The Creative Potentials of Modelling

Models, Model-use, and the Activity of Modelling as Methods in Structural Design

Johanna Ruge

The Creative Potentials of Modelling.
Models, Model-use, and the Activity of Modelling
as Methods in Structural Design

Johanna Ruge

Dissertation

Design and Analysis of Structures || HafenCity University Hamburg

Supervisors:
Prof. Dr.-Ing. Annette Bögle
Prof. Dr. Kathrin Wildner
Prof. Dr.-Ing. Mario Rinke

DOI: 10.34712/142.44

Acknowledgements

I started this dissertation in 2018 – exactly five years ago. Looking back, I have learned a lot during this time, both professionally and personally, and I have much to be grateful for, especially the many people who have supported me along the way.

First, I want to thank my supervisor Annette Bögle, who has introduced me to the topic of structural design and creativity in engineering, and thus awakened my interest in this field of research and encouraged me to pursue a topic in it. Thank you for your professional guidance and advice, for challenging me and for helping me to grow during the last five years. Furthermore, I thank my additional supervisors, Kathrin Wildner and Mario Rinke, for their support and valuable feedback.

This dissertation is an empirical study on the generation of creativity during modelling activities in structural design, based on over 40 qualitative interviews with structural engineers and a four-week participatory observation in the engineering office Bollinger Grohmann Vienna (B+G). I owe immense thanks to each of my interviewees and the people at B+G, who have met me and my research with curiosity and openness, and who have contributed significantly to it with their time and experience.

In this line, it is important to say that I did not have any experience with qualitative methods before I started my PhD. The work in an interdisciplinary research project together with researchers from the social sciences for the first 2.5 years of my doctorate allowed me to acquire these methods. I am grateful to all of my colleagues in this project, from whom I have learned a lot about methodology and research in general. Particularly, I want to thank Venetsiya Dimitrova, my sparring partner for several years, who has also kindly commented and proofread this thesis, and Joachim Thiel, from whose experience and evaluations I have benefitted multiple times.

During the last 2.5 years of my doctorate, I was supported by the Studienstiftung des Deutschen Volkes – something I am particularly grateful for. Their scholarship allowed me to really focus on my dissertation – a privilege I very well know is not granted to everyone pursuing a PhD.

Multiple other people have also supported me with advice, feedback, and help, whether content-wise, methodologically, or personally. Particularly, I want to thank Ingrid Breckner for her methodological advice and the time and energy she invested in supporting me. Further, I thank all of my colleagues from the chair of design and analysis of structures for the many conversations on our PhDs, life, and everything in between, and my friend Hanna, who – in addition to her personal support – has also helped me with valuable comments on my thesis.

Last but not least, I want to thank my family, Hanna-Maria, Jürgen, and Sophia, and my friends. Finally, I thank my partner Benedikt, who has supported me in many different ways, on many different levels, uncountable times – by giving me advice, inspiring me, making me laugh even when I didn’t want to, and reminding me to not take everything so seriously. Thank you for everything.

Abstract

This dissertation deals with the creative potentials of model-use and modelling understood as methods in the structural design process. Hereby, structural design is considered as the creative process of developing a load-bearing concept for a structure or building. While previous research on the structural design process was largely based on specific examples, an abstraction to the methods used in the process is so far lacking. Specifically, there is a lack of knowledge on which methods contribute to the generation of creativity; yet creativity is a crucial prerequisite for addressing the multiple challenges the construction sector is currently facing, such as the transformation towards sustainable construction. Previous research suggests that the use and development of models representing the structural design or parts of it play an important role for the generation of creativity within structural design. However, an in-depth understanding of how model-use or modelling are related to the generation of creativity is lacking.

This dissertation aims to shed light on the generation of creativity in structural design. Particularly, it focuses on model-use and modelling as central practices of this process. Hereby, the model is seen as an agent with a generative capacity and the ability to actively contribute to the structural design process. The goal is to generate a better understanding of models, model-use and modelling as methods in the structural design process, and of their contribution to the generation of creativity. The main research question is: *What are the creative potentials of model-use and modelling in structural design, and how can they be comprehended conceptually in a method of modelling?*

To answer this research question, the dissertation combines different qualitative methods from the empirical social sciences with an interdisciplinary literature review in a grounded theory process. First, qualitative interviews with structural engineers were conducted. The interviews centred on the structural design process, its underlying methods, model-use and modelling, and their contribution to the generation of creativity. Second, a participatory observation of modelling practices in an engineering office was carried out. The empirical data was analysed using different coding techniques and comparative analysis. The generated findings were compared and contrasted with findings from an interdisciplinary literature review on models and modelling in the fields of structural design and philosophy of science and technology, and further validated using triangulation, expert validation, and peer debriefing.

The dissertation provides multiple insights on methods practising engineers employ in the structural design process and particularly on model-use and modelling. First, central mechanisms inherent to models are specified, as well as their effects and impacts on design development and communication, which are the main goals in the structural design process. Second, three ideal-typical translation processes – content-centred, communication-centred, and environment-centred – are identified, which can be conceptualised as the basic elements of the activity of modelling. Third, two different practices of modelling, namely an engaging with either the model content or the model environment, are described. As a synthesising result, a method of modelling is developed, which aims to provide orientation to engineers engaged in structural design processes.

Through these findings, the dissertation provides with a better understanding of models, model-use, and modelling in structural design, as well as of different strategies for creativity for structural design processes. Conceptually, implