11).

Figure 6.10: By adjusting the Candela outputs and the total Lumens in the material properties section of simulation, the emitting light can be adjusted to match the samples. (Image: author)

Figure 6.11: Examples of the international process and the resultant images of the light simulation. (Image: author)

The simulated lanterns were first analysed in a closed box to define the true colour and glowing effects. Later, they were placed at the specific coordinates of Frankfurt am Main matched to the local weather conditions. The atmospheric conditions that can be simulated by Ecotect are based on a sky model defined by the Commission

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455 Radiance is a ray-tracing open source software that predicts illumination and visual quality and that evaluates new lighting and daylighting technologies.
Internationale de l'Eclairage (CIE), which is obtained by ‘mathematical models of ideal luminous distributions under different sky conditions’.

The developed CIE sky models rely on ‘average’ light conditions. Unfortunately, this limits the model and the simulation cannot simulate a changing sky due to increasing clouds, for example. Thus, it quickly becomes a complex system to model a perfect glowing effect that represents the true material behaviour in Frankfurt am Main in late April for a period of four days. The surrounding lighting conditions must be taken into account, and the changing weather must be predicted as precisely as possible to ensure a feasible result. In addition, the lighting analysis shows no evidence of the UV radiation required to gain an advantage of the performance of the LaPM.

Renderings and image manipulation to assume the lighting performance of the new material is one method of communicating possible benchmarks of the design and helping to further develop the material research (see Figure 6.12). However, this process cannot be utilised as a design tool due to its lack of detailed inputs and outputs.

![Figure 6.12: Rendered version of one half of the pergola structure during the day (left) and night (right). (Image: author)](image)

Results

One hundred and fourteen lanterns were placed within the pergola structure in the forecourt of the Alte Oper to be visible and easily accessible for visitors to the Luminale.

The installation did not have the envisaged effect of a continuously passive lighting system that could contribute to the chosen space. The differences in the afterglow effects are illustrated in Figure 6.13.

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To prove the concept and allow visitors to experience the glowing effect, they were provided with strong UV flashlights. Once the lanterns were exposed for about 10 minutes to the UV light, the after-glow effect could be reproduced (see Figure 6.14). These arose from the significantly lower sunlight intensity in Frankfurt, compared to the original studies that were conducted during a Melbourne summer.

In addition, the glowing effect, which was perceived as brightness, was materially dependant on the surrounding public light conditions in Frankfurt, whereas the ‘light pollution’ was inherently lower in Melbourne.

These experimental studies in illumination design demonstrate the need for a close connection between digital simulation and physical prototyping as a means of exploring advanced engineered dynamic materials. These studies illustrate that, for each responsive material, the environment content (e.g. Australian summer vs. European spring) for charging the pigment

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457 Light pollution describes the effect of direct and indirect light on global lumination and glare effects, which result in bright-light fog that impedes the view of the night sky. A high level of light pollution is a sign of bright lighting systems that have distorted the perception of the surrounding lighting conditions.

as well as the ambient external illumination as a background will dominate its performance and require quantification in the modelling process.

Further, the experiment showed that basic prototyping processes that provide familiarity with the material by the ‘act of making’ cannot be overlooked, even if advanced simulation tools are applied. As Bob Sheil states: ‘Where it is implied that materials are synthesised as physical and digital matter, it is important to remember that built architecture is not made of points, vectors, splines and algorithms, but of stuff that has a habit of misbehaving unexpectedly’.  

The right weather conditions, overall sun exposure (intensity and time) and surrounding public lighting conditions must be taken into account for the successful functionality of the glowing material. Sunlight intensity and exposure cannot be predicted precisely, although assumptions can be made based on material experiments that assist in making design decisions.

The dynamic response of the material that drives the glowing effect must be incorporated with predictive simulation. Influenced by the smallest change in the environment, the dynamic relationship between material and environmental stimuli makes it difficult to express and represent the materiality with common analysis techniques. To enhance the function of the glowing effect and to introduce it in the architectural context ‘a systematic reconciliation between scientifically measured characteristics’ and ‘experimental determination of the visual perception of their performance’ will be needed in the future.

My collaboration and communication with a materials scientist was a process of understanding his mind-set, and vice versa. A discussion was sometimes difficult, particularly in relation to the material constraints. For example, the materials scientist was sure that the material would work under any circumstances because he evaluated the material in the laboratory using his scientific methods. I was concerned about the

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458 Sheil, 'Distinguishing Between the Drawn and the Made.'

459 A detailed explanation of the phosphorescent effect and its glowing process can be found at the Material Lexicon page:17

real application and functionality under real conditions, but I was more focused on the simulation to look for design strategies to help make sense of the material. Both strategies missed the opportunity to define the constraints needed to create a successful installation.

As an outcome of this collaboration, Professor David Mainwaring, Leanne Zilka and I reflected on the installation and design process. A closer communication and a repetitive design process with additional physical tests to cover different scenarios would be beneficial to overcome the experienced obstacles. Furthermore, this case study opened the question of authorship and trust, which I will elaborate in the final Chapter 7.

**Project Summary**

This project discussed the possible integration of design tools and physical prototypes to establish a new material thinking around the scope of phosphorescent materials in the early design phase. This early engagement includes materials science and architecture simultaneously. The materials scientist introduced the material to me and contributed material knowledge to the project.

The case study suggests that, with commercially available architectural design software, using Autodesk® Ecotect® Analysis, the virtual modelling of the LaPM features could be partly reproduced. This partial simulation was only possible by comparing the real glowing effect with the simulation. The effect and efficiency of the material situated within the real environment could not be accessed via this particular software, and it was limited by the environmental background light and the perceived glowing effect. However, the available scientific measurement techniques of justifying the material properties are not suitable for the common light design, which is based on light intensity rather than light emissions at different wavelengths. The opportunities generated by LaPMs necessitate the active derivation of physical material properties before the implementation of the generative techniques involved in computational architecture. Further studies of the material and new measurements that contain the necessary light units could lead to a better integration of the material in design software.
6.5 Material Sensing and Visualisation

Introduction

This section presents sensing technologies as a means of engaging with material properties on a direct and physical level. I present two projects that address this topic: first, a minor experiment that involves my first experiences with sensing technology; second, a group workshop that aims to investigate the sensing technology in the realm of material property visualisation.

I will introduce the key ideas of sensing, physical computing and physical composites as key drivers behind this investigation.

Physical Computing

Physical computing is viewed as the next level of computer interaction with the human body. Dan O’Sullivan and Tom Igoe describe this need as:

\[ \text{We need computers that respond to the rest of your body and the rest of your world.} \]
\[ \ldots \text{We need to think about computers that sense more of your body, serve you in more places and convey physical expression in addition to information.}^{461} \]

They describe the concept of physical computing as a conversation that takes place between the physical and digital world. Further, Massimo Banzi highlights that physical computing enables designers ‘to prototype new materials’ that ‘create meaningful experiences between (humans) and objects’.\(^{462}\)

Working only with digital design and simulation tools often leads to lacking in understanding of the designed system. Material properties such as weight, density and strength can be simulated but remain inexperienced or, as Kenneth Frampton argues,

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‘On a computer screen, forms seem to float freely, without constraint other than those imparted by the program and by the designer’s imagination.’

Next to this statement of the danger of neglecting reality in the virtual model, a digital simulation is often time-consuming when it comes to matching the reality. A digital simulation that reflects the reality requires a clear formulation of the simulated environment, especially of a material system that is associated with complex interrelations such as geometry and material, forces and restrictions, and environment and time. Hence, an abstraction of the simulated model, which is usually based on geometry-related constraints, is established, thus limiting the simulation outcome and flexibility of the simulation. An advanced simulation that represents reality can only be achieved through a close observation of the material behaviour and physical experiments that inform and compromise the virtual simulation.

An interaction of the material via physical computing combined with digital real-time feedback and simulation technology may therefore enhance the understanding of novel material systems.

Sensing Techniques

The simplest sensors that one could integrate into the material and design process are force-related sensors such as pressure, bending and touch. While these sensors are not new and are relatively easy to use, the data that can be gathered from these devices is limited. One could argue that more advanced sensors such as ‘strain gauges’ could be

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464 Ahlquist and Menges, “Physical Drivers Synthesis of Evolutionary Developments and Force-Driven Design.”

465 Weinstock and Stathopoulos, “Advanced Simulation in Design.”

466 A digital real-time feedback system can sense digital and analogue data, process the sensed information and react to the received information in a predefined range in real time. The reaction can be a shape change of a virtual 3D model, colour change effects or a string of text that changes its content or values.

467 The strain gauge is a simple physical device that can be easily applied to measure the strain of an object. As the object deforms, the strain gauge deforms as well and changes the electrical resistance. This causes a change in the measurement of the current flow, which indicates that the object is tensioned or compressed.
used; however, due to the complex set-up that is necessary to utilise them, they do not appear to be applicable for a flexible, intuitive design strategy.

A viable alternative to expensive sensing devices is capacitance-based sensors, which have the advantage of being multifunctional. Capacitive sensors are currently used because of their relatively accuracy; they are easy to integrate and they offer a range of applications. Capacitive sensors are based on conductive material that detects anything that is conductive or that has a different dielectric charge than that of air, and that is used to sense changes in the electrical fields around them.

The relative freedom in material application and new open-source environments for interaction design make this technology the most appropriate method of developing new scenarios for embedded computing in the built environment.

**Computational Composites**

The notion of a 'computational composite' is explained by Anna Vallgårda and Tomas Sokoler by the introduction of the computer as a material combined with dynamic materials. They argue that computational composites are material composites in which at least one material has computational capabilities. Further, Vallgårda discusses the need for designers to obtain an embodied sensation of the meaning, in which the materials change in space over time. In her research, she suggests that theoretical knowledge should not be founded within the paradigm of information technology, but in the understanding of the computer as a material. That is, the computer is described as the material itself.

In my further design studies, I refer to the computer as a control and simulation tool for real-time interaction; thus, it not only perceives the dynamic material behaviour, but it

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471 Vallgårda and Sokoler, 'Material Computing – Computational Materials.'

can also engage with the material in real time. The material itself is viewed as a composite that combines the sensing, actuation and control mechanisms to change shape, colour or conductivity.

To understand the perception of material behaviour, I investigated sensor techniques and control mechanisms in the realm of physical computing that could be easily integrated into the design process. Advanced engineered dynamic materials require the sensing and representation of their material properties in order to be fully integrated in the design process.

This technology enables the designer to interact with materials during an early stage of engagement, and this should be explored further. Thus, the next two experiments in this section explore the ideas of sensing, computational materials and the physical–digital interaction with materials as a way of understanding, discovering and utilising material properties via anticipation as design drivers.
6.5.1 Design Project 3—Performative Skin

Project Introduction

One example of sensing technology embedded in material structures is the research of Mette Ramsgard Thomsen and Ayelet Karmon, who use capacity sensors to understand how localised sense-data can be integrated into the design process using dynamic material representations. Their work ‘Listener’ and the ‘Smartgeometry Workshop 2011’ are proof of the concepts for this technology.\footnote{Mette Ramsgard Thomsen and Karmon Ayelet, ‘Computational Materials: Embedding Computation into the Everyday,’ in Digital Arts and Culture Conference, vol. 7, 2009, 426–7} I was a participant during this workshop in the ‘Performing Skins Group’ led by Thomsen and Karmon, in which I developed a tool to predict and simulate the material behaviour of a fabric. The existing ‘base diagram’ was reconstructed and visualised as a meshed geometry, which was used to produce a realistic representation of the final geometric assembly of the knitted surface.

The intention of this Smartgeometry participation was particularly interesting to me so I could become involved in self-made sensing technology and parametric-driven CNC manufacturing approaches. During these intensive four days, I wanted to test and combine digital design tools, real-time feedback and CNC fabrication techniques to learn more about the sense-making approach of material properties.

Materials and Design Constraints

The workshop offered the opportunity to work with different types of yarns to create our own fabric composite. Fishing wire, cotton, rubber and conductive yarns were particularly interesting. The array of yarns provided several combinations of fabric composites that could change the stretchability, density and most importantly, the conductivity of the fabric.

The conductive yarns embedded in the fabric can sense, with the help of the capacity-sensing technology, the changes in the surrounding electro-magnetic (EM) field (Figure 6.15). The sensing intensity could be increased by knitting multiple threads into the fabric. Once the conductive yarns are embedded, the fabric can read and send a signal that can be interpreted via a microcontroller and a processing sketch. The interpretation
and the fine-tuning of the transmitted signal had to be constantly re-calibrated due to interference of the EM field.

The design of the knitting layout via a parametric model and the fabrication of the fabric via the CNC knitting machine were limited to four different knitting patterns that were provided by Thomsen and Karmon.

Figure 6.15: Work in progress with one of three fabric prototypes connected via a microcontroller directly with a parametric model in Grasshopper. The connections and conductive yarns were tested and configured frequently due to a fast change in the electro-magnetic field that was distorted by the amount of computers and metal parts close to the prototype (image: author)

Computational Approach

The digital design process involved in working with a parametric graph was created with Grasshopper. The associated model was the basis of the digital design of the fabrics and was provided by Thomsen and Karmon. The base model visualised an abstract representation of the knitting pattern based on the knitting directions (see Figure 6.16). With the help of this model, it was possible to distort the knitting pattern using attractor fields474 (see Figure 6.17 and Figure 6.18).

474 Attractor fields are simulated force fields that can, within a pre-set radius, attract or repel an object or deform it based on the strength of simulated forces. Attractor fields and points are being used as digital architectural design
This line-based graph was then interpreted as a CNC code and fabricated. The participants in my group and I felt that the interpretation of the graph was difficult and the prediction of the outcome was uncertain. I started to define geometrical rules that could be incorporated in the ‘base model’, which helped to visualise a meshed surface close to the final fabric outcome. This part of the parametric model could be adjusted and refined due to the knowledge gained about the tension and stretch properties of the first knitted prototypes.

strategies to simulate not only forces but also to generate forms and geometrical deformed shapes or discover and simulate the motion of traffic, liquids or sound distribution.
The parametric surface introduced high and low points to create the correct knitting topology. The location of the high and low points was a variable based on the ‘tension length’ of the knitted fabric that was studied during the workshop.

Finally, I introduced a surface subdivision algorithm\(^4\) to simulate the smooth topology of the knitted fabric (Figure 6.19).

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\(^4\) A subdivision surface is a recursively-defined surface by subdividing a polygonal mesh into smaller elements that approximate the smooth surface. Edwin Catmull and Jim Clark, 'Recursively Generated B-spline Surfaces on Arbitrary Topological Meshes', *Computer-Aided Design* 10, no. 6 (November 1978): 350–355.

\(^5\) The circuit for proximity sensing and the processing code for interpreting the data is based on the Capacitive Sensing Library by Paul Badger: http://arduino.cc/playground/Main/CapacitiveSensor?from=Main.CapSense.
This approach to the representation and integration of novel materials helped to develop an understanding of the relationship between environmental effects and material systems through the haptic-intuitive interplay between the digital simulation and the physical material testing (Figure 6.21).

This design process required a bottom-up strategy in which different issues with small virtual and physical prototypes were identified and resolved individually before assembling the larger structure. For example, the redesign of the parametric model was only made possible by isolating smaller parts to understand the translation of the knitting pattern into the 3D virtual model.

The first attempt to work directly within the existing model failed due to the complexity of the parametric sketch. The sketch included the information for the ‘base model’ that was necessary to generate...
the CNC code, the translation of the geometry into a readable file format for the knitting machine and a pre-given set of attractors. This sketch was a computational-heavy construct and made it inaccessible for further modifications due to a slow reaction time of the parametric model in response to the changes.

The embedded proximity sensing raised another issue of controlling the sensitivity of the data reading. With each additional embedded conductive thread, the overall knitted structure became more difficult to control, and the calibration of the sensed data was the biggest problem and needed additional adjustments over the period of the exhibition.

Result

Figure 6.22: Impressions of the final knitted structure attached to a tensegrity system with embedded conductive yarns. (Image: author)

On the negative side of using alternative sensing techniques such as proximity sensing, it became clear that the trade-off between the exact sensing of the data and the design intention is hard to match. Sensible conductive materials can be affected by electrical and magnetic fields that are stronger than those produced by the human body and might distort the recorded data. In this project, the substructure was assembled from a tensegrity structure (see Figure 6.22) that was bolted with metal screws that instantly increased the sensitivity of the proximity sensing. Thus, it was difficult to calibrate to obtain useful data to control the virtual model.

Nevertheless, once the calibration was adjusted to the surrounding conditions an interaction between the user and the sensitive fabric could take place. The fabric
became, similar to a touch-screen, a control tool for the virtual parametric model and the visualisation of the real-time reconfigurable ‘hill-surface’ indicated to the user the next possible solution of a further CNC-knitting cycle in response to the ‘pressure’ of the touch of the visitor.

Project Summary

The direct engagement with materials via modern digital media and tools is referred by Höfler as a continuation of the Bauhaus philosophy represented by Albers and Itten. In contemporary architecture, this is especially a field of research in regard to structural and adaptive design as the work of Iwamoto, Menges, Hensel, Thompson and others are showcasing, which I outlined in the previous Chapters 3 and 4.

With the advent of affordable sensor technologies and microcontrollers, a new dimension of material perception as design tool is becoming available for architects and design disciplines. Above all, technical wearables already engage with dynamic materials in a playful way and develop and discover new design methods as the materials become available. Leah Buechely, for example, directs ‘The High-Low Tech group’, a research group at the MIT Media Lab. Studio Roosegaarde, in collaboration with fashion designers Maartje Dijkstra and Anouk Wipprecht, has developed a series of adaptive fashion objects that interact with the wearer and the environment. The Smart Textiles Design Lab at the Swedish School of Textiles have examples of the growing society of technical wearables.

In architecture, the new paradigm of computational material systems with embedded physical intelligence helps to bridge the gap between physical modes of material exploration and digital design tools. This method allows for new modes of discovering material properties, thus influencing design decisions and contributing to innovative outcomes.

477 The work of the High-Low Tech Group is investigating high and low technological materials and processes to integrate them into our society. http://hlt.media.mit.edu/

478 Studio Roosegaarde is a design studio that is concerned with digital design and explores the boundaries between humans and technology. By utilizing new media and design tools the studio is creating interactive social designs that trigger human senses to create a sensual engagement with their environment. http://www.studioroosegaarde.net/

479 The scope of the Smart Textiles Design Lab is covering the development and experimentation with new expressions for textiles through the use of various technologies and textile techniques. http://www.std1.se/
By enabling the virtual prototyping of a physical material system based on a parametric model combined with physical computing, a virtual interaction with the developed system can for example visualise the behaviour in the material of the fabric before composing the real fabrics. The introduction of sensing technology and physical computing seems to be in line and extending the palette of available tools to design and work with materials as design drivers.

### 6.5.2 Design Project 4 - Material Behaviour Project

#### Project Introduction

Based on the initial experiences with embedding sensing technology and representing material behaviour, the third experiment further investigated the potential of a combined sensing and simulation approach.

The ‘Material Behaviour Project’ was part of the multidisciplinary workshop called ‘Designing the Dynamic’ in November 2011. The theme of the workshop was to investigate dynamic feedback systems and performance-driven design challenges in real time. The challenge of designing an integrated digital and physical dynamic model to engage with environmental stimuli was placed outside of the typical comfort zone of an architect, especially working within the unfamiliar field of sailing. The aim of the workshop was to become more familiar with digital and physical design prototypes and simulation tools to support intuitive real-time design decisions.

#### Purpose

The Material Behaviour Cluster was organised and led by fellow PhD candidates Daniel Davis, Chin Koi Khoo and myself. The project further investigated capacitive sensing technology and addressed the question of how we can sense and represent the response of textile materials to external stimuli. By studying and developing material models that were equipped with different capacity sensors, the workshop aimed to design and manufacture sails to help the designer establish material awareness at an early design

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480 The workshop was organised by the RMIT Design Research Institute, Future Fabric of Cities flagship, the School of Architecture and the Spatial Information Architecture Laboratory (SIAL) in Melbourne, Australia and led by Hugh Whitehead and Jane Burry.
stage. The combination of sensing technology, parametric modelling and simulation was the scope of the cluster challenge.

First, I set out to study the sail design and manufacturing process of the leading sail-making company North Sails Group, LLC and their approach to designing high-performance optimised sails. The fabrication process of the thermo-moulded 3DL® sail of North Sails served as the starting point of our own design exploration.

**Material Approach**

The specific material-oriented design task began by experimenting with several reinforcement materials and sailcloth. On the first day, the group investigated combinations of cloths and reinforcements. Different materials such as Kevlar®, Dacron® and Mylar, which are all lightweight and flexible materials used in sailing, were combined with nylon fibres, wool and even human hair (Figure 6.23). The material compounds were either single-layered Mylar sheets with an additional reinforcement layer on one side, or they were created using two layers of Mylar with the reinforcement layer in-between, similar to the thermo-moulding process of North Sails.

The material samples were tested for stiffness and flexibility by bending them manually and recognising the changes. The haptic-intuitive engagement was part of the personal experience to understand the material properties.

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481 This is a sail-manufacturing technique to optimise a sail according to the aimed performance in specified areas.

482 Kevlar® is the registered trademark for a para-aramid synthetic fibre. Developed at DuPont in 1965, this high-strength material is spun into ropes or fabric sheets that can be used as an ingredient in composite material components.

483 Made from PET fibres, also known as polyester.

484 Mylar® is a polyester film made from stretched polyethylene terephthalate and is used for its high tensile strength, chemical and dimensional stability, transparency, reflectivity, gas and aroma barrier properties, and electrical insulation. DuPont invented it in the early 1950s.
In preparation for the intensive four-day workshop, I tested different possible sensing technologies in addition to the capacity sensors I was used to. I investigated pressure- and bi-directional flex-sensors\textsuperscript{485} to study their usage for this particular approach of sensing the bending and tension of sails (Figure 6.24).

The available palette of pressure and bending sensors for microcontrollers in particular offers a wide range, but they often have a limited range for sensing. The pressure sensors need an actuation force of at least 100 g and can take up to 10 kg force. For intended use for a small-scale version of a sail, the sensors must have a certain resistance and only start to bend and flex when at least 100 g forces are applied. Small-scale sails

\textsuperscript{485} The flex sensors that were tested during the project were the FS sensors by spectrasymbol. http://www.sparkfun.com/datasheets/Sensors/Flex/FLEXSENSOR(REVA1).pdf
are affected by the rigidity of the sensors, and the performance of the sail may not be simulated correctly.

Due to my prior investigation of commercially available sensors and the discovery of their stiffness (the sensors have a resistance and are very rigid), it became necessary to develop lightweight and easy-to-use sensors to avoid an effect on the sail behaviour. During the workshop time, experiments were conducted with sensors from anti-static conductive foam\footnote{Conductive foam is used to provide protection to sensitive electronic parts, printed circuit boards and other electrically sensitive equipment that has to be shipped.} that changes its capacitance in a measurable way when being bent or stretched. The results of these initial tests were promising because the sails did not appear to be affected as much as, for example, the applied flex-sensor.

**Computational Approach**

Before the workshop, I initiated a first test set-up of the sensor to develop the circuits and ensure that the sensors were sensing and recording data. I designed a parametric model that represented the shape changes of the sail by reacting to the recorded data of the sensors. The sensors were linked to an Arduino micro-controller, which sent the data via Firefly to Grasshopper. The fabric motion was controlled by the recorded live-stream of the sensors and translated into a force to simulate wind pressure (see Figure 6.25). The virtual fabric was simulated as a particle spring system based on the physics game engine Kangaroo by Daniel Piker\footnote{For a more detailed explanation, see Chapter 4.} (see Figure 6.26).

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Figure 6.24: Simple set-up of the tested commercially available sensors (one pressure sensor, three bi-directional flex-sensors and one softpot membrane potentiometer); Left image: Examples of the self-made conductive foam sensors. (Left: Circular sensor; Right: straight sensor) (Image: author)
This quick and easy set-up proved that the sensors worked and the data were recording. It also showed that it would be possible to realise a virtual simulation of a sail during the workshop time. Nevertheless, the workshop aimed to visualise the sensed data within the programming language Processing. A visualisation with values of the data stream, colours and graphs of more than one sail simultaneously appeared to be more feasible.

At the workshop, the participants began to develop reinforced patterns based on the RC boat’s sail. The designed reinforced patterns were based on the force flow lines, which were in turn based on existing examples of present sail-making companies such as North Sails and Doyle Sailmakers Inc. and adapted by the participants to design new

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488 Doyle Sailmakers are one of the largest sail-makers and sail-design companies and specialise in designing racing and cursing sails. [http://www.doylesails.com/index.html](http://www.doylesails.com/index.html)
patterns. The grasshopper plug-in flowL™ was used to design and develop the reinforcement lines (Figure 6.27).

In the second phase of the four-day workshop, the aim was to correlate the outcome of the digital investigation into the sail design and the physical material examples. Three different sail designs (a self-design designed sail, a typical tri-radial cut pattern and the original RC boat sail) were chosen to be equipped with sensor fields in order to compare and visualise the sail behaviour.

As a representation tool for the multi-streamed data, Daniel Davis developed a Processing script\textsuperscript{489} that could align the recorded data of the six sensors side by side to compare all of the data simultaneously.

Our testing set-up aimed for a subsequent visualisation of the recorded data that could be used as an empirical design tool that gives the user and observer an idea of the material performance and relationship with the simulated environment. The visualisation of the processing sketch visualised the data interactively by constantly changing the colours and sizes of the values. Each sensor was represented by a circle with an inner number that changed its diameter and colour according to the size of the value (see Figure 6.28).

\textsuperscript{489} The script can be found in the Appendix A2
Results

To test the developed sail material under ‘real’ conditions, we used an RC boat as a reference. This allowed us to produce a series of five small-scale sails that could be attached to the boat and tested. The test set-up was placed in a controlled interior environment, which allowed an easy examination of the material behaviour. This was clearly an advantage for the intuitive learning process. Analysis in a closed space gives the opportunity to compare the performance of different sail designs under the same wind conditions repeatedly. The wind was simulated by three commercial fans with three different wind speeds.

At the end of the investigation, three sails were mounted in flexible frames and connected to a live-streaming visualisation of performance data. Data validation was based on the comparison of the sensor mapping. The sensors were placed at two locations on the first and second thirds of the sail to cover the region of highest pressure in the sail (see Figure 6.29).
The outcome of the wind test was designed to visualise the highest mean data values of the compared sails. The performance of the sails is indicated by the standard deviation of the values. A poorly performing sail will be visualised by high fluctuations in the sensor values due to disrupted airflow caused by vibration of the sail, which will increase the standard deviation. A luff sail (a poor performance of the wind-affirming side) has an uncontrolled airflow and will result in low sensor values compared with the lead sail.

In this respect, the self-designed sail (Sail A) had the best performance and responded with the closest average data value compared to the other sails. It experienced the most pressure/bending force. The sail with the tri-radial cut pattern had the worst performance. The original RC boat (Sail C) was utilised as a compartment of Sail A and Sail B (Figure 6.30).
The presented values are based on resistance changes within the sensors and cannot be translated into a real pressure unit such as N/m². Therefore, the values are only viable in comparison to each other and have no individual meaning.

During the set-up of the final installation, it became clear that each developed sensor had a different data output, even though they had the same dimensions. Adjusting the sensors via the processing code and Firefly sketch was time-consuming but mandatory for a successful simulation. We faced the same issues with the calibration of the sensors and with the ‘Performative Skin’ experiment. The self-made sensors are very sensitive, and a reliable use of capacity sensors requires recalibration before running each wind pressure test.

However, by bridging the gap between physical and digital simulation and visualisation, a better understanding of the sail and the material performance can be developed. With the aid of the sensors, the Arduino micro-controller, parametric modelling and coding of the recorded data could be visualised in a simple and understandable real-time changing graph (see Figure 6.31).
Figure 6.31: Final installation of the material behaviour cluster of the ‘Designing the Dynamic’ workshop. The three sails are tested with commercial fans and the sensed data are projected as a life-stream. (Image: author)

Project Summary

This project was not meant to be accurate in terms of the real data of the measured pressure, and the focus was not on the scientific approach of the testing set-up. Rather, it was proof of using simple and easy-to-learn sensing techniques and design principles to analyse another level of material behaviour and to train the perception of distinct material properties. The user can combine these flexible digital simulation techniques with simple geometrical models to gain a better understanding of dynamic materials. This is particularly helpful for informing design decisions at an early stage. The experiments and explained techniques suggest that we need to link the physical properties to a design-oriented understanding in order to obtain a better understanding of dynamic materials.

Following this understanding of the design process and the studies of Anna Vallgärda and Tomas Sokoler, I propose that a fully accurate descriptive function of materials may not be needed in the early design stage. Rather, the designer must engage in a level of
imagination in the early design phase. I agree with the argument of Ramtin Attar, who stated that an ‘early design exploration is essentially a speculative process with its own dynamics, involving intuition and spontaneity’. Aish argues that it is a process of ‘making inspired decisions with incomplete information’ that ‘explains the necessity of a counter balance of our intuition’.

This cannot be achieved using only sophisticated software tools that need high-resolution and detailed modelling. Further, advanced software is often ‘computationally expensive’ and slows down the design process.

A test of this statement and an exploration of the possibility of combining physical computing and digital design tools will be outlined in the following design project. Once such a design method for an early design phase is developed, a precise simulation of the multifunctional materials would be advantageous, as the Lantern project showcased.

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491 Aish, 'From Intuition to Precision', 10–14

6.6 Augmented Composites

Introduction

The fourth method of exploring advanced engineered dynamic materials converges on a joint approach of simulation, sensing and physical interactions. Based on the findings of experiments 2 and 3, the interest of the following experiments lies in the control and actuation of dynamic materials.

While the sensing techniques discussed in the ‘Performative Skin’ and ‘Material Behaviour Project’ offered methods of interpreting and understanding a material system, the question of whether the techniques can be utilised as a design tool for dynamic materials suggested that further exploration was necessary.

Following Kolarevic’s argument that the physical interaction and ‘iterative experimentation, error, and modification that could lead in the end to some innovation…’ and Jerome Frumars’ statement that ‘the rapid and iterative design strategies contribute to the development of high quality materially driven architectural designs’, I further explore iterative experimentation with the help of physical computing and digital simulation as a means of creating a basic knowledge to work with, and design, dynamic material systems.

As discussed in Chapter 4 and highlighted in the outcome of the online survey in Chapter 5, adequate design strategies to understand and communicate material may support the decision-making process and lead to innovations in applying dynamic materials in architecture.

The goal, as described by Interview Partner No. 2, is to create sustainable systems that reduce energy waste by replacing electrical devices with smart materials and supporting adaptive and innovative architecture.

'We control shape memory springs by solar heat gain, without using any electricity or computing devises and sensors. Everything is happening within the material …'


A physical simulation as experienced in the previous experiments appears to build an awareness of materiality and what a material can do. My research appears to confirm this as an important parameter, for occasions when multifunctional materials are considered a material solution.

Especially the exploration of the dynamic material behaviours and the shifts from static material properties as Kennedy\textsuperscript{495} states it can benefit from the simulation approach.

Although the physical interaction with materials and models is a valuable tool in the process of understanding material impacts, Weinand argues that digital tools are crucial for exploring potentials of unknown phenomena and material systems.\textsuperscript{496}

On the other hand, it seems the haptic-intuitive engagement with the material inspires the design and learning process to unforeseen solutions. This process of making is, for Kenneth Frampton, an important part to learn about the ‘material dimension of architecture, its intimate relation with properties like weight, thrust, and resistance’ while he further states that digital design procedures often appear to neglect the material dimension.\textsuperscript{497}

Therefore, I investigated the use of microcontrollers in combination with physical experimentation as an additional design tool. Microcontrollers might enable us to create environments to examine the behaviour of a dynamic material system in a time-lapse scenario. Real-life effects such as light, moisture and capacity can be controlled and utilised via microcontrollers to simulate the timespan of a day, week or year within a shorter timeframe. For the following two experiments, I applied the microcontroller as a design tool for dynamic material systems called ‘Augmented Composites’ (ACs), which are material composites that combine the functions of actuation and sensing as designed objects that are related to adaptive architecture. ACs are assembled material composites based on smart materials that may incorporate additional materials as substrates. ACs can be controlled via digital media and are part of a digital and physical design process to encounter the possibilities of dynamic material systems.

\textsuperscript{495} Kennedy, ‘Responsive Materials.’


6.6.1 Design Project 5—Pasta in Bed

Project Description

The workshop entitled ‘Pasta in Bed’ was organised in collaboration with a multidisciplinary team to investigate sensing technology and simulation as a digital design method to design and create ACs on an architectural scale. Pasta in Bed was conducted at the Städelschule Architecture Class, Frankfurt am Main, Germany, and was coordinated by Andre Chaszar, Anton Savov, Peter Liebsch and myself. The scope of the workshop introduced the extent of designing and creating dynamic material systems to the students of the First Year Group.

The workshop was developed to acknowledge the concept of ACs as a method to discover materials as a design driver for architecture. Over one month, the students were introduced to different materials and assemblies such as thermochromic pigments, conductive paint and yarn, and muscle wires (SMAs). Additionally, a palette of potential substrates such as wood veneer, plastic, paper and metal was given to the students as a material toolbox.

The ‘Pasta in Bed’ theme required the students to participate in the environment and to reflect on the everyday spaces that we inhabit. Microenvironments that are influenced by human presence, temperature and humidity were to be studied, and a bi-directional interaction with the design material systems took place. To address the synergy effects between material performance and social space, the testing and implementing of the ACs was essential. The resultant working prototypes were presented at the final exhibition—‘Rundgang Show’—which takes place every year to display the school’s research to a broad audience.

498 Andre Chaszar is a structural engineer and consultant at B+G Ingenieure, Frankfurt am Main, Germany. He is also currently a PhD student at the DU Delft, Netherlands, with a focus on collaborative potentials and mechanisms of these and related fields (e.g. construction, materials science and informatics).

499 Anton Savov is an architect based in Frankfurt. He is a Research Assistant and teaches at the Architectural Masterclass at the Städelschule, Frankfurt. He is currently finishing a PhD in computational design at the University of Architecture, Civil Engineering and Geodesy (UACEG), Sofia, Bulgaria.

500 Peter Liebsch is the Head of the Design Technology Group Australia (DTG) at Grimshaw, Melbourne.
My role in this collaboration was as the material consultant for the students. I introduced the different types of advanced materials, their properties and potential methods of controlling the materials. I also guided the process of working with the microcontroller and demonstrated how to design a parametric feedback model. As I was based in Melbourne, Australia at that time, I was not engaged in the day-to-day progress of the students. However, every week, I participated in a videoconference to support the design process.

**Material Explorations and Constraints**

The workshop began with deep research by the students into how the introduced materials could be modified and controlled by external forces such as heat, moisture and electricity.

The preliminary material studies involved testing different material mixtures and composites. It became clear that, for example, the sensitivity of thermochromic dyes could be altered by mixing them with different ratios with an acrylic base. As a result, the colour-changing effects range from not working to very fast changes. More importantly then, the material mixture is the choice for the substrate. If a material is less thermally conductive, the colour change does not occur as long as the heat source is not increasing. Thus, the rule of thumb was formulated: that changing the mixing ratio could be used to fine-tune the heat-sensitive colour actuation, but the substrate had to be a good thermal conductor in the first place (see Figures 6.32–6.33).

![Figure 6.32: Actuation of Green thermochromic dyes using two nine-volt batteries and nichrome wire as a control mechanism of the heat source. The nichrome wire is used as a means to translate electricity currents into heat and is wrapped around the coloured surface. (Left): Substrate: paper; mixture: 3 ml green dye; 1 ml acrylic base; (Right): Substrate: veneer, mixture: 4 ml green dye: 1 ml acrylic base. (Images: Ali Sheikholeslami, Anand Jariwala, Gde Aditya, Joel Roy, Moritz Rumpf, Saba Barani, Sean Buttigieg)](image)

501 A detailed description of the material can be found in the Material Dictionary on page 22.
In the realm of self-made sensors, conductive materials play an important role. To create one’s own composite material with sensing capacity, conductive fabrics, foams and inks are very helpful. In particular, the available conductive inks\textsuperscript{502} are promising regarding their ease of use. No technical skills such as knitting or sewing are required, and they can be applied to almost every surface. Considering these positive benchmarks, the students investigated the material’s ability to integrate sensing into a dynamic material system.

In addition to different mixing ratios with water (see Figure 6.34), the colour was also tested with regard to its sensing capabilities of the human presence by its capacity abilities (see Figure 6.35).

\textsuperscript{502} A detailed description of the material can be found in the Material Dictionary on page 20.
The studies with shape memory alloys (SMAs) focused on the actuation, the actual lifting force and the motion of the alloy. To use the shape memory alloys, it was crucial for the students to understand the limits of the alloys in relation to the design. Due to the high resistance of the wire, it could be heated to its transition temperature by passing electricity through it.\textsuperscript{503}

The students’ experiments focused more on electrical actuation rather than on temperature. They saw the advantage of controlling the behaviour of the alloy, which could be easily influenced by the designer rather than by the environment. Consequently, the experiments were based on the use of nine-volt batteries and a series of geometrical studies to determine the type of geometry and length of wire that would be suitable for further exploration (see Figures 6.36–6.38).

\textsuperscript{503} A detailed description of shape memory alloys can be found in the material dictionary on page 18.
Figure 6.36: Experiment to define the pull-force of the SMA wire. A small bag filled with weights is pulling the wire. Once the electricity activates the wire, it lifts the bag until the wire is almost straight.

Figure 6.37: An experiment to define the movement and shapes that can be controlled by the SMA. The wire is attached to paper with small screws to be able to shrink. While the wire is actuated, the paper is bent.

Figure 6.38: Scope of movement made possible by placing the same wire at different locations. Wire position A creates the largest movement, while position C has the lowest movement. In all three positions, the applied current and the wire are the same. (Images 6.38-6.39: Gezim Bono, Kavin Horayangkura, Kiwoo Kim, Lerpong Rewtrakulpai, Lila Ghamar, Tadaioni, Madjid Montazeri, Ritayan Rath, Shima Moradi)
The material experiments evolved quickly to become part of the computational design process due to the introduced control mechanisms via electricity. The transition between physical and digital experimentation was experienced by the students as an important part of engaging with the material.

The design phase for the final installations was limited to one week due to the longer estimated construction phase of two weeks. Within one week, four groups developed four adaptive installations that interacted with their environments and responded to the presence of visitors and their actions by utilising one or more of the newly discovered materials.

**Group Results**

The student group of the ‘Good Walls make Good Neighbours’ project were particularly interested in the dialogue between inside and outside conditions. A wall is suspended from the ceiling, and the active veneer tile components were derived from a triangulated pattern (Figure 6.39). The tile components are activated by either the outdoor weather conditions, the indoor room temperature or by SMAs. Additionally, sitting on an adjacent sofa that could sense a human presence via pressure sensors could activate the installation. The sensed data activated either the muscle wire or an integrated steamer and lights that slowly changed the geometry of the veneer tiles in response to the moistured or drying process of the wood (Figure 6.40).

![Figure 6.39: Principle of the designed pattern. The colour code represents equal triangles.](image)

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The ‘Kitchen’ installation incorporates a cooking theme and presents a counter with a cooktop. The overhanging canopy and the wall with the integrated ‘greenhouse’ is complementary and creates a kitchen-like scenario. The design proposal included capturing the cooking steam that passes up through the opened veneer panel, which is activated by the steam. The vapour is ‘caught’ off a metal plate behind the canopy and the condensate drips back into the greenhouse to water the plants (Figure 6.42). Further, in response to sensing a visitor in the proximity, translucent flexible plastic hatches open and provide access to the herbs for cooking (Figure 6.41)
The ‘Passive Kinematic Wall’ creates a passageway at the beginning of the exhibition space. Two frames facing each other are assembled from flexible plywood strips that create an interactive space (Figure 6.43). Increasing the pressure at indicated points on the strips can manually deform the strips into a series of configurations throughout the passage. Thus, the visitor becomes the actuator and moderator of the sculpture. The ‘pressure points’ are made of thermochromic paint and indicate via a colour change the required pressure and time (relating to the strain of the wood) executed by the visitor to ‘flip’ a strip (Figure 6.44).
Figure 6.43 Principle of the convex and concave space created by the two frames and the flexible plywood.

Figure 6.44: Final installation. The thermochromic patches invite the visitor to press the plywood; Right Image: Close-up of the thermochromic patch and its heat sensitive function. (Images: Ali Sheikholeslami, Amir Peyman Poostchi, Ayax Garcia, Kiwoo Kim, Melissa Swick, Petr Khраптович, Shima Moradi)
The fourth group of students developed the concept of ‘Wrapping Veneer’ and experimented explicitly with the behaviour of wood veneer. An analysis of the exhibition space and the wish to not use water, mist or an external heat source led to a combination of veneer that changed shape by integrating shape memory alloys. Two suspended surfaces comprising horizontally arranged veneer strips formed a semi-enclosed space that reacted to the visitor’s presence (Figure 6.45). The vertical battens encapsulated a thin metal wire mesh that sensed via the capacity proximity method and activated the muscle wire to contract and expand depending on the position of the user (Figure 6.46).

Figure 6.45 visualises the concept of a semi-enclosed space created by one or two surfaces. The user engages with the spatial encloser, which interacts with the presence of a person.

Figure 6.46: Final installation and its different stages of movement. (Upper left): Initial stage of the veneer elements. (Lower right): Surfaces interacting with the visitor at their most deformed geometry. (Images: Amr Al Janadi, Gde Aditya, Gosha Muhammad, Joel Roy, Moritz Rumpf, Saba Barani)
Project Summary

The result was an exhibition that played with the idea of domestic microclimates that involve moisture/humidity and temperature differences and that can be influenced by users’ actions and the presence of the human body. Four installations within the gallery space interacted with the visitors on different activity levels and scales. The workshop was held in the German wintertime; therefore, the interaction between the warm interior space and the cold external environment was also investigated. The work had a strong influence on the students and their design ideas, particularly in relation to the shape memory alloys.

Due to the constraints of the material—for example, an applicable bio-force is needed to return to its original shape—the ability to ‘close’ the tiling or hatches of the installations was considered an issue that could be analysed via physical experimentation.

After the physical testing phase, a microcontroller was introduced and established the connection between the physical and virtual design environment. This gave an opportunity to control the dynamic material via electrical signals that were created via several sensors such as photoreceptors, temperature sensors or conductive ink. The pulsing frequency of the electronic signal can be modulated and programmed according to the environmental response that it aims for. The SMAs and the thermochromic inks can be controlled and stimulated via the electrical signal of the microcontroller. The applied current causes a state change of the internal structure of the material and changes either the shape or colour. In addition to the specification sheets that the manufacturer provided as a guideline to work with the material, physical experiments with the novel material characteristics were essential for the workshop participants to become familiar with the constraints of the materials.

The digital tools, especially the use of the Arduino and the Firefly components, helped provide an understanding of the geometric relationship between the different developed material systems. Direct work with the material and the artefact that someone wants to create is an important lesson for the designer in order to know the material’s capabilities. The empirical studies and the haptic-intuitive engagement support the gathering of knowledge around the topic of the materials and possible design outcomes.
6.6.2 Design Project 6—MicroSynergetics

Introduction

The final designs of the ‘Pasta in Bed’ project were all based on the empirical studies of the materials, and the design process itself focused on the physical engagement with the materials. The developed digital design tools, apart from the Arduino and Firefly components to control the current flow, were only applied by the workshop participants at the final stage and did not contribute to a better understanding of the materials. With the last research project, I wanted to further explore the creation of ACs and the integration of digital design tools in the design process. I focused on the development of design methods, including simulation and physical prototyping for engaging with material properties that are reactive to the microenvironment.

The workshop took place at Rensselaer Polytechnic Institute (RPI) in Troy, New York, and was part of the Smartgeometry Venue 2012–‘Material Intensities’. Workshops at Smart Geometry are conducted over an intense period of four days and include designing, exploring, learning and fabricating. Leading from the successful and interesting collaboration at the ‘Pasta in Bed’ project, Andre Chaszar, Anton Savov, Peter Liebsch and myself co-organised this workshop as well.

The design scope of the workshops was to use advanced engineered materials to reduce the use of energy to drive mechanisms and architectural apparatuses that might control the building envelope or other architectural systems. The agenda to pursue a synergy of material performance and social space aimed to introduce the same novel materials as in the ‘Pasta in Bed’ project.

The design process once again involved the control of the intrinsic material properties by providing digital design tools to support the understanding of the limitations of the designed material systems. This methodological approach was thus extended and comprised a new layer of digital visualisation and analysis tools. For this reason, and due to the intense and short workshop, we established a laboratory-like environment (Figure 6.47) where material experiments, their outcomes and digital design strategies were shared and discussed among the participants.
Material Experiments

The material exploration with the dynamic materials began by introducing the materials, their properties and basic control. At the beginning, the participants investigated the materials with nine-volt batteries to understand the functions of the different materials. The haptic-intuitive exploration involved the actuation of the material to explore the state change abilities of the materials. For example, was the length change of the SMA wires of interest to define the actual motion that could be executed by a certain length of the wire? This was important because, for the final installation, we wanted to replace the batteries in the microcontroller, which can be operated with nine- and 12-volt power adapters. The different voltage levels do not change the shrinkage level of the wire; rather, it controls the overall length of the wire that can be actuated.

The experiments with the materials and kinetic geometrical configurations were explored, and the direct contact with the material brought up first design ideas and then developed a perception and understanding of the material properties.

Another series of tests with the SMAs involved the design of geometrical concepts to perform a variety of complex motions (see Figure 6.48).
The increasing awareness of the constraints and possibilities of the materials through the hands-on process of discovering material properties and combinations was the driving force for the participants. The working environment of an experimental workshop where everyone was sharing their discoveries supported their anticipation. First, combinations were explored such as combining thermochromic ink and conductive ink (see Figure 6.49) to create a sensor that responds in an analogue way to the user to indicate that the sensor is activated by the colour change.

The material studies were accompanied by the first design sketches, and the participants formulated their targets within the first one and a half days. Overall, the interaction and manipulation with the SMAs and the conductive inks were the preferred materials. The thermochromic inks were considered a secondary material that could additionally be combined with the other two materials. The conductive ink was discovered by the participants as a powerful material to sense, actuate and control the functionality of the shape memory wires without any additional electronic equipment. Surfaces and ‘sensor fields’ that could react to the presence of potential visitors or ‘touch screens’ similar to the Apple iPhone© technology were imagined.
The basic AC comprised a layer of conductive ink, a substrate, an optional layer of thermochromic ink and the SMA (see Figure 6.50).

![Diagram of AC assembly](image)

Figure 6.50: Principle diagram of the assembly of an AC. (Image: author)

**Computational Approach**

The digital design procedure was based on learning to program the Arduino® microcontroller with the Firefly Grasshopper™ components for Rhino and how to interact with the physical components. During the experiments with the Arduino and the augmented materials, it became clear that the difficult part would not be to learn the software or to design kinetic systems; rather, it became a task of understanding the principles of electronics. The circuit design was crucial to a successful functional material composite. As a start, the participants were introduced to a set of basic circuits that could be used to work with the materials and explore their functions (see Figure 6.51).

![Diagram of circuit](image)

Figure 6.51: Sketch of the circuit to understand the electronics: (Left): A schematic drawing of the circuit provides a better overview of the elements and its connections (Right) (image: author)
The circuits could be developed further and serve as a platform to investigate several options of using different resistors or sensors. In addition to the augmented materials, we provided simple light sensors that could be used to analyse the surrounding lighting conditions that the elater on designed material systems could react to.

The investigated behaviour of the materials resulted in simple digital parametric kinetic control tools that were developed in Grasshopper™ to study what kind of motion could be achieved with the designed kinetic system. The tools provided the visualisation of the changes of the geometrical topology and were used to develop further own kinematic structures (see Figure 6.52).

In addition to the geometrical parametrical models, the aim was to simulate and analyse the behaviour of some of the developed ACs to gain a better understanding of the design, especially the kinematic movement and possible resulting stresses and dynamic simulations. The dynamic behaviour was simulated with the Grasshopper plug-in Kangaroo. Kangaroo was a promising tool for rapid simulation, based on a particle spring system, to predict material behaviour. The stiffness of the springs can be adjusted and the virtual model can be leveraged to meet the real material system behaviour. Unfortunately, this ‘tuning’ and adjusting of the spring system is time-consuming when the true performance needs to be simulated. Nevertheless, the simulation is helpful to get a feeling for the performance in order to develop the system further (see Figure 6.53).
The analyses was executed with Scan& Solve™ and one participant in particular utilised the analyses techniques combined with the spring system to understand better the performance of the shape memory wires (see Figure 6.54). The analyses investigated the resulting stresses in the material system that was deformed by the shape memory wires. This analysis had to be conducted via an iteration process due to the lack of a direct link with the parametric model. Each change of geometry had to be analysed again; thus, this process was more time-consuming than the spring system simulation. The physical simulation with Kangaroo and the analyses with Scan& Solve helped the student to gain a new understanding of the function and stresses of the developed system.
Finally, the digital design process and the experiments with the microcontroller and the ACs raised the question of how a material system that responds only to the environmental conditions could be controlled by the user. A façade was envisaged that would be equipped with SMAs that control a shuttering system only by their ability to change shape actuated by the sun exposure. There might be the case of a climate with...
direct sunlight that causes the SMA to operate, but at the same time, it might start to rain; therefore, an override system controlled by the user would be helpful.

With the advent of the microcontroller, the development of the above described bidirectional system becomes feasible. The electrical signal that the microcontroller sends to activate the actuation of the shape memory wire can be overwritten or blocked to suppress the current flow and the actuation of the SMA. By accommodating an available Wi-Fi connection via cloud technology that collects the signals of the material helped to initiate a link to a smart mobile device. In this case, we used an iPad® to control the material system via a remote control. A tailor-made control tool could open or close the signal stream of the microcontroller. Once the signal was stopped, the actuated wire stopped performing. Using the remote control, we could then send a signal again that opened the stream to actuate the SMA and perform the opening of the system again (see Figure 6.55).

Figure 6.55: Close-up of the iPad with the tailor-made remote control based on the TouchOSC software and a simple parametric geometry that could be controlled with the software. (Left): Final prototype of a ‘façade’ — panel that reacted according to light changes. Once a photo-resistor was reading a low light value, the SMA wire started to open the translucent plastic triangles. The motion could be stopped and actuated via the remote control. (Image: Peter Liebsch, design by Peter Liebsch and author)

505 In this case, the remote control tool had the control functions of opening and closing the system and to override the received signal from a light sensor to give the control back to the user. The software was based on the TouchOSC (Open Sound Control) technology. http://hexler.net/software/touchosc
Results

The final installation consisted of 10 single interactive components that communicated with the user and the micro-changes of the environment via the self-made capacitive sensors based on the conductive ink and the use of photo-resistors. Each augmented composite was equipped with either one or more of the smart materials and at least one type of sensor.

While some participants were more interested in the kinetic systems that are possible due to the use of SMAs, others were more interested in combining different materials into one composite that could sense, actuate and change colour as a ‘stress’ indicator at the same time. The 10 augmented composites varied from an interactive ‘flower’ (see Figure 6.56) to gills that opened and closed in response to light changes in the environment (see Figure 6.58) and a kinematic ‘perpetual mobile’ (see Figure 6.57).

Figure 6.56: Motion process of the interactive flower. The leaves sense the presence of the visitor and actuate the SMA, resulting in a bending movement of the leaves. Once the visitor is not in a sensing distance, the leaves start to relax. (Image: author, design by Tore Banke)
Before finishing the installation, many small prototypes were produced to understand the materials and to become familiar with the work of the microcontroller and the design tools. In the beginning, everyone was very ambitious and started to develop very complex systems that, in the end, were not working because of the constraints of either the materials or the electrical components. This was a necessary experience to understand the limitations as well as the possibilities that come with the materials and the use of electronic components (see Figure 6.59). A 12-volt power source can actuate a maximum length of 45cm SMA, for example.
The biggest challenge was to work with the electrical components. Certainly, a disadvantage is the do-it-yourself process and the use of cheap and flimsy products. As a result, we faced the problem of destroying a series of resistors and even two microcontrollers due to too-high voltage. In addition, the self-made sensors needed to be adjusted constantly to the surrounding light conditions to actuate the ACs. This shed light on the dependency of the advanced engineered materials and their surrounding conditions.

It also became obvious that this way of engaging with the materials and the use of microcontrollers as a design and simulation tool requires a basic knowledge of electrical systems. For a beginner and non-expert, the creation of the circuits becomes a challenge (see Figure 6.60).
Project Summary

The developed design methodology established a promising approach to engage in an early stage with novel material systems using hands-on material experiments, physical computation and digital simulation.

The introduced ACs that involved techniques such as physical computation via the Arduino© microprocessor showed evidence of the use of the microcontroller as a
simulation and design tool for architectural applications. This becomes possible with the use of sensors that register the change of motion, proximity and temperature differences within the material to combine simulation and real-time sensing techniques to create an interactive material system that reacts according to intrinsic material properties.

Even though the approach of working with microcontrollers and physical computing elements requires a basic knowledge of electrical systems, the results of the project showcase that these basics can be learned and applied in a short time frame. Once the knowledge is established, the work with the multifunctional materials is a design task that leads to unforeseen outcomes and novel design ideas can be developed. A big advantage of the simplicity of the different components used during the workshop period (such as the Arduino, the basic sensors and the use of solder-free connections) makes it easy to recombine and experiment with the electronic part as well as with the materials.

Using a laboratory-like environment, as Sevaldson expressed it, established an open material experimentation that helped individuals and the entire group to discover material properties. The discoveries can be described visually and formulated as parameters that provide confidence via anticipation in relation to designing with new materials. As a result, the implementation of physical computing has become a valuable design tool for architectural ideas.

6.7 Summary, Chapter 6

In this chapter, I explained the difficulties associated with exploring multifunctional materials in an architectural context. The notion of simulation and analyses software was discussed in the realm of design tools, and I demonstrated several methods of engaging with smart materials based on digital design tools and physical haptic interactions.

The joint exploration based on digital and physical encounters of material properties and the understanding to apply materials as design drivers is a strategy that coincides with the ideas of Miodownik, Ramsgard Thomsen and Menges. Digital design tools...
tools, with regard to material simulation, have their strength when all variables are known and a series of parameters can be altered to study the changes of geometry or material responds in regards to material properties and environmental effects.

The physical experiments with the multifunctional material systems allow for a haptic-intuitive experience that often when applied for the first time results in innovative solutions, as Piano and Rice reflected.

A possible collaborative framework for integrated material knowledge was outlined and tested in several design experiments. That a closer communication between architecture and materials science is necessary for establishing innovative material systems in architecture stems from the arguments by Addington, Schodek\(^{510}\) and Brownell.\(^{511}\) While they propose a closer nexus almost exclusively based on exchanging information via new modes of selecting materials, I investigated digital design and simulation tools combined with physical computing as an area for solutions.

Sensing technology was developed as a design and information tool that works efficiently with smart materials and provides knowledge of the material characteristics.

Multifunctional materials have the ability to alter over a period of time, and this time-dependent alteration is a design concept that challenges architects and engineers alike.

The introduction of physical computing in order to create time-laps simulations of a real behaviour is a helpful tool to discover the potential of a material. The combination of software and hardware becomes a flexible set of design tools that can help architects to explore and introduce materials. The outcome of the material explorations and the implications associated with the presented projects will be discussed in Chapter 7.


\(^{509}\) Achim Menges, 'Integral Formation and Materialisation: Computational Form and Material Gestalt,' in Computational Design Thinking, ed. Achim Menges and Sean Ahlquist (Chichester, West Sussex: John Wiley & Sons Ltd., 2011), 198–210.

\(^{510}\) Addington and Schodek, Smart Materials and Technologies in Architecture.

\(^{511}\) Brownell, 'Material Ecologies in Architecture.'
Discussion and Conclusion

Introduction
The Common Ground
Synergies between the Physical and the Digital
Conclusion
Thesis Paradigms
Key Findings
What the Future Might Hold
Discussion and Conclusion

We only need an understanding of what is conceptually important to architecture; we don’t need to take over the complete knowledge of other disciplines.\textsuperscript{512}

Introduction

My research journey was driven by the triangulated research concept and draws together theoretical research, experiences of the real world by practice, and material explorations.

While the theoretical research covered a considerable range of methodologies and contextual knowledge, it also provided the grounds to address and cross-link the practical experiences with my personal material explorations. The experiences that I gained from practice guided further literature research, and informed the development of the interviews and the survey. The material explorations were commenced by my own curiosity in order to become familiar with novel materials as design drivers, and to understand the physics and the chemistry behind the materials. Those explorations were driven by the outcomes of the interviews and the survey, as well as the literature, and the work in practice on real projects. The outcome of the material explorations could not always be reintroduced into practice but gave ground to further speculation and a ground for discussion with colleagues in practice and research partners.

In this final chapter, I review the possible implications of my research in the area of emerging material explorations as a design method in an early stage for architecture. As Matthias Kohler\textsuperscript{513} argues for an understanding of the importance of conceptualising ideas, my thesis focuses on a direct participation with materials as a means to support communication and innovation.

This chapter is structured in four sections. In the first, 'The Common Ground', I delineate the territories of architecture, engineers and materials scientists. I reflect on potential common grounds—mainly material-driven—and how my research is situated in relation


\textsuperscript{513} Ibid.
to this topic. Section two, ‘Synergies Between the Physical and the Digital’, features possible interdependencies of design representation and materiality. I correlate similar conducted research and project work that deals with new modes of engaging materials to discuss further the material practice of architecture. ‘Conclusion’ is the third section and reveals the findings of my exegesis and the fundamental contribution of the work. In the last section, ‘What the Future Might Hold’, I speculate on the future potential of my investigations and how the research might be extended to facilitate and utilise material systems through digital and physical simulation and interaction. Further, I stress the possibilities for trans-material design collaboration and the impetus for lateral thinking.

The Common Ground

In Chapters 3 and 4, I outlined the potential of a common ground for collaboration among architects, engineers and materials scientists. My argument for a common ground is accompanied by a desire for change towards a flexible and free architectural practice where ‘fabrication techniques, engineering dynamics, and materials science’\(^{514}\) are part of an integrated design procedure.

Collaborative research platforms that begin to articulate the nexus between architecture and materials science indicate a future direction towards a transdisciplinary design approach. Part of the United Kingdom’s Knowledge Transfer Network (KTN), is the ‘Smart Materials Beacon’,\(^{515}\) an open cross-platform that supports material development, manufacturing and design. The KTN recently organised the inaugural ‘Inspiring Matter’ conference that took place at the Royal College of Art in London (2–3 April 2012). The conference findings indicate that the worldviews of design and science disciplines are still far from coexisting in the realm of material-driven decisions. However, according to Hugh Aldersey-Williams, designers do not need to ‘understand materials at a scientific level in order to appreciate their creative potential’\(^{516}\) and there is a need for a platform for designers


\(^{515}\) [https://connect.innovateuk.org/web/smart-materials](https://connect.innovateuk.org/web/smart-materials)

to ask ‘usefully “naïve” questions that scientists would not ask themselves, both opening up creative possibilities and anticipating public responses’.517

Another recently initiated network is the Materiability Research Network, formed in July 2012 by the Chair for Computer Aided Architectural Design, Eidgenössische Technische Hochschule Zürich (ETH Zürich) and Interaction Design, Zürich University of the Arts. This research network is dedicated to the exploration of smart materials. With an experimental approach to research, it supports the integration of smart materials applications in architecture and contributes to an awareness of this new material technology in design processes. The network is collaborating with the Swiss Federal Laboratories for Materials Testing and Research for Industry, Construction and Commerce known as EMPA (Eidgenössische Materialprüfungs- und Forschungsanstalt) to gain the support of materials science.

One of the Materiability Research Network’s projects in particular showcases the potential of a cross-platform and transdisciplinary approach. The project ‘ShapeShift’ is featured on the network’s homepage518 and explores the possibilities of soft dielectric electroactive polymers (EAPs).519 The authors describe the resulting kinematic prototype as a ‘soft-kinematic structure’520 that responds to electrical impulse. The project was driven by prior material investigations and a close collaboration with the materials scientists from EMPA. However, the project also revealed the need for further exploration of EAPs as an architectural material and design driver because they require a high voltage (5000 volts)521 and are fragile due to the continuous stretch and shrinkage forces of the material itself (research shows that the material tears frequently). This project can be considered a first step towards collaboration with materials science at an early design stage that supports both material development and design strategies. It is a symbiotic model in which both disciplines clearly benefit from each other.

517 Ibid.


519 EAPs are thin polymer-based films that once actuated with an electric charge. They convert electrical power into kinetic force and change their shape. This behaviour is similar to the shape memory effect explained previously.


521 Ibid.
Research networks and platforms are a necessary step towards a closer collaboration to foster a better understanding of new materials as design drivers in architecture, as the ‘Lantern Project’ in Chapter 6 showed. Although the material performance of the photoluminescent material was limited, materials scientist David Mainwaring and I considered a further collaboration to promote the early involvement of materials science, especially when novel materials are recognised as significant to the design process.

Stronger and frequent affiliations with materials scientists may lead to a change in trust and challenges the manufacturing and fabrication industry, which is part of a slow uptake of innovative ideas in architecture.

*Part of the problem is the sheer power and capacity of the building industry of today and the philosophy which underlies it. . . . People can no longer see the relationship between [the] individual capacity to build, individual inventiveness and the physical environment being constructed. . . . The real issue in design must be to break the mould of industry-controlled predictability which dominates so much.*

Several practices, such as Enric Ruiz Geli and Cloud 9, Decker Yeadon, J Mayer H and Kieran Timberlake, demonstrate that the obstacles of a traditional and conservative manufacturing and fabrication industry can be overcome. These practices actively seek new relationships between architecture and science in practice, academia and research. Establishing such relationships is only possible, however, via new modes of collaboration, and methods that question and reinterpret established product development and manufacturing processes.

A reflection of my research is that these material systems will support the development of an interactive dynamic architecture that contributes to a reduction of energy waste, limiting the use of materials and control mechanisms to create a responsible and yet multifunctional architecture. The challenge lies not only with architects, but they can be the mediators and initiators as shown by the practices mentioned above. However, if they apply established and tested standard methods and solutions throughout their

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work, rather than seeking to take risks or consider unorthodox applications, innovative outcomes cannot be achieved.

As Pallasmaa argues, the ‘risk’ usually:

\[\ldots\] implies the mental uncertainty of advancing on untrodden paths, as the actual risks in relation to safety, durability, appearance and suchlike can usually be minimised by working experiences, careful calculations, research, experimentation, and laboratory or prototype tests.\textsuperscript{523}

My own experiences at B+G and the work with materials and materials scientists confirmed that there is no hard line between science, engineering and design in practice, and therefore the opportunity for collaboration is thinkable. The risks cannot, of course, be eliminated, but they can be minimised by the establishment of good communication and a clear understanding of the work. The task for architects and materials scientists is to become aware of and familiar with the constraints within the design process. While the architect is mostly interested in the application and usage of the material, as I discussed with the ‘Lantern’ project, the materials scientist tends to focus on increasing the material’s performance. This difference in approach is particularly true when it comes to an initial assessment in a public space, where a profound knowledge of the material properties is required to ensure that the proper material functionality is addressed. An architect’s imagination and education, as well as reliable information, are crucial when choosing a material. As a result, rather than branching out, designers tend to use the same materials that have been used often in the past.

The materials selection processes presented in the Deichman Library Project in Chapter 5 offer a first step towards collaboration by providing a tool for architectural and engineering practices to screen materials and become familiar with the available palette of material products, building up knowledge and experience. The flexible multi-criteria selection process, which was developed for the library project, can be customised for each project. At the same time, we must recognise that this is a time-consuming process and necessarily constrained by the available and well-situated materials in the market. It is by no means a tool for exploring design effects visually or spatially, which is an essential part of architecture. Further, it does not necessarily support imaginative and

\textsuperscript{523} Pallasmaa, \textit{The Thinking Hands: Existential and Embodied Wisdom in Architecture}, 72.
innovative design processes because of the building restrictions defined by local authorities and institutions.

Synergies Between the Digital and the Physical

Kolarevic stated that new techniques and digital tools reintroduce the notion of craft, which allows a novel interpretation of material qualities for innovative design strategies. Not only does the advent of modern CAD/CAM tools support this claim, but with a combination of physical and digital encounters of material behaviour, new relationships between the design intent and the real world can emerge. These interdependencies between new technology and common materials were presented by the Hermès project in Chapter 5, as well as the utilisation of interfaces that connected the digital analyses, digital design tools and digital manufacturing processes. The timber elements and their specific properties were defined and implemented in the digital model so that the wood pavilions could be manufactured and fabricated in regard to the material behaviour.

With respect to the multifunctional materials previously discussed in Chapter 6, it is essential to engage with the materials and work with them on a physical level to understand their true behaviour and the design constraints that come with their properties. As Valentino Breitenberg, a neuroscientist and cyberneticist, said:

> It is much more difficult to start from the outside and try to guess internal structure just from the observation of behaviour. It is actually impossible in theory to determine exactly what the hidden mechanism is without opening the box, since there are always many different mechanisms with identical behaviour.

According to Ilpo Koskinen, Professor of Industrial Design at Helsinki’s Aalto University, the problem with studying a certain phenomenon is that many factors shape and create it. Therefore, he sees potential in ‘studying phenomena in a laboratory’ to rule out any of the possible explanations with a high degree of certainty. In the case of my


526 Ilpo Koskinen et al., *Design Research Through Practice From the Lab, Field and Showroom*, vol. 133 (Waltham, MA: Morgan Kaufmann/Elsevier, 2011).
personal inquiries in relation to multifunctional materials, this way of engaging with phenomena refers also to the concepts in Schön’s ‘reflection-in-action’ \(^{527}\) and Sevaldson’s \(^{528}\) ‘repetitive-circular’ design processes. The laboratory-like studies can support the study of material systems in a controlled environment where the natural driving forces are the subjects of experimentation.

I have argued in Chapter 4 and Chapter 6 that the re-emerging approach of material-driven design concepts is not only by digital inquiry, but also through physical anticipation and the establishment of a laboratory-like design framework supported. This hybrid form of engaging with materials from a design point of view is especially important to accommodate a haptic-intuitive engagement in respect to multifunctional materials. Only direct contact with the material in combination with digital tools can help unravel the internal structure in order to understand its material qualities. Exploring designs driven by materials therefore becomes an essential task where architects should work with easy-to-apply design strategies that involve digital and physical aspects for encountering the material possibilities. This strategy can be best applied at an early stage to promote ideas and instigate innovation in the field of manufacturing, construction and design.

I suggested that an approximation is adequate to generate the necessary rules of thumb and to understand a material’s behaviour.\(^{529}\) Through material exploration, material properties can be observed and described visually, and formulated as parameters that can provide the confidence required to design with the new materials. The design explorations ‘Material Behaviour’, ‘Pasta in Bed’ and ‘MicroSynergetics’ projects of Chapter 6 build upon each other and exemplify the potential of an integrated design exploration based on parametric design, real-time simulation and physical computation. The results of the experiments show that with a dynamic model and the resulting interdependencies between material performance, external stimuli and design development, a better understanding of a material system can be developed.

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Furthermore, through the experimental work with the dynamic models and the materials, it became clear retrospectively with the work on real projects that more research has to be conducted to apply the promising material properties in reality. For example, a precision in documenting the material performance and including the data in more depth in a digital model to better map and understand the interdependencies is of great value, I believe.

Through the emerging DIY mentality in architecture and design related disciplines, programmable micro-controllers and electronic equipment such as the open-source Arduino© board are becoming widely available as design and testing devices. The Arduino has become a new design tool—a hybrid of sketchpad and cutting knife where the synergies of a digital and physical material observation, via working prototypes, enable the architect to explore material behaviour. Physical computing can serve as a simulation tool for representing natural life cycles in a time-lapse version of reality that establishes some certainty about how the materials might perform.

Braitenberg explains the usefulness of any prototype of any kind that helps to understand its internal structure or behaviour as a ‘pleasurable and easy’ way to ‘observe the full repertoire of behavior’, which may ultimately lead to unexpected results that contribute to design strategies driven by material effects.

Since the last five years, the idea of material modelling and material empathy in architecture has become once again a topic of discussion, with a particular focus on the digital-haptic relationship. Juhani Pallasmaa notes that ‘the connection with the process of making continues to be seminal’ and that it is important that ‘the real world of materiality and gravity, and the sensory and embodied understanding of these physical phenomena’ cannot be simulated with digital tools only. The physical engagement with the material is also vital. Menges describes this process of physical and digital making as one that helps us to understand material behaviour ‘as a means of creating not only space and structure but also micro-climatic conditions’. I investigated this approach with the ‘MicroSynergetics’ project in


regard to sensing material behaviour triggered by changes in the environment in order to reveal the synergies between ‘augmented material composites’ and environmental impacts. The applied methods of a combination of physical and computational discovery in a real-time scenario via physical computing allowed for a better understanding of the possibilities of multifunctional materials. This method is in line with the material investigation by the Bauhaus movement as I proposed earlier in Chapter 3 and the novel methods promoted by Kolarevic\textsuperscript{533}, Menges\textsuperscript{534} and Pallasmaa.\textsuperscript{535}

Conclusion

My body of work has described an exploration of engagement with advanced engineered materials in early design phases, through a combination of computation and physical experimentation in architecture. My work has spun from real-life projects such as the Deichman Library in Oslo, the Wood Pavilions in Paris and the Lantern Project in Frankfurt, to experimental work such as the workshops organised in Melbourne and Troy. Within this combination of projects, I became aware of the design impacts of building regulations, time constraints and a certain resistance of the building industry to investing in innovative and novel materials. The academic-related projects gave me the freedom to explore different ideas that could not be done in the daily work of practice. Crucially, my research deals with the implementation of new material systems and technologies in an early design phase. Further, my research also contributes an intense analysis of the relationship between architecture and materials science to stimulate a deeper conversation on the topics of emerging materials in architecture. Finally, my research supports the development of novel materials, especially real-time adaptive materials, as a design-driving concept.

Exploring material characteristics intuitively—by directly experimenting with the material in combination with parametric and physical computation techniques in the early design process—establishes a new level of knowledge on the topic of novel materials in architecture. This conceptual framework derived from my first-hand

\textsuperscript{533} Kolarevic and Klinger, \textit{Manufacturing Material Effects: Rethinking Design and Making in Architecture.}

\textsuperscript{534} Achim Menges, 'Material Computation Higher Integration in Morphogenetic Design,' \textit{Architectural Design} 82, no. 2 (2012)

\textsuperscript{535} Pallasmaa, \textit{The Thinking Hand: Existential and Embodied Wisdom in Architecture.}
exploration of material-driven design in practice and a social enquiry based on interviews and a survey supported by experiments conducted in an academic setting.

**Thesis Paradigms**

In Chapter 1 (Introduction), I outlined my research motivation and observations and presented the conceptual framework of my thesis with three main topics: Material Thinking, Material Representation and Interdisciplinary Communication.

In Chapter 2 (Approach and Methodology), I described in detail the design of my research. I presented the concept of the embedded practitioner and outlined the model of a triangulated research method to emphasise the importance of the collected data from empirical, quantitative and qualitative studies.

Chapter 3 (Material Development and Its Effect on Architecture) framed the research area by reviewing existing literature and case studies regarding the material culture in architecture. The historical review of material inventions discussed the continuous flux of material developments and their impacts on architecture. I described the process of material innovation and technology that supports architectural advances and the constraints that come with contemporary approaches.

I identified three key findings in respect to the integration of novel materials:

1. Closer collaboration and an exchange of knowledge are required in order to drive innovation and introduce novel materials in architecture.
2. New materials require new design strategies which architecture as a design discipline should be investigating to support innovative design solutions.
3. Practical investigation and hands-on experiences with new materials may support an understanding of the importance of the work of other disciplines.

In Chapter 4 (Architecture and Materials Science Synergies), I examined the correlation between architects, engineers and materials science. The origin of materials science and the established theoretical framework was discussed in terms of their interdependency with architecture and engineering. Via interviews, I identified some of the key issues affecting the slow integration of novel materials into architecture. The notions of macro- and micro-scale were discussed, and I stressed that the different worldviews of architecture and materials science is one obstacle that needs to be addressed for a
successful future collaboration. The interviews and the literature review provided support for a level of representation and knowledge transfer that encourages modes of collaboration. I also identified that architects, engineers and materials scientists each work with computational methods in their fields that might be useful in filling knowledge gaps within the other fields. An additional physical layer of experimentation offers an understanding of material behaviour and design purpose that is important for a multidisciplinary framework.

Chapter 5 (Observing the Real World) discussed my work at Bollinger+Grohmann Ingenieure and the knowledge I gained from this experience. The project work and the survey build on the discoveries in Chapters 3 and 4. I observed the common design and research tools of an engineering practice to investigate possible interfaces with materials science.

In Chapter 6 (Exploring Materials), I liberated myself from the framework and conventions of practice to understand and experiment with design methods for exploring novel material systems. Three distinct methods were tested: theoretical encounter and design with the materials; digital analyses and simulation; and physical testing. As a result, I defined material explorations as a method to investigate material properties as a design driver in the early-stage design process. The concept of augmented composites establishes a learning method to facilitate a material awareness through anticipation and physical computation.

The experiments showed that a material awareness leads to a possible collaborative framework for an integrated material knowledge. The outcome of the material explorations provides evidence that sensing technology can be utilised as a design and information tool to make sense of novel materials and material composites, and to provide knowledge of material characteristics.

**Key Findings**

The selected literature confirmed that there is an increasing need to engage with novel material systems to develop alternative solutions to the challenges that architecture is facing—in particular, the growing requirement for sustainable design solutions; the necessity to understand computing; to incorporate environmental information; and the increasing number of specialised professions. Enric Ruiz Geli describes this situation:
‘Now, in the information era, architecture has to be a technological platform, in which bits, connectivity, new materials and nanotechnology are more important than old materials.’

Today, with the help of bespoke material systems, we can control the interior climate and respond to exterior stimuli. Poor operation of these systems, which are complex and require high computational power, is often ‘blamed on inadequate control systems or on poorly designed envelopes’, according to Michelle Addington. The development of architectural applications with simplified mechanics to create an even interior space that reacts and changes according to external stimuli is promising. The challenge lies not in the palette of materials or technologies currently available, but in our lack of understanding of the constraints and possibilities of material-driven design processes.

The literature review and the interviews revealed that even though materials science seems to be a part of a whole different legacy, architecture and civil engineering could benefit from inside knowledge of this discipline. However, the literature and discussions with materials experts and scientists suggested that the biggest obstacles today are the different worldviews and the level of communication that hinders a closer collaboration between architecture, engineering, construction and pure science.

The survey and my personal experiences supplied evidence for this claim and found that currently, materials science is the most isolated discipline with the construction industry. The analyses and cross-references of the survey further suggested that in relation to the advanced engineered dynamic materials, the use of static analyses and modelling techniques are the most used tools.

The occurring problems for collaboration between designers and materials scientists and an integration of multifunctional materials in the design process can be summarised as follows:

The three main disciplines that can drive material innovation in the building industry—architecture, engineering and materials science—face new levels of complexity in regards to communication and representation. Appropriate methods for exchanging knowledge and establishing design skills are currently based only on tailor-made


interfaces, if they exist at all. In Chapter 5, the Hermès project revealed the possibilities of such an interface to fluently exchange data and knowledge-based information. The interface made it possible to analyse the design and structural solutions in multiple ways and served as a communication platform for all parties involved. However, rather than working with static simulation methods and common visualisation tools, I proposed a shift towards dynamic computational models and early physical engagement with novel material properties.

A key finding of my inquiry is that to explore novel material systems, we need flexible and easy-to-apply design methods to engage and understand the effects of these systems. Static drawings and key-frame simulation or analysis tools remain inadequate to discover the full potential of dynamic responsive systems based on novel material systems.

I conclude with the statement that ‘microcontrollers have the potential to become the new sketchpad’ for design explorations in an early design stage and beyond. Physical material exploration is vital to generate the necessary rules-of-thumb for the material’s behaviour. Through experimentation with the materials, their inherent properties can be discovered and described as functions for a digital simulation. The digital simulation can be integrated with digital design tools to express the material’s behaviour, and guide form-finding and optimisations, as I demonstrated in Chapter 6. Further, I presented within the design projects in Chapter 6 the notion of a haptic-intuitive material exploration, which supports a holistic design approach for discovering the whole dynamic potential of novel materials.

My research offers a starting point for further educational possibilities in architecture and suggests a new level of engagement with materials. Besides the educational aspect, my works also suggest, with the work carried out by practice, areas for communication and trans-disciplinary collaboration among architects, engineers and materials scientists. The research shows the importance of a level of thinking about materials that is concerned not only with the generation of form, but also with formulating strategies to design with and through material properties. I argue that with the control and design of a physical data-driven material system is another interpretation of the notion of the craftsman that can be aligned with the concepts of CAD and CAM as a means to address and demystify intrinsic qualities of materials.

While the methods explored may be seen as purely an academic and research-oriented approach, these techniques with novel materials can also be introduced within practice.
Similar to the work on physical models to explore the spatial relationships of a design in the cityscape, the physical computational models can act as a strategy not only to discover the right materials but also to foster a closer relationship with the materials expert. The feedback link via advanced digital simulation and analyses tools that have the capacity to simultaneously compute the results in more detail and using multi-criteria will give architects, engineers, materials scientists and clients the confidence to step into a closer discourse.

**What the Future Might Hold**

This thesis is incomplete in the sense that there will be other approaches to the engagement of novel material products to come. However, the potential for a dialogue with materials science was a salient point that emerged from the interviews, the survey and my personal experiences at B+G. The goal here is to initiate a discussion and to contribute to the discourse of architecture and materials science. My research holds the potential for further investigations and might be expanded in the fields of ‘material-driven design processes and representation techniques’ to contribute to an awareness of materiality in architecture.

Throughout my work at B+G and my personal material explorations, as well as being identified by the interview partners, a big challenge is still to interpret and make sense of the supplied data sheets of materials. The technical descriptions are often not suitable to be used as design guidelines; hence, the materials get branded as being too complicated to use. Alternately, a discussion with the material manufacturer becomes a frustrated situation because the involved parties might not address the right questions to gain confidence in applying and working with the material.

My research suggests that further investigations could focus on building up a series of rules that guide the process of design using advanced dynamic materials from an architectural point of view. These rules would be similar to the ‘rules of thumb’ that exist in the realms of architecture and civil engineering—for example, that the depth of a truss is dependent on the depth-span ration and can be determined by the ratio of 1/10,538 or that the deflection of a floor should not exceed 1/240 of its span by applied

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dead and live loads.\textsuperscript{539} Such rules, based on the materials’ properties, would be a major advantage in starting to design with novel materials. The publications of Heino Engel and his diagrammatically explained structural systems, \textsuperscript{540} Jesse Reiser’s visually and verbally described design methods, \textsuperscript{541} and Moussavi and Lopez’s diagrams for form finding\textsuperscript{542} demonstrate the usefulness of rules of thumb. The opportunity of novel materials necessitates the active derivation of physical material properties prior to the implementation of the generative techniques involved in computational architecture.

Further, I see potential in the development of real-time feedback systems that inform digital simulation and analyses based on the results of physical experiments to limit the constraints of the materials and to create digital tools for designing and analysing the effects on the overall design solution. Such a real-time feedback system could be established as a growing and adaptable online material systems database, initiated and curated similar to open-source platforms. In such a way, everybody could inform the data based on their own experimental results and constantly update the source of information. Of course, this type of platform depends highly on the credibility of the authors’ work. The authorship as well as the administration of such an open network is challenging and addresses a whole other opportunity for further research. The distinction between academia and practice in architecture and the link with materials science offers the potential to analyse, in more detail, decision-making processes and common interfaces to close the knowledge gap, and to admire the work of others. In this sense, the research conducted in the area of transdisciplinary interactions offers an interesting new contributor: the materials scientist, who requires further exploration. New modes of collaboration and practice that are actively involved in material development would contribute to innovative processes for introducing novel materials in architecture.

Besides the direct impact of multifunctional materials, the literature review and the practice-based experiences showed that a major contribution of transdisciplinary


\textsuperscript{540} Heino Engel, \textit{Tragsysteme} (Ostfildern-Ruit: Verlag Gerd Hatje, 1997).

\textsuperscript{541} Reiser, \textit{Atlas of Novel Tectonics}.

\textsuperscript{542} Farshid Moussavi and Daniel Lopez, \textit{The Function of Form} (Barcelona: Actar, 2009).
interactions will be to change the landscape of manufacturing and building regulations. Constraints to the use of novel materials in architectural design—such as manufacturability, long-term development, high risk, cost, and lack of efficient design and manufacturing tools—are already recognised by materials science and related disciplines and inform their manner of practice. Here, I see further potential for establishing a collaborative framework by linking research, practice and academia.

I believe that models such as embedded practice research and laboratory-like design research across a multidisciplinary framework will allow for further speculation and facilitate the establishment of design tools and methods that allow a more effective integration of novel materials in architecture.


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Appendix

A1 Transcripts

A2 Script

A3 List of published work

A4 Public Recognition and Cited Work

A5 Full Articles

A6 Research Time-line

A7 Smart Materials in Architecture
A1 – Transcripts

The following three transcriptions are reproduced and represent a sample of the 7 conducted interviews. The other four interviews can be additionally requested. No part of these interviews may be reproduced without the permissions of both the author and the interviewee.

A.1.1 Interview Partner No. 2:

Why are innovative Materials and Technologies attractive to you and your work?

Especially new materials and technologies have new capabilities that we did not have before. And I see a huge opportunity there to actually address significant problems of our time.

Like in our Case Study: Smart Screen where we try to solve specific problems. There we control shape memory springs by solar heat gain, without using any electricity or computing devices and sensors. Everything is happening within the material and that is something that we were not being able to do before. Another example is in general that we can enhance the performance of many materials like with our carbon nanotubes that we could imbed within composite materials.

So I see a lot of potential to address the possibilities to architectural issues because architecture has a strong impact on our environment.

What do you think of smart materials related to architecture?

The use of smart materials is changing rather quickly, not due to architects actually using it, but they are being used in many other fields, like product design and industrial design, and they kind of drive the research in the field.

Architects are a little bit behind that movement they prefer to use products that are already on the market. I think that research in general speeds up faster and faster. Just look at the development of solar technologies for example, there have been huge innovations in the last years and you can see similar developments in plenty of other areas that are dealing with novel materials.

What is your decision process for choosing materials for your design? At what stage does that usually happen?

We research materials in generally and then we are trying to find architectural applications for those. We are looking at their capabilities, their performances. It is a more bottom up rather than a top down research.
If you are using untypical materials within your design context, what are the applications you are using it?

*I do not have necessarily a focus in my practice on special applications. A lot of them have to do with mediating with the interior and the exterior environment. That is a main issue in architecture and there is a lot of energy that goes into that. Within this field we have developed a big expertise over the last years but we are also looking at problems like water quality or how you can conserve energy in generally.*

How do you plan and design with new materials and technologies?

*We strongly build up our own knowledge through intensive reading articles and then we are working often with scientists together but for certain research we have our own lab in our office.*

Do you have a fixed budget for your research?

*We do fund quit often our research by ourselves but we also get grants from organisations like the Boston society of Architecture or New York State Council for the Art. We do also competitions where we first exploring new materials and then propose a research after that. Nowadays we have a lot of companies that are giving us the materials and asking us to experiment with tem to find architectural applications.*

What are your sources of inspiration for the application of new technologies and uncommon materials?

*Our source of inspiration is mainly based on reading scientific papers from the medical area and then we decide to look at certain aspects of some interesting material behaviours to work with them in more detail. Sometimes you can translate conducted problems from the medical research directly into your own research, like the shape memory alloys, where the research is strongly pushed by medical applications for heart surgery and there is an interesting parallel world because they are tuning the material to body temperature and that very much relates to our environment.*

What are the obstacles for applying results from material research in an everyday practice?

*It is depending on the material but the more you know about the material the more you know about the obstacles. Like at the beginning it seems so fantastic and then you just jump in and then you realise all the issues along the way. So this is actually why a lot of our projects are taking a really long time to realize them. But it seems that the research is speeding up more and more and that makes it easier to work with the materials itself.*

How much time do you spend for material and technology research during a project?

*The main focus of our office or research lab is based on material research.*
Are you working together with material scientists and institutes to develop customized materials for your projects? If so, how would you describe the cooperation of designer and scientist?

For certain projects like for example the Smart Screen project we worked together with material engineers from an institute in Japan, where they manufactured the material to our wishes to be able to change the material regarding the room temperature.

There is definitely a huge learning curve in terms of how do we communicate and work together with scientists. Basically a scientist is not really talkative to someone who seems to have a limited knowledge about his own topic. I had a view phone calls where the scientists was talking to me just for a view minutes and then decided that I am not equipped for the conversation and hung up on me. But you have to be strict and after every phone call or talk it got better and better because I learned more and more each time. But that is a long time ago, by now I am very confident to talk with them and collaborate with them.

It also depends on the cultural background. The Japanese labs for example or a lot of companies in Europe are very open-minded. But I do not want to generalise it. The important fact is that as long as you are talking more or less the same language than you can work with them much better.

We also have our own research Database that is open to the public and that helps to invited people from different backgrounds and it also makes life easier if you want to work with scientists together. But because of copyright issues it is now limited to certain group of people.

What does it require to introduce new techniques to the different design and building industries?

It does require a lot of research and it is a case-by-case situation of course if you want to use novel materials. You have to deal with authorised labs that are analysing your application and you will get a special permission for each application. And that is another fact why it takes a very long time to use your ideas in a real environment.
A 1.2 Interview Partner No. 5:

Why are innovative materials and techniques attractive to you and your work?

There are a lot of ways to answer. What I am particularly interested in is the, bow to design the structure of materials on micro and Nano meter scale all the way up to the millimetre scale really in terms of designing the structure of a material and then making those materials scalable to cm or meter for applications. So I am interested in developing those types of materials for a number of different applications in fact, but it is the interface between how you design that micro structure and its properties on the micro scale that I think is much interesting. In particularly in architecture I feel that we can contribute by designing specific types of properties, which is bow a liquid wets the surface by changing how the microstructure is present at the surface of the material. Those types of properties can change quite dramatically though like weather it is the colour of the material or the way bow it wets liquids or the way it is nucleate ice, those are all things that are quite interesting to me. But what I think our best role is to controlling how that structure evolves at the micro scale but then talking to people who use material at the macro scale.

Can you name maybe some other areas that you think that your research can contribute to?

That is one of the most interesting things that you’re looking to different things. So we are looking to non-wetting surfaces, we are looking to sort of ice nucleation and the way water roles up but the other type of the work what I do is on highly porous materials so what we would call Nano porous materials and those have a variety of different types of properties and applications. And one of them for exmaple would be maybe capturing carbon dioxide, if you could design a high surface that can sort of react with carbon dioxide and capture it and then as the building exists and is exposed to atmosphere over time you can gradually take carbon dioxide similar to the work of concrete that deals with this idea. And I think one of our materials we are being able to design can have that property. But also those materials like titanium-oxides which are photo catalytic for the degradation of organic species and after those organic species are glutens in the air so there is a kind of self-cleaning property that those materials can have when there exposed to ultra violet light they can decompose organics that lend of the surface. There are a lot of interests in the kind of cleaning property of those materials as well as energy production.

There is a lot of interest in developing new very highly efficient but inexpensive forms of photovoltaic systems and that is also one thing that we can take in count.

What is your decision process for investigating and using the right material? Do you first think of an interesting application or first thinking of interesting properties and then look for an application?

For us it is happens both ways almost 50/50. Many times we find a new structure for a material and then we look around for an application based on how we could control it or what it does. The other time it is much more that we are designing for some application or for a grant that we proposed that we can design a new surface.
Is it more a bottom up or a top down development?

We specialize in bottom up methods; we really like to try to bring in ideas from the Nano science and from the microstructure evolution to really make materials, design from bottom up and the self-assemble from the bottom up. But at the same time the really powerful thing is when you combine the bottom up method with a top down patterning. So for example you’re now in computer science you use photolithography, which is a really standard top down method. You use photolithography to define a pattern but then you use a bottom up assemble to kind of assemble within the pattern. You can do a lot of very interesting things that way.

These types of materials that we have most working on recently, these non-wetting structures are kind of arrays of hosts and walls and things on the surface and we use a top down to make the structure originally and then we use a kind of a stamping process to replicate that in inexpensive materials and that is a kind of bottom up method in a way so that is another example of it. You need a top down method to make the initially structure but then bottom up methods are what you would use to replicate it inexpensively. There are a lot of interesting tricks to work with.

What is then your decision making process?

We sometimes develop a material or a structure where we might think we know that it is good for but in actual fact when we talk to other people (industry partners of other institutes) it does not really go anywhere. They are just not interested. I think it is just usually by talking to people then you got an idea of how it could be used. And that is why meetings and conferences are so important and interesting.

Like the architecture meeting in London was really interesting to sort of interact with architects and get a sense of what do they need or what are they looking for. The meeting in London was really the first of its kind for me of a first big interaction with architects and the architecture world. I think it was quite interesting and I got a feeling that bringing in new materials is something that could make a big difference in architecture. That is my feeling and I think that at the moment there are some interesting ideas in architecture. There are ideas of sort of adaptive designs but there a very little of these projects that take a real advantage of the properties of the materials themselves. And architects tend to treat the material what we would call continuum material that has some property and it has this colour and you can make it this big and it is cheap. And I can see why they are doing that because costs are one of the big things. So you cannot just go with the things you know but I feel that we will make buildings adaptable and give them these new kinds of properties. And there is a great opportunity to do this from the bottom up with new materials. I mean we can already adapt to a lot of applications but we can just do that by knowing what people are looking for.

What are your sources of inspirations?

Journals, articles, conference talks and talking with people. But we also have a sense of what kind of properties might be useful. Look I have a project that making surfaces that prevent bacteria from sticking to the surfaces. And actually I need to talk to a person who knows more about that. But I can already sense that this is a useful
property because for example in hospitals you need surfaces where a contamination is able to spray from one surface to the other. But to really know what the people need I should go and talk to the people in hospitals and see what they really want.

How are you then developing those projects?

In our particular case we are working in a group with twenty people and maybe half of them are experienced scientists and the other half are younger students. And then our department consists out of several different groups, there are all kind of peoples around so I think that there is always an opportunity to get an advise about something you go and find someone to help with. I think that happens quite a bit but I think also you tend to have an instinct of about how a particular material synthesis or process can work. You would start with your own experiments but then you properly go and talk to people and ask them things like: can you do it under this conditions? or can you do it this big? There is a lot of talking to people and I think that is very important. Otherwise you will never learn how to make something new and the fact that it is new means that no one has done this before. There is always this cycle of where you develop your things for the first time and then you can go to the next step.

What are the biggest obstacles to you and your work?

The biggest obstacles to us is that we are very good in making materials by focusing on how to design a structure on a small scale but you know the pieces that you are making tend to be max. 5cm to 10 cm big. We can study a lot of things with these small pieces like for example with our ice-project we did a lot of interesting research on how ice forms on the surface but then we published a paper and companies got interested and a whole bunch of people including the building industry asked us how we would use that and they want materials that are just huge, they want to cover a façade or a whole building, which makes sense and that is where we immediately face an obstacle because we are not a company and we cannot produce big stuff even to test. And this is where things brake down very quickly because we would need then a company that would make big areas of it and that requires a third party to come and help us and or collaboration partner meets a quite a lot of people and try to negotiate and that’s where it gets very tricky. And of course it depends on the material and how it is made. I mean sometimes scale up is not a big deal but it tends to be scaling up is the number one obstacle and cost as well.

In our particular case we are actually very good funded and we are kind of lucky that way. So funding tends not to be the big issue it is mainly time and men power, finding time for the right people to work on something is one of the biggest challenges. But then it is also a problem finding the right company to work with and to help us to scale up the material that is also one of the big things.

How long does it take to develop a material?

Usually things happen reasonably fast and for us it depends on finding the right financial source like grants and sometimes the military. Especially military resources fund a lot of basic science so it is not really for a true military application but we got also funding’s from companies like BASF and sometimes it is just government
funding. The time-scale to develop those things can range quite a bit and for some grants we need to develop the material quite quickly like say within six months. If it is more on the side of a science research project it could be a view years that you can work on something so I really think that it depends on the funding source and the application.

Are you working with Architects and Designers together?

Yes we try it more and more. In our institute we have a section of Adaptive Architecture and that is sort of being led mostly by Chuck Hobermann but at the moment it is still quite small and it does not really include a lot of people so it concludes some of our people from the material science and some of the graduated students from the design department but they are not really involved right now. And we have been employing some other people like mechanists, 3d-printer experts to help us to make things but we are not very well established right now in the school.

We like to build up on that more and get more people involved from different institutions. It is still early days for us but that is something that we are trying now to get on.

How is this collaboration working? How are you communicating?

At the moment it is more that we start to develop a certain material or a property and then communicate with Chuck to get an idea of how that fit into the architectural world and how would architects use it or how he would use it. So things kind of evolve from there because he is directing the company and the projects form his point of view. His insides have been most of the time right. We are just starting now and collecting design ideas from the outside to develop. I think we are just starting now to develop materials with maybe a sort of architectural property in mind but have not come really far with that actually. So we basically work on some ideas showing them to Chuck and he says that’s nice or that is not working for architecture, can you change that into this? And so on. It starts to be well developed but I think within the next view years we can become a full circle where people like Chuck and Chuck are actually designing stuff with us. I think that will go to be happen it is just a matter of time.

Is there a difference of problem identification and describing of things?

Actually I think there is. There is quite a big divide there in how architects and designers think of materials and the way we as scientists think of materials and the way we think of buildings. So I think sometimes we are using the same words but they have a different meaning. And that was an interesting thing about the conference in London that a lot of the language that architects are using is kind of foreign to how we as engineers and scientists are using the words and that is an interesting challenge to make sure that you are talking about the right thing and that you are understanding where the problems are.

Can you maybe give an example?
I guess even with the word structure we tend to think of very small scales. We think of microstructures, anything less than a millimetre whereas architects use that word in a whole different context and it just words like that where it really depends on the context. The word adaptive as well, I mean at the conference I was actually surprised about how broadly some people where defining that word. I mean to us it really means in terms of a building that it is changing its shape or the façade changes its property whereas in the architectural talks a lot of them where talking about how a building is changes its use and how people adapt with a building. I can remember there was one talk that seemed to say that when you are moving the furniture around made the building adaptive. And to me it was a bit like OK we can do that already so let’s do something new. But I guess it depends how you will look at this. I guess to architects it seems the interaction with people and how people perceive the building and interact with the building is very important and to be honest as an engineer it is not that process and we are not thinking like that, it is more about the building itself and the structure.

So what does it then require to introduce materials to architecture?

Actually I did not realise that this is such a big problem before we started to look into this area. I did not really predate how conservative the industry is to incorporate new materials so it means you have to do a lot of things to make a material exceptional and used. Cost is obviously one thing but I think you need to demonstrate and to test a lot of things. The performance, the stability, does a lot of prototypes to show it is gone to be used before the industry would pick up the idea. And it also seems to me that the architects themselves are interested in new things but they are not really important in the process. It is more the engineering companies to me that seem to be the important part of that. Because they need an understanding of what this material does and how it would be used and they would decide or would help the architect to decide what kind of material should he use and how you work with it. So you really have to talk to those people and demonstrate a lot.

Is it different then to work with other industries like the car industry or with companies from the product design area?

I think there is a lot of resistance and I think we have to change the industry but at the same time I am looking at other industries like micro-electronics or car industry or products like I-pods and things like that. Those disciplines seem to be much more used to adapting new materials because that is a much bigger part of what makes them innovative. So I think even though they still have to be careful and they have to be really sure that the material performing that way that it needs to. I think they use new materials more frequently. I think this is one of the big differences and also the scale of the products and the mass-customisation.

I think the best route towards introducing a material could be by working with existing materials and integrate them and make new components. Basically substitute something what is already there and people do not have to change radically the manufacturing and construction process.

The big problem with industries that I have is that it seems that they want to have everything already ready. They do not want to accept any level of development. They assume that you made the material and we can use it. But there is this point where you have to scale things up and the companies do not want to be a part of that process.
They do not do any kind of research and I think it is a shame and they are expecting everything developed by us. So they need to do some stuff as well to make something happen.
A 1.3 Interview Partner No. 6:

Why are innovative Materials and Technologies attractive to you and your work?

Beginning of the 90’s especially in Harvard at the GSD the interest of new materials and materials in general was very high. At the moment the focus and interest lies more at the field of form creation, generation and parametric design.

With the call of Achim Menges we have now established a research that is located in-between of these two sides. This is the new rising star of research.

Personally for me it is not a question of material or form it is the combination.

In the time of our last Dean Toshiko Mori the research and the teaching was more material orientated. The students learned in the first semesters how to work and experiment with easy to use materials like plywood, concrete and even wax. And the results were very good. The results were not real architectural designs but projects that were dealing with the nature of the material and the understanding how to work with the properties of the materials were developed. I am more interested in the new middle way of combining materials and the form finding. For example I am working at the moment on a project in Singapore and it is a mixed used building with a community centre and a church (10.000 sqm, 7 stories, a very dense building).

There is of course a tropical climate and we are looking now into the different materials to design with the right ones. Important factor is the sustainability and the use of location-bound materials. For that project I am working closely with Christoph Reinhart from GSD and he is a building scientist and architectural educator working in the field of sustainable building design and environmental modelling. And we are running a view tests according to for example the density of a metal mesh to gain a better performance for the sun shading for instance. And this will be one of the main developments in the near future. There is a huge potential for helping architects to design the right screen or skylight with simulation and analyses tools to quantify and qualify the right shape and position.

Most of the projects done by people like Achim Menges are more or less producing just screens, with new materials. I do not now one real project that is using these new technologies but this will be the future.

What do you think of smart materials related to architecture?

Photovoltaic are sort of smart materials for me. I am especially interested in how we are dealing with these materials. How can we design and not only use them as an application. In terms of photovoltaic for instance I think it is not appropriate just to attach the cells onto a wall or add them onto the roof. We have to design with these techniques in a smart way. The usual smart materials have a big potential but they have also a big disadvantage that they are just working in a small scale very good. The translation into a big building is often too expensive. We can see a strong movement in the automobile sector where these materials are often in use but in the building industry we are still at the beginning. If it comes to the level of teaching how to use these materials or
what these materials can offer the results of the students is every time exciting and wonderful. It helps to explore the potential of these materials in the design classes, exploring new transitions of shape and geometry, energy saving and so on. But for a daily architecture it is a problem of costs, a problem of guarantee, there is no willingness in these new materials to use and to experiment with them.

Small-scale projects like pavilions can help to understand the material properties and to show clients and manufacturers the potentials. My colleagues are using the pavilion as an experimental laboratory and a case study to introduce new ideas and techniques and after the analyses of the results of the pavilion they try to apply the new gained ideas into their real projects.

What is your decision process for choosing materials for your design? At what stage does that usually happen?

I try to integrate and to introduce in an early stage the materials to work with the material and to articulate the design with the material. But there are totally different approaches like for example Scott Cohen who is just looking for the right form and the material questions come at the end. I am looking for a more material wise design approach.

If you are using untypical materials within your design context, what are the applications you are using them?

For me it is important that the material has a certain design quality, of course the performance of the material is part of it but performance is not producing architecture. Architecture is performance and much more. Numbers and values are not producing results and a new architecture. The interest of using new or certain materials has to come from the designers’ point of view. Engineers can maybe support the role of a material with their property values but at the end the material has to support the architecture. For example if we look at the project in Singapore one of the main criteria’s was to connect the inside with the outside. Many of the buildings in Singapore have due to the tropical climate just small windows and the sun and the heat is one big problem. We are now trying to build a glass façade with a covered metal mesh to reduce the sun impact and in the upper level were we have the church we are working with skylights to control the light. But this is also quite difficult because the sun is more or less perpendicular because of the geographical location. And therefore we are now introducing a roof garden and the landscape architect is designing with the plants a natural shading device. Like in the colonial architecture were trees and their leaves are providing a natural roof and a natural cooling system. In that specific case the plants are also a “material” and one of the big questions is how to simulate this situation in the design process.

So for me I think at some cases we can also consider plants, air and atmospheres as a smart and building material.

How do you plan and design with new materials and technologies?
We are trying now to write a script that is looking for specific lighting conditions for the church room. We are looking for the right amount of lux and we are trying to reduce the glare effect of the glass façade. To start with, we first measured under real conditions the sun blocking power of the plants and used this to reproduce the effect in the calculation programme. But to simulate everything in terms of the material properties and to predict the impact of the behaviour of materials I am just starting now to get involved with. The university is a much better supplier for such a research and the practice itself is a good area for testing the researched results. One of the biggest problems in the practice is that most of the architects do not have the access to a broad filed of experts from other fields to simulate and to integrate the results of a simulation in the design process. In the university someone is better connected.

So if it comes to a collaboration of different fields we need a bigger budget to design and this is not very often the case. And if there is a big time pressure because of the short time schedule to finish the project the collaboration is much more difficult and more expensive to do.

What are your sources of inspiration for the application of new technologies and uncommon materials?

Because I am a professor and I am teaching new materials at the university I am of course inspired by the results of the students even though we are not using the new material but we are trying to use the idea of the properties to design something new. But in my case it is more like if it comes to a real project and a realisation it comes to a clause of proven and tested materials but in a new context and in a way that they are not used before. We are using now new technologies to control the perforation of the metal mesh for example to control the light. It is more the combination of the simulation techniques and proven materials that creates something new. It is very often the case that the client do not has the money and the time to experiment with you together on something new.

What are the obstacles for applying results from material research in an everyday practice?

Especially in the USA there is a clear distinction between designer and contractor. Architects are not really cooperating with the construction companies and they’re just leading the design. We have a lot of legal problems and the problem of property and guarantee. The building industry is very conservative. I was working for 5 years for the construction company “Hoch Tief” at the R&D sector and there we had more support of the company for new materials but at the end we had to work with the same materials. For the industry one big issue is that a material has to have one clear big potential and that the physical properties are well known and that it is easy to be used. If a material might support the industry to gain a new market or to extend the market, the lobby will push it to introduce it to the building industry. The willingness of experimenting with new materials is in the building industry not usual. But some architects are trying to push the boundaries like Sheila Kennedy and Kieran Timberlake. With a prestige project the client has the duty to experiment but with usual buildings there is now chance to do so.
What is your opinion about collaborations to material experts and scientist to develop new materials and technologies for your purposes (if you have not have such an experience before)?

Of course it is desirable to collaborate with other disciplines but the language and the interests between architects and engineers are still different. There is a lot of antagonism in the room. And the collaboration is often very trivial. Where the material scientist is not taken seriously the ideas of an architect because they do not have any idea of building physics and we do not understand the language of the engineers. In that field we need still pioneering work and the right people from both sides that are willing to work together. And then sometimes it is very fruitful but I as an architect want to build buildings and this needs often other criteria then an engineer or a scientist is used to. The ambitions of the different people are often not the same and they do not really profit from each other’s support (in the field of the academic research and design fields).

We are trying every time to introduce engineers in an early design stage also in the research and teaching of students but it is not often very successful. Architects are qualitative educated and engineers are quantitative educated and that is already one big problem for further communication. There are just a view engineers that have a different sensibility of architecture like Cecil Belmond and so on. The value system is not matching.

So the next question is really does an architect now has to be a little physicist or a chemist? Or is it more a question addressed to the material scientist that he has to become more familiar with the real world. Maybe he has to come down from his scientific oriented horse a bit to support the architects stronger. I assume the truth is somewhere in the middle.

The whole question of interdisciplinary work is nice but I think someone has to be disciplinary first and then an interdisciplinary workflow can be possible. And especially in the academic field where everyone wants to be professional known in their own field it is quite difficult because these interdisciplinary projects are not so recognised but also in the practice the interdisciplinary boundaries are very resistant and no one wants to give up a little of his own ideas.

What do you think about collaboration with experts from other disciplines like the car industry, aerospace industry or production design, to benefit from their knowledge of design and construction new technologies?

There are a lot of books published about a workflow and a collaborative framework with proposals to integrate the different design and planning teams more like in the automotive industry and the aerospace industry. They are existing since the last 20 years but I cannot see a big influence of them in the architectural practice. I think it is more important to introduce in an early stage of the education of architects and engineers the living example of a good collaboration to break the conservative education system and to broaden the mind of the next generation of planners and builders.
For example if we take the book of Schodek and Addington we can say that the book has not a big influence because it is still too technical for architects.

What does it require to introduce new techniques to the different design and building industries?

The best way of introducing a new material into architecture is a prestige project and a lot of commercial. So we need a precedent to introduce new materials.
A2 – Script Example

The following projects and prototypes are order in a time related order. The list does not aim to be complete rather it gives a comprehensive overview to emphasis the increasing appearance of architectural ideas engaging with smart material systems.

```java
/**
 */
import processing.serial.*;
import cc.arduino.*;

Arduino arduino;
int index = 0;
int stepSize = 5;
graphLine galeftA;
graphLine galeftB;
graphLine gamidA;
graphLine gamidB;
graphLine garrightA;
graphLine garrightB;
PImage background;
PGraphics graphs;
int stepsY = 6;
int stepsX = 4;
PFont fontA;

void setup() {
    //size(800, 600);
    //size(800, 600, P2D);//more speed
    //smooth();//slows it down a bit
    size(800, 600, JAVA2D);//better quality
    smooth();
    frameRate(15);
    galeftA = new graphLine(0, 260);
    galeftB = new graphLine(0, 260);
    gamidA = new graphLine(281, 540);
    gamidB = new graphLine(281, 540);
    garrightA = new graphLine(560, 799);
    garrightB = new graphLine(560, 799);
    graphs = createGraphics(width, height, JAVA2D);
    graphs.smooth();
    graphs.background(0, 0);
    fontA = loadFont("LeagueGothic-36.vlw");
    textFont(fontA, 36);
    textAlign(CENTER);
    arduino = new Arduino(this, Arduino.list()[0], 57600);
    for (int i = 0; i <= 13; i++)
        arduino.pinMode(i, Arduino.INPUT);
}

private PImage getMyBackground() {
    if (background == null) //check to see if we cached (previously drew) the buffer.
    {
        int newHeight = height + stepSize * 4;
        PGraphics backgroundGraphics = createGraphics(width, newHeight, JAVA2D);
        backgroundGraphics.beginDraw();
        backgroundGraphics.smooth();
    }
```
backgroundGraphics.fill(96, 96, 96);
backgroundGraphics.rect(260, 0, 20, height+100);
backgroundGraphics.rect(340, 0, 20, height+100);

return backgroundGraphics.endDraw();

}

void draw() {
    //for (int i = 0; i <= 5; i++) {
    //print(arduino.analogRead(i));
    //ellipse(280 + i * 30, 240, arduino.analogRead(i) / 16, arduino.analogRead(i) / 16);
    //}

    imageMode(CORNER);
    int imageY = -stepsY * stepSize + (index % stepsY) * stepSize;
    image(getMyBackground(), 0, imageY);

    int offset = 200;
    int multiplier = 3;
    int x = width - stepSize; //index * stepSize;
    int yLeftA = arduino.analogRead(0);
    int yLeftB = yLeftA + 10;
    int yMidA = arduino.analogRead(1);
    int yMidB = yMidA + 10;
    int yRightA = arduino.analogRead(2);
    int yRightB = yRightA + 10;

    graphs.beginDraw();
    gaLeftA.draw(yLeftA);
    gaLeftB.draw(yLeftB);
    gaMidA.draw(yMidA);
    gaMidB.draw(yMidB);
    gaRightA.draw(yRightA);
    gaRightB.draw(yRightB);
    graphs.endDraw();

    image(graphs, 0, 0);

    PGraphics temp = graphs;
    graphs = createGraphics(width, height, JAVA2D);
    graphs.smooth();
    graphs.background(0, 0);
    graphs.beginDraw();
    graphs.drawImage(temp, 0, 0, stepSize);

    graphs.endDraw();

drawCircle(130, 350, yLeftA, 0, 260);
drawCircle(130, 500, yLeftB, 0, 260);
drawCircle(410, 350, yMidA, 280, 540);
drawCircle(410, 500, yMidB, 280, 540);
drawCircle(680, 350, yRightA, 560, 800);
drawCircle(680, 500, yRightB, 560, 800);
    //drawCircle(200, 300, yMidA);
    //drawCircle(200, 450, yRightA);
    index++;
}
graphLine(int _xMin, int _xMax)
{
    _xMin = _xMin;
    _xMax = _xMax;
}

void test()
{
}

void draw(int newX)
{
    int safeNewX = newX;
    if(newX < 0)
    {
        safeNewX = 0;
    } else if(newX > _xMax - _xMin)
    {
        safeNewX = _xMax - _xMin;
    }
    graphs.fill(145,207,240, 80);
    graphs.noStroke();
    graphs.quad(_xMin, yStart, _xMin + safeNewX, yStart, _xMin + oldX, yEnd, _xMin, yEnd);
    graphs.stroke(186, 186, 186, 100);
    graphs.strokeWeight(2);
    graphs.line(_xMin + safeNewX, yStart, _xMin + oldX, yEnd);
    oldX = safeNewX;
A3 List of Published Work

A 3.1 Conferences:


A3.2 Journals:


A 3.3 Book Chapters:


Bohnenberger, Sascha, Chin Koi Khoo, Daniel Davis. 'The Emergence of Material Systems through Anticipation of Material Properties'. Will be published in *Designing the Dynamic*, 2013
Appendix

A4 – Public Recognition and Cited Work

A 4.1 The Lantern Project; Luminale 2010 Catalogue:

Luminale 2010
A4.2 Design the Dynamics 2011; Future Fabric of Cities
Flagship 2011 Catalogue:

Designing the Dynamic Design Research Workshop
EXPERTS BY
Hugh Whitehead Foster + Partners
23-24 November 2011

Designing the Dynamic Design Research Workshop Invitation

Members: Design Research Team, Research Workshop and Team:
Micro Synergetics

This year, each of the workshop groups took the theme of "Material Intensities" and developed design problems to investigate it in different ways. The "Micro Synergetics" cluster led by Sascha Bohnenberger, Peter Liebsch, Anton Savov and Andre Chaszar aimed "to develop a collaborative design workflow including simulation and physical prototyping for engaging material properties reactive to a range of day-to-day architectural environments."
The Micro Synergetics group experimented with a wide range of materials including conductive and thermochromic inks, paper, acrylic, wood veneer, nichrome and SMA (Flexinol) wires, as well as a variety of control schemes for overriding the materials' natural responses to changes in environmental conditions.

Harvard Graduate School of Design Responsive Environments and Artifacts:

http://rea-disappearance.wikispaces.com/Micro+Synergetics
A5 – Published Samples

A5.1 A model for Transdisciplinary Design in Passive Illumination

Published in:

A Model for Transdisciplinary Design in Passive Illumination
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ABSTRACT. The advent of new materials that are responsive to external environmental stimuli pose a challenge for design practices exploring such innovations as they become available. A transdisciplinary approach between architects, engineers, designers and material scientists is viewed as an active response to such a challenge. Here, a flexible workflow and shared language is introduced and explored in terms of advances in the fabrication of low-light phosphorescent materials, which have the potential to organically light urban infrastructure.

Keywords: energy, passive, lighting, sustainability, transdisciplinary, simulation

1. INTRODUCTION

In architectural history, material development has had a decisive influence on the innovative strength of architecture via the link between the built form and available material systems. In a wider sense, technology, which includes materials, is constantly developing and as such, we have new builds on both sides of the divide and how we use it. Digital computation and simulation are another technology that has integrated design symbols, morphogenesis and parametric & CAD modelling [1] and together with the use of responsive or smart materials provides the opportunity to create new forms of environmentally responsive architecture. Only by the development of new materials and techniques can light, energy efficient and economical buildings be feasible and thereby meet the demands of advanced architectural thinking. Such smart materials require a higher level of design process to place them within this environmentally responsive paradigm.

With the levels of primary energy consumption attributed to lighting exceeding 30% in developed countries, the current recognition of present light energy management signals a challenge to both urban design and technology to address this while maintaining nighttime amenity or as John C. Bell put it ‘modernisation’.[2]

The following paper addresses the role of a transdisciplinary approach between architects, engineers, designers and material scientists in such a challenge. A methodology for a flexible workflow and shared language will be introduced. This will be explored in terms of advances in the fabrication of low-light phosphorescent materials, which have the potential to organically light urban infrastructure, buildings, public open spaces and even interiors.

2. LIGHTING ENERGY

As John Bell notes, if we follow the line of thinking which informs current urban design practice, we will, in the near future, live in an efficiently illuminated, zero-emission continuum of well-directed moderate luminous intensity, thus minimizing environmental impact, achieving a relatively low carbon footprint and avoiding and mitigating for climate change and ecosystem management [2].

For example, an increasing number of lighting solutions [2] based on solid state lighting (SSL) particularly LEDs and OLEDs (Organic Light Emitting Diodes). Australia equally encourages an energy efficient and cost effective approach to lighting. More efficiently efficient technologies can be implemented both quickly and cost effectively. Most importantly, efficient lighting not only can, but must necessarily reduce the amount of light available, but provide the right amount of light in the most efficient way possible. While the first goal is to change from traditional lighting to SSL, other materials could complement this and further diminish primary energy use. Advances in phosphorescent materials are beginning to allow for longer-lasting coloured pigments able to illuminate for prolonged periods. While these new materials would not act to replace incandescent and naiver lighting, they could complement them providing an alternative illumination source in spaces such as urban infrastructure, although such smart materials require enhanced design processes able to site them in their environmental context. In order to do this, these new materials require these higher level design processes to situate them in their environmental context so that accurate modeling can take place prior to implementation.

3. DESIGN OPTIMIZATION

3.1. Design and Engineering

Today architects and engineers have developed several methodologies to analyze and simulate the architecture and the structure of buildings. Due to the possibilities of digital computation, we have the ability to verify within a short timeframe the results of a vast range of design options. Branko Klokovic explains the emergence of these techniques as a ‘generative tool for the
derivation of form and its transformation - the digital morphogenesis exploring the possibilities for the "finding of form". Here, he surveys the digital generative techniques, in computational architecture, in terms of spatiofunctional space, isomorphic surfaces, kinematics and dynamics, keyshape animation, parametric design, and genetic algorithms.  

Such approaches are based on software rush-ups often conducted through several software packages such as RHINO for 3d-modelling ANSYS for structural analysis and ECOTECT for environmental impact simulator.

For example, this enables the design and creation of economical structures and geometrical patterns for facade cladding as seen in the performance design of the Serpentine Pavilions of Toyo Ito and Álvaro Siza in collaboration with Cecil Balmond.

To be able to inform design with newer more dynamic material properties, more flexible systems able to deal with physics and parametric design principles in a real time environment are required. With the increasing development of computational software and analysis both architects and engineers will be able to redefine new ways of engagement with other disciplines such as material science and structural engineering in order to implement novel materials especially those sharing dynamic functionality to develop lightweight, energy efficient and economical buildings.

3.2. Material Science

To date architectural engineering has transitioned through “specific material and energetic interventions in the physical environment” yet the materials themselves essentially remain static with respect to their functionality. These new technologies and theories of digital computation and morphogenesis are now leading to a shift from generative tyranny to a material-based approaches and an understanding of the significance of the behaviour of materials in their own complexity. The study of material structures and their ability to inform the design has become a serious subject of professionals as well as academic concern as noted by Riva Coman. We are now at a point where materials can be truly functionally responsive. That is, materials able to respond to an external stimulus, interacting with the environment through that stimulus and provide dynamic material functionality to a structure. Thus, we now have the opportunity to create real-time responsive architecture as well as the need to understand the changing physical behaviour of responsive materials so that they become accessible to computational design platforms.

In the case of current real lighting effects simulation and analysis may be achieved through several software platforms e.g. DAYSIM, RADIANCE or INSPIRER.

3.3. Exploring Implementation

Physical modelling and prototype production fulfills a broad range of functions in the design and engineering process. Hershel and Menges [1] point out that with onset of these digital generative design techniques, especially optimization, they shift from purely representational models to a systematic approach providing analysis of performance capacity verification of geometries and topological assemblies, and an exploration of modes to fabrication and assembly. Functionally responsive materials add an additional significant requirement to this design and verification process. That is, it needs to provide a demonstrable verification of a material's ability to respond to an external stimulus, interacting with the environment through that stimulus while providing dynamic functionality to a structure.

Illumination design demonstrates this need for a close nexus between digital simulation and exploring physical prototypes within the context of their environment. Visual perception including colour as Peter Baren [8] points out is "beyond the eye and into the brain". Here, Baren suggests a new paradigm for illumination: Perceptionism, "that continues beyond the eye, up the optic nerve into the brain (being) less concerned with what the eye sees literally than the way the brain interprets what is seen."

Exploration of phosphorescent materials within an inner urban environment was explored recently by placing 114 tannets within the pergola structure.

![Figure 1: Simulation of the glowing effect and analysing the Lux power](image)

The forensic of the Alto Opéra in Frankfurt, Germany. Initially, the afterglow characteristics were simulated with RADIANCE to provide ray-tracing analysis (Figure 1) from empirical inputs of colour and illumination intensity (Lux) for comparison with the prototype illumination at night. Conventionally the response of the eye is characterised by the intersensation of colour and light intensity as
dictated by optic cone and rod photo-receptors. The difference in both light sensitivity and spectral response in daylight compared to night results in an exponential increase in intensity sensitivity and a shift towards blue in wavelength sensitivity at night (Faraday's phenomenon), as illustrated in Figure 2. Visual perception, being largely governed by retinal illumination (measured in Trilambas) is governed by the brightness level of an object in comparison to its total background and this is a highly different phenomenon requiring modelling and assessment within the context of the environment whether day or night.

Development of phosphorescent lighting requires such simulation which needs quantitative inputs of the source's performance parameters. Optimization of the material properties of the phosphorescent source will require systematic reconciliation between scientifically measured characteristics as above and experimental determination of the visual perception of their performance. Figure 4 illustrates the prototype lanterns at night within the environment of the Frankfurt Auto Cyber forecourt as an early experimentation.

4. TRANSDISCIPLINARY APPROACH

Kjell Moe, in his recent book Thermally Active Surfaces in Architecture, presents a primary premise that any coherent and reliable practice of sustainable architecture and urbanism can only emerge from a coherent understanding of our techniques (or collective theories, techniques and technologies) [10]. In "Rethinking Sustainable Design Solutions," Michael Addington [11] points out that it is perhaps sustainable lighting that could bring very disparate disciplines together such as the physics of light, the psychology of visual perception, the engineering of lighting systems and the social history of the role of technology, culture and marketing. It is then architecture that maps a definite lighting outcome whether within a building or urban landscape. The opportunities generated by the newer lighting technologies e.g. LEDs and optical fibres as well as truly functionally responsive materials e.g. longer afterglow phosphors and up-converting phosphors necessitates not only early transfers of knowledge but also the active derivation of physical material properties prior to the implementation of the generative techniques involved in computational architecture.

Currently a more post-rationalist approach to collaboration has already resulted in a state of early engagement of designers, architects and engineers, extending the boundaries of fabrication and building technologies. Such cross-disciplinary interventions are probably apparent in other sectors such as the automotive and aerospace industries. In architectural design and engineering, new tools and thinking models have been developed as a meta language.
between the different disciplines such as the BIM-Model (Building Information Modelling). Architects and engineers employ this technique to collaborate and share design strategies in an early design phase. However, this method is not applicable for every design phase and is not for everybody. Successful implementation requires designers to continue using their long-standing design tools and processes without productivity loss in their core tasks. Figure 5 illustrates a conventional approach to disciplinary collaboration characterised by linear interactions occurring as required, although not suggesting a particular discipline priority. It portrays the knowledge base brought by each discipline to solve problems sequentially towards the final design outcome.

5. CONCLUSION

With lighting consuming a significant portion of electricity production and as much as a half in many buildings, and thermal efficiencies of fossil fuel generation in the region of 30%, design practices have a significant incentive and opportunity to explore and implement newer technologies for lighting in urban environments. Materials that provide passive lighting in such environments such as longer afterglow phosphors and up-converting phosphors can contribute progressively towards the options to reduce the demand for delivered electrical energy. The advent of such new materials will require effective design innovations brought about by close trans-disciplinary interactions which the current progress towards computational architecture and engineering design frameworks.

Rather, a trans-disciplinary approach can centre on an evolutionary design strategy involving initial interplay between the contextual strategy, material opportunities and implementation modelling. Here, the nexus between problem-based knowledge and solution-based outcomes as termed by Audington [11] is addressed early on and in a structured way. Figure 6 illustrates the oneness of such a design process.

Here, trans-disciplinary design represents a set of fluid interactions between the competencies of the disciplines that not only results in early problem identification and solving but also in enhanced innovation induced by new interactions at the interface of discipline areas when faced with a common goal such as sustainable energy consumption.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


A5.2 Lattice Spaces

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Respecting Fragile Places [29th eCAADe Conference Proceedings, Ljubljana (Slovenia)]
26-29 September 2007, pp. 751-758

Lattice Spaces
Form optimisation through customisation of non developable 3d wood surfaces

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Abstract. This paper discusses a collaborative project by RDAl architects, Bollinger + Grohmann and the timber construction company Holzhaus Amann. The project is located in a former swimming pool in Paris and is part of the new interior of a flagship store of the French fashion label Hermès. In late 2006, Rossano Domen Architects, asked Bollinger + Grohmann to collaborate as structural engineers on a challenging design proposal within a very short timeframe. Three wooden lattice structures, the so-called “bulls” and one monumental entrance with a similar design approach characterize the interior of the new flagship store. The lattice structures are dividing the basement into different retail spaces. They vary in height (3.9 m) and diameter (8-12 m) and have a free-form shaped wicker basket appearance. Wood was chosen to create welcoming and elegant wooden structures. The project was made in collaboration with Holzhaus Amann.

Keywords: digital production; parametric design; mass customization; wood; digital crafting.

INTRODUCTION
The French fashion label Hermès had entrusted the RDAl agency, which is responsible for designing most of the Hermès stores worldwide, with the design of a new space, in Paris. In the discussion held in 2005, the new swimsing pool building Hermès’s new “La Maison” furniture line is being displayed.

Three pavilions with an organic design, are forming the main interior of the new shop. The staircase that naturally leads the visitor towards the pool and forms the link between the entrance and the open space of the swimming pool is the fourth naturally shaped object in the space.

Three shapes of different forms and dimensions are constructed in wood to support the philosophy of Hermès as a sustainable fashion label with a high-quality approach.

Starting with that vision the architects worked in a close collaboration with Bollinger + Grohmann to...
turn this concept into a feasible, self-supporting "object". The deadlines, the complexity, the multi-formats exchanges and the communication with collaborators on the project, it was necessary to organize a smooth workflow between visual aspect, geometry, structural properties, structural optimization and execution process.

Digital Wood

Who would have thought that wood would become a high-performance material that is used in the most complex geometrical and structural ways that we can imagine due to custom made programs that are describing not only the geometry and the structural performance but also calculating the most efficient way of producing and fabricating the wood elements, this material got a renaissance in the building industry. This "old" material offers us a broad range of beneficial properties; it is easy to work with, affordable and accessible to many, a new way of engagement with the material through digital design and fabrication processes. Joining, laminating, carving, bending, cutting and finishing become sources of design ideas (Robert Woodbury, 2007). Within the last few years wood has become a construction material for advanced complex geometries in architecture; examples for this material revolution are the Korkeasaari Lookout Tower in Helsinki, the roof of the Centre Pompidou in Metz or the recently produced Parcoal pavilion in Stuttgart.

The understanding of the material behaviour and its properties is becoming more accurate with the development of new analysis techniques in various realms. Material scientists and biologists are looking closer and understanding the complex structure of wood at a nano scale, engineers and architects are shaping the geometry according to the performance of wood.

The Hermes project is following that trace and shows new possibilities of working and designing with wood.

Material specifications

The basic design of the here-described "buflle" was thought as a kind of a wicker basket structure that reflects the concept of sustainability and natural beauty with its appearance. In order to develop such a structure that is on the one hand self-supporting and on the other hand will meet the high design criteria of Hermes and RDA, we had to look first to the possibilities of creating double curved wooden elements.

Since the mid 60's the knowledge of different approaches to control and bend wood is available. The following example explains the various techniques that were published in the book Principles of Wood Science and Technology/Solid Wood (Kolmén, Franz-F. P. and Côté, J.; Wilfred A, 1958).

To be able to complete the project in the given tight timeframe we decided to collaborate with a timber construction company from an early design stage. In order to develop a solution for the rationalization of this complex design detail we recognized the understanding of execution principles as well as structural, geometrical, visual and time wise elements; four variants for the execution were seriously

![Figure 1](image1.png)

**Figure 1**: Inspections of the architecture (final design)
considered, tested and discussed with different possible wood construction companies:

1. The steam bending process was too labor-intensive and besides that fact no one was able to produce 12m long laths within the short construction time frame.

2. The two-dimensional bending approach with single curved laths. This process did not answer fully to the aesthetical requirements because the aesthetical understanding behind the design was more related to a fully 3 dimensional curved line that describes the geometrical shape of the barrel.

3. Bending and milling the laths was designed to bend manually the elements in two directions until they meet the required boundaries for the final milling process. The process has the advantage that it is simple for the manufacture since everything is numerically controlled. The process is also relatively fast but in the end this process was considered too industrial for the craft tradition of Hermès and for this project it would lose the quality of the design of the wood because the grains are not continuous if you are cutting extreme curved wood laths.

4. By carrying out the bending and gluing of the wooden laths directly on site and adapting the length and thickness of the elements to the curve was after a short discussion with the fabricator not satisfactory. Aesthetically and structurally the solution would not fit into the criteria of the architects. The structure would consist out of too many end pieces and small elements. The work exclusively on site was also considered too dangerous in terms of time, structural quality and aesthetic quality (example: La Chapelle des Diacresusses in Versailles).

5. The Laminated bending approach was the last construction method that was considered. The process consists of gluing several laths together in the right shape. This is very labour-intensive and time consuming but offered the possibility to optimize all aspects of construction, form, structural performance through adapted geometry.

**GEOMETRICAL ANALYSIS AND FORM FINDING**

To fulfill the design wishes of the architects and the short construction period the parametric design software was linked to our structural solver. The advantages of using a parametric strategy are that all element parameters can be manipulated while constraints and dependencies between elements are maintained. The dynamic models that result are able...
to respond to changes and offer a degree of flexibility and coordination. These processes of anticipation and response make up the dynamic of life and apply currently to everyday consideration of design, fabrication, and construction and to conceptual explorations of dynamic conditions like Weinrock's (2004) pointing it out.

Equipped with a rough 3D model based on a pure volumetric model by the architects, because they developed the appearance of the wicker baskets with a bitmap pattern, we started to analyze the shapes in order to develop the first scripts to create 2-dimensional shapes of each leaf.

The 3D "bulbs" were following no particular geometrical rules and had therefore no continuous curvatures or dependences between each other. To be able to create producible elements that we could analyze we developed certain "rules" and created a reparameterized geometry that we could work with. A script that was developed within the scripting environment of the 3D-modeller Rhinoceros by McNeel automated that process.

The reparameterization

A set of curves was created with a certain distance to the original surface. This results in a set of horizontal curves that could be analyzed in terms of their curvatures. We optimized the curvatures wherever necessary. From these horizontal Bézier curves, we could reconstruct and improve the surface close to the original geometry. This operation permits the creation of a vertical regular surface. This surface is built up from two-dimensional parameters in U and V direction, which are represented as lines on the surface. These U and V lines serve as guiding lines for the definition of the axis of the leaf.

Tessellation

The wicker-basket pattern was created by the division of every constructed horizontal curve through a number of points. By introducing an offset at each horizontal curve of the division points we are able to design and control the diagonal pattern.

The crossing of the curves in two directions creates a lozenge pattern. Since the aim was to have the impression of regular shaped and equal sized diamonds on the whole surface, we thought of the diamond pattern as a tessellation. The creation of the curves creates an actual 3D-tessellation on the surface, eg. a diamond pattern of tiles on an irregular surface. Several scripts controlled and equalized each enclosed diamond on its size of surface, parallel lines, etc. This script ensures the regularity in size and density of the diamond pattern over the irregular shape.

Figure 1

reparameterization process
Laminated bending approach

The Laminated bending approach was chosen to realize the hull and the stair cladding for two reasons.

It combined high-accuracy technique and mathematics with high-skilled woodworking. All laths were perfectly pre-designed in a CAD model and precisely cut, including all necessary holes. This approach ensures a full digital control of the final result. The digital approach revealed any unforeseen effects in an early stage and control of all necessary parameters: what you draw is what you get.

However, this process required advanced material skills to bend and glue these elements together. The developed technique provides an almost continuous wood grain from the natural solid wood which is advantageous both in structural and aesthetic sense.

To obtain the laminated bending approach the geometrical optimization had to be clearly described. The optimization consists of a mathematical phenomena: a double curve of a rectangular section can be designed through the sum of two simple curves combined with some twists.

Each single curvature is describable and thus developable; this means that the laths can be cut from a simple flat panel. This operation on its own would not create an ever-changing non-describable double curvature of a rectangular section. To obtain the real form and to obtain that laths perfectly lay onto each other at the nodes the rectangular section needed to be twisted. Since wood cannot be infinitely twisted, we also gave restraints to the twist in the laths. Due to the nature of wood bending and twisting, it is directly manually possible and this material behavior inspired us to choose this solution.

STRUCTURAL ANALYSIS AND EXECUTION PARAMETERS

Fast modifications and updates of parameters were made possible by the development of programmed parametric geometries to be able to control the overall shape of the guiding surfaces and different design partners' parameters.

The input parameters for the code were such as slats curvature tolerance, slats intersection angles, intersection area and slat dimensions, bending density, alignment and torsion tolerance. The evaluation and optimization of the generated models were based upon structural analysis results, visual
appearances and execution techniques and discussions with the different design partners.

With the introduction of a whole set of analysis scripts, we could now optimize the model structurally and aesthetically. Already in this phase, the geometrical model communicated with the structural geometry via Excel and a Com-Interface in order to gather necessary information for the optimization.

Typical scripts for analysis include curvature control and the distance to the initial surface.

The developed surface of each "bulle" is horizontally regular by a horizontal offset of two curves and the surface created between them remains a controlled surface. Every surface can be developed within a certain tolerance by simply canceling the elements.

The initial scripts are related to flat parts lying on the surface. The structural analysis gives the input of the necessary thickness on the wall of the等到。To obtain geometrical the thicknesses of the walls and bearing in mind the execution process, we considered the following; The developed surface can immediately be used and cut out of a wooden panel.

An extra script was introduced in order to twist the laths exactly at the right position around the nodes. The neutral surface of each lath (middle of the lath) was used to do this.

In a second iteration of the offsets, we built in an extra step to control the curvatures and the maximum allowed thickness of the wall of the lath. This was introduced as an iterative design process in order to be flexible and precise at the fabrication stage of the project.

The data are produced at the factory and live work. Three wooden elements with 14 mm thickness and 60 mm width are cut from flat plates and placed on a false work. The slats have to be slightly bent and fixed in the correct geometry manually. After placing and aligning the laminates, these are glued and held together with bar clamps, so as to produce the composite carrier.

The set of customized parametric tools was also used to develop an exchange feedback platform between 3D models, structural models and Excel sheets. All involved parties were using different software packages and had varying interests in different scales of information. Here a customized workflow was necessary and the whole collaboration was optimized by data exchange files. Hence a close communication between the different members of the project could be introduced.

Detailing

The structures are assembled by four connection details which are all load bearing elements and will be briefly explained. The crossing points of the rods: These are connected to a central shoulder bolt with a diameter of d = 10 mm and two eccentrically placed dowels in order to be able to absorb the torsional moments occurring in the node.

The central shoulder bolt is integrated within the laminated wood elements.

The connection of the bars on the door consists of steel axles, which are welded to the profile of the door. The bars are slotted after the axles, to hold the bar in the central axis. Fixing is by means of two shoulder bolts itself, which thus form a double-shear connection.

The compression ring is placed in the plane between the two bar levels and is connected in the intersections of the wooden slats. To ensure the load transfer between the pressure ring and rods, angled shoulder bolts are also connected to the steel section.

The supports are made of flat steel feet which are oriented according to each slat with unique angles. These feet are welded to a flat steel plate following the outline of the bulle.

Customization

To realize the project, specific solutions for bracing joints, openings and foundations were conceived and discussed with the architects. Both our work on digital and physical models helped us defining the execution process. Following the principle we adopted for our physical model, the idea of a specially adapted scaffolding system to control curvature of the wooden slats developed. Eventually
the production established a high-end process of CNC cutting, scaffolding, bending, gluing and assembling of wood pieces to create the final double curvature wooden slats.

Every single wooden sculpture shows a different curvature of non-developable surfaces. Various alternatives for the construction were seriously considered and tested: steam bending, bending in combination with milling and assembling smaller pieces to continuous slats. The final manufacturing process was defined due to the concept of easy production of the single slats, a fast mounting solution and to have an invisible node.

The pavilions and the realized monumental railing of the staircase show the possibilities and opportunities of the digital workflow in the context of design and structure with complex geometries. The key here is to adopt the targeted free forms and the structural system until they meet the demands of the architectural approach. This requires a very close cooperation of those companies involved in planning and construction.

Figure 6
sculpted wood slats

CONCLUSION

The understanding and the knowledge of the construction and design material in that particular case wood are identified as one of the main indicators for the success of the project. Digitally simulating the right material behavior was inspecting not only the geometrical form finding, but also the structural performance of the overall shape of the four different bulks. This understanding of the material was the common thread that also connected the involved planners and partners. The architects with their ideas about a sustainable emerging interior for the fashion label Hermes, the engineers with the knowledge about the geometrical constraints and the load bearing abilities of wood and the expertise of the fabricator Holzbau Ananas could establish a workflow and a collaborative framework around the material properties.

Not only had the material defined the collaborative work around the implementation of the properties of the material into the parametric design and optimization process: it led also to a variety of design...

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options and proposals. Equipped with this clear advantage an optimum of design and fabrication in a short design and construction period was possible. These insights of the project and the relationship between material behaviour and geometry in order to create optimised constructions and fully promising design solutions will be a focus of future projects.

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A5.3 Sensing Material Systems – Novel Design Strategies

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Sensing Material Systems - Novel Design Strategies

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Abstract
The development of new building materials has decisively influenced the progression of architecture through the link between built form and available material systems. The new generation of engineered materials are no exception. However, to fully utilise these materials in the design process, there is a need for designers to understand how these new materials perform. In this paper we propose a method for sensing and representing the response of materials to external stimuli, at the early design stage, to help the designer establish a material awareness. We present a novel approach for embedding capacitive sensors into material models in order to improve material performance of designs. The method was applied and tested during two workshops, both discussed in this paper. The outcome is a method for anticipating engineered material behaviour.
I. INTRODUCTION

After a period of intense digital focus, there is a new era of material awareness. This has been powered by fast technological progressions in digital design tools (such as parametric design, form finding algorithms and emergent systems) and catalysed by the growing range of digital fabrication methods (such as CNC machining, 3D printing and robotics). After a period of rapid development in digitally design tools for architecture the ability to simulate and model materials are radically changing the realms of material thinking.

1.1 Context

Recently published publications by designers and theoreticians such as Michael Meredith [1], Lisa Iwamoto [2] and Rivka Oxman [3] are defining a new era of tacit knowledge through material research and design. This understanding is based on a relational, intersubjective work where material is seen as a facilitator for design decisions.

The growing palette of materials and technologies offers a range of new research fields but also raises questions about how designers apply this stream of unfamiliar construction materials and design tools. Our knowledge of commonly used materials—such as steel, glass, concrete and wood—typically comes from centuries of haptic experience and experimentation. But this tacit knowledge has not yet been developed for many new materials. For designers these new materials present a risk, which is typically expressed as a marked preference for the familiarity of traditional materials.

The problem still remains, that many designers lack the detailed knowledge of material behavior necessary to use engineered materials. This is largely due to the education of architects, which tends to privilege geometry over materiality. However, this education is experiencing a shift, or perhaps an extermination, towards a new understanding of materiality. Once again the ideas of Max van de Ruij, Josef Albers and László Moholy-Nagy are returning to the fore, as students are asked to design in the name of the material. Of particular relevance is Josef Albers’ Vorkurs of material studies [4], where he proposed an integrated research and design process between material and matter. Albers argued the whole potential of the material could only be achieved through its full understanding. In his course students were taught to reduce the material to its extreme to create an optimized well-balanced design (Figure 1). Recent methodologies in architecture by the likes of Achim Menges, Michael Hensel [5,6] and others [7] have re-established the ideas of performance and emergent material studies to produce new architectural strategies, which Carolin Hoffer also mentioned in 2010 [8].
In this paper we posit that to be able to apply an unfamiliar material to a design, a new level of encountering the material properties is needed. This is especially true if designers want to work with novel engineered materials. In this sense, physical experiments with the material itself are an important way of generating the necessary rules-of-thumb and gut feeling of the material's behaviour. Through material experimentation, material properties can be discovered and described as parameters that can inform digital simulation. The predicted properties of a material system create a solution space with a range of possible outcomes following Albers understanding; there is not one optimal solution there are just many different possible solutions [4]. Therefore, physical material experiments can integrate with digital design tools to better express material behaviour and either guide form-finding or assist designing with the new material observations. With the today's technology, integration and interfacings of digital and physical material systems seems more reasonable than ever: Bridging the gap between the digital and the physical world is an on-going research interest of academics and design practices (MIT Media Lab - Tangible Media Group, SMART Solutions Team - Büro Happold) [9,10]. This paper aims to contribute to this investigation by articulating a method to sense, test and visualize micro changes of materials for a better material understanding.

Therefore within this paper, we propose a method for sensing and representing the response of materials to external stimuli, at the early design stage, to help the designer establish a material awareness. The presented research reflects upon the spirit of the Bauhaus ideology of material knowledge, the so-called Materialwissen [4]. And this spirit is applied to a series of experimental architectural workshops to test the methods proposed within this paper.

![Figure 1: Paper folding experiments by Josef Albers and Students. Black Mountain College. New Haven. 1946. (photograph by Gonocoro Nato)](image-url)
2. DESIGN EXPLORATION THROUGH SENSING MATERIAL PERFORMANCE

Parametric design tools are capable simulating real-time physics to visualize material behaviour. Environmental measurements, such as measurements of sun exposure, heat, or moisture, can be used as parameters to influence model behaviour. Physical measurements of force can be used to calibrate particle spring simulations. These flexible simulation techniques, combined with simplified geometrical models, can lead to a better understanding of new materials, helping inform design decisions at an early stage. When it comes to the understanding of these materials, we need to link the physical properties to a design-oriented understanding. Robert Asch describes the design process as ‘making inspired decisions with incomplete information’ and explains the necessity of a ‘counter balance of our intuition’ with a well-developed sense of premedication [11]. Usually the collection of material properties is established via time-consuming experiments requiring the measurements of forces and strength, as well as other physical and chemical functions. This detailed data set is necessary to define a descriptive function giving the closest real material performance. However in this paper we propose that a fully accurate descriptive function of materials is not needed in the early design stages. Instead we suggest an approximation will suffice. This approximation can be informed by fast, low-tech measurements with rulers, protractors and observation, and the simulation can be conducted in particle spring simulations that give a feel for the reality of using the new material.

Developments in the last century have produced a range of sensors that can be used for recording and sensing small changes in materials. There have been a number of projects investigating the possibilities of engineered materials combined with sensors to create advanced composites that enable ubiquitous and embedded interactivity [12]. Leading examples include robots and technical wearables that can sense light, touch and the presence of bodies. The introduction of capacity sensors, in particular, has progressed the sensing and augmenting of space, which has been exemplified in projects

by Marco Coehlo (Figure 2) [13]. Leah Buechley and the Research Team of the high-Low Tech group at the MIT Media Lab [14]. The prevalent use of capacitive sensors stems from the fact that this is a technology with a relative high accuracy, ease of integration and a wide array of applications [15]. In capacitive sensors conductive materials are used to record changes in the electrical field around them with response to an interference of a conductive objects (human body and others). Applications vary from more standard uses in electrical engineering to more speculative prototyping in the case of design proposals. The relative freedom in material application and new open-source environments for interaction design make this technology most appropriate as a way to develop new scenarios for embedded computing for the built environment.
There have been a number of applications of this sensing technology applied in architectural practice, often to produce flexible and responsive tectonic skins. In Soft House by ‘Kennedy and Violich’, the flexible textile membrane (Figure 3) is used as infrastructure for natural photo-luminescent pigments, light-emitting diodes (LED) and film-anchored photovoltaic cells that control and respond to internal and external forces [14].

The use of capacitive sensors is not limited to just sensing changes in the local environment; they can also be used to measure pressure, bending and tension forces within the material. Here, measuring is not directly related to real forces but indicates the degree to which the sensor is being bent or pushed. In our research we have used this data to monitor the material and inform digital representations of the material behaviour.

This method can be adapted to provide real-time feedback for calibrating pseudo physical material simulations (Figure 4). In the pseudo physical simulation, the designer can explicitly design and specify which geometric properties they want to leave free, which they want to constrain, and how they want to link them. The spring algorithm then expresses approximate material behaviour without precisely measuring the material properties (Piker, 2011) [7]. Modifying the properties of the pseudo physical simulation with sensed data, the sensing itself becomes a design driver for architectural ideas and solution finding strategies based on the investigation.
2.1. Setup of the sensor network

While touch sensors are not a new technology, recent advances in programmable micro-controllers, such as the open-source Arduino, is making capacitance-based touch sensors a viable alternative to other expansive sensing devices. Touch can be sensed in a capacitive-sensing system through the interference caused to the electrical field surrounding an electronic conductor. A human body is filled with conductive electrolytes covered by a layer of skin and it is the conductive property of fingers that interrupts the electrical field making capacitive touch sensing possible [18]. The conductor does not literally need to be touched since the electric field extends past the surface of the conductor so anything close to the conductor is enough to register the change in current. This technique already has many different applications, such as in touch-displays. In order to apply these techniques to sense material changes we can use the predefined ‘capSense’ library by Paul Badger that turns two or more Arduino pins into a capacitive sensor which can sense the electrical capacitance of the human body. The ‘capSense’ method reports the variable values (in arbitrary units) and this can be then visualized or reused in different ways. The circuits that are needed in order to operate the sensor and to measure the sensed values are very simple and work with low currents. The integration of the capacity sensor technology into a digital design tool such as parametric software can be achieved by small and easy to build electronic circuits.

We applied capacitive-sensors to measure the material performance of two projects: Performing Skin, led by Miette Ramsay and Ayelet Karmon; and Material Behavior, led by Sacha Bohnenberger, Chin Koi Kho and Danilo Davis. In Performing Skin, the conductive fibres integrate as part of the structure of a knitted surface, while in Material Behaviour, removable conductive foam sensors are attached to the flexible surfaces of sails as seen in Figure 5.
2.2. Mapping of sensor data to graphical representations

The problem for designers working with unfamiliar materials (like sails or fashion textiles) is anticipating how these materials will behave, particularly if the required data gathering has not yet happened. The introduction of simple sensing techniques can help, but the data from the sensors needs to be represented in a meaningful way for the designer. The two workshops use Arduino micro-controllers linked with the programming environment Processing to normative data and provided targeted visual feedback (Figures 6 and 7).

Or as Robert Ash asks: “How can we augment the cognitive processes?” [11]
3. DESIGN EXPLORATION

A model of abstraction as a mediating language drives the two projects. They both use a simplified representation of materials undergoing forces visualised and fed back into the design process. This simplification is necessary in order to understand the intricate relationship between force and material system.

Within the Performing Skin Workshop different yarn types were woven together in a digitally controlled process with a CNC knitting machine. The three-dimensional knitted structure contained different material properties, which were combined with a control tool allowing the user to re-shape the knitted fabric. The second project examined how pre-fabricated sails woven from flexible material types such as Dacron, Kevlar and Mylar could be used to embed sensing as a representational and sense-making tool of the material behaviour. Here the sensor communicated the different material reactions according to the wind forces in three types of sails.

3.1. Performing Skins

Performing Skins was held as part of Smart Geometry 2011 at the Royal Danish Academy of Art. In the workshop we investigated techniques for embedding sensing in complex composites. Using knitted fabrics as a model for material thinking, we examined how CNC knitting technologies can be directly interfaced with architectural design environments. The workshop relied on techniques developed for the Listener research project [19, 20] enabling the embedding and interfacing of capacity sensing and steering of fabrication. The aim for the workshop was to build an understanding of how this localised sense-data can be integrated into the design process using dynamic material representations and be used to develop site and use specific materials.
In the workshop groups were asked to develop their own composite materials working with a range of different yarns with particular performance. By integrating clamshells that stretch and extend, polyethylene monofilaments that stiffen, and extrude, alongside natural materials such as cotton, wool and linen we experimented with the interactions between structure and material behaviour. The complex textile composites were further extended by integrating conductive fibres (Figure 8). These fibres are spun with silver filaments that enable the flow of electricity.

The conductive fibres were used for capacitive sensing. The sensing was used as a way to simulate human presence, as humidity sensors often use capacitance as part of their technology. Simulating environmental changes through human presence became a strategy for design in the workshop itself, to allow the work to be about multiple scales and multiple locations, not so much as a way to sense human presence in and of itself. By interfacing the fibres to the Arduino micro controller, readings of humidity changes in the local environment could be taken.

The first prototypes were used to generate a pool of sensed data. The workshop explored methods for integrating the sensed data with the material design process. Learning from the listener prototype, base diagrams of material structures were prepared as a means of interfacing the CNC knitting machine. The diagrams were set up in an architectural design environment (Rhino, Grasshopper and Firefly) allowing participants to directly engage and change the geometric information that informs and encodes the g-code for the CNC knitting machine. The diagrams are abstracted information models that do not directly depict the material form of the finished fabric nor the behaviour of its fibres but instead structure the fabrication data. As visual representations they are intuitive to understand and therefore easier to manipulate that the direct g-code.

Figure 8: Final Project of the Performing Skins Workshop. A CNC-knitted fabric with embedded sensing technology.
The workshop established an iterative design process in which generations of materials inform one another. As local information is gathered by the embedded sensors they inform and change the following set of material designs. In one exploration led by Sascha Bohneberger and Chin Koi Khoo, the diagram was developed to predict and simulate the material behaviour of the fabric. The diagram was reconstructed as a meshed surface, which was further tuned to produce an accurate representation of the final geometric outcome as visualized in Figure 9. The sensed data gathered from the conductive yarns of the prototypes were implemented as an interface for the diagram and, as a user feedback system, was the most striking element of the workshop. Allowing designers to directly understand the relationship between environmental impact and design change enabled prototyping different physical changes on the parametric model when the material is touched before embedding this behaviour in the material of the fabric.

![Figure 9: Real-time feedback of parametric model. Different states of topology changes according to sensed human presence.](image)

### 3.2. Material Behaviour Project

In a workshop led by Sascha Bohneberger, Chin Koi Khoo and Daniel Dave as part of the ‘Designing the Dynamic’ conference at the Royal Melbourne Institute of Technology, we conducted an investigation into forces carried through sets of different materials and reinforcement patterns. The study was inspired by the work of North Sails and their approach to designing composite fabrics that are shaped into optimised forms. The flexible yet resistant composite materials and the aesthetics of these composite materials when combined into continuous surfaces drove the design investigation. This specific material exploration of composite materials is a challenge that architects and researchers like Greg Lynn [21] and Johan Brittum [22] have investigated, although their work tends to abstract the material for design reasons.

The goal of the workshop was to quickly capture the shapes of the sails under load and use this analysis predict a better design outcome. The difficulty of simulating the nuances of textile bending stiffness, elasticity, and torsion—particularly in composite materials—necessitated the use of physical simulations. The substrate of the sails was a lightweight Mylar, which was then reinforced with various materials like Kevlar, Dacron and Mylar. The location of the reinforcing initially was based on internal force flow of the composite traditionally understood in sail making. This understanding was
supplemented by our own FEM simulation of the load paths through the
sails, which were then rationalised into cutting patterns through a
parametric modal. The fabrication process was a scaled down version of the
North Sails 3DL manufacturing process [23]. Two sheets of Mylar were
laminated together sandwiching a middle layer of the reinforcing material
(cut to shape). The lamination process forces the three layers to behave as
one new composite material.

To analyse the different performance of the sails we attempted to
measure the pressure and bending of the sail in two key locations. It was
necessary to make our own sensor for this purpose since all of the
commercially available sensors could not be attached to the sails without
having a noticeable effect on the shape due to their weight and their
stiffness. The solution was to construct a sensor from conductive foam,
which when bent or stretched changes its capacitance in a measurable way.

To sense and record the data, the sensors were linked to an Arduino
microcontroller, which sent the data via Firefly to Grasshopper. The
validation of the data was based on the comparison of the sensor mapping.
This setup allowed for three sails at a time to be measured simultaneously,
either under real wind conditions or by simulating wind with three
commercial fans (Figure 10).

The three sail rig was connected to a visualization of the live-stream of data
(Figure 11). Of the three sails developed, Sail A had the highest mean data
value, indicating it was experiencing the most pressure/bending force. The
standard deviation of these numbers indicates how the sail is catching the
wind, since a poorly performing sail will vibrate in the disrupted airflow,
casting fluctuations in the sensor values, which increases the standard
deviation. Sail B was the worst in this regard. This data tells a very valuable
story about the performance of the sails, the subtlety of which would be
lost in a purely digital simulation, while the detail would be invisible to
someone inspecting the sails in a purely physical manner. It is only through
bridging this gap a better understanding of the original Sail C occurs and
can be developed further in regards for better wind drag performance.
4. CONCLUSION

The increase in new materials presents a challenge for designers who want to take advantage of the performative gains but lack the familiarity with the materials to confidently design with them. In this paper we have explored two projects that begin to articulate how designers can combine early stage prototypes with inexpensive electronic sensors to inform their digital design process.

Performing Skins demonstrates how surfaces can be revised based on user interaction. In this case through sensing the touch of the user and generating a new CNC-Knitting patterns to engage with this interaction. The sensing of the sail in the Matal Behaviour workshop has a very different outcome. Here the sensors are used to gather preliminary performance data that would be impossible to gather through digital simulations and that was too sensitive to capture without embedded digital sensors.

This early stage feedback on material performance necessitates a bi-directional link between digital and analogue models, where sensed changes in material behaviour of either model is feedback into the system to give a more full understanding of the project's early stage performance.

Furthermore through the haptic-intuitive engagement with materials and the described way of representing the material performance a new understanding of the material performance is formed. These types of linkages between the digital and the physical world have the potential to change how designers engage with materials by enabling them to embrace...
the unfamiliar with the confidence they will be able to tune the system to capture its full benefit.

In architecture this strategy is not only helpful for gaining a better knowledge of novel materials but can also be thought of as an design and control system for adaptive architecture with an imbedded feed-back system to react to environmental changes.

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Sensing Material Systems - Novel Design Strategies
A6 – Research Time-Line


1. Competitions
   - Hermes Wood Pavilions
   - Structural Timber Design
   - Digital + multi-criteria approach
   - Cross-cooperation with fabrication

2. Framework
   - Defining Research Method
   - Material Development and Its Impact on Architecture
   - Material History
   - Contemporary Material Development and Challenges for Architecture
   - Discussion of Multi-functional Materials and Their Possible Applications

3. Material Design + Research
   - Material Research
   - Computational Design
   - Structural Design

4. Online Survey
   - Micro-Synergies
     - Participatory mapping of real-time interactions and reactive environments.
     - A combined design strategy of digital, computational and tangible making.
     - Material exploration with advanced technology.

5. Throughout the Design
   - Designing the Dynamics
     - Exploring mixed techniques of representing material behavior.
     - Developing micro-sensors for lightweight and flexible materials.

6. Parts in Red
   - Testing workshops and computational design with "smart materials" building working prototypes.
   - Developing the idea of augmented composites.

7. Influencing Practice
   - Micro-Interactions
     - Why are innovative materials and technologies attractive to you and your work?
     - What do you think of smart materials related to architecture?
     - What is your decision process for choosing materials for your design? At what stage does that usually happen?
     - What are the obstacles for applying results from material research in an everyday context?

8. Evaluation and Reflection
   - Reflecting on Background Research
   - Evaluation of research and project work
   - Developing concepts for engaging with novel materials
   - Discussion of my project and its context
   - Reflection of project work
   - Future potential and further research

Appendix
A53
A7 – Smart Materials in Architecture
References

The list does not aim to be complete rather it gives a comprehensive overview to emphasis the increasing appearance of architectural ideas engaging with smart material systems:

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Hylozoic Grove


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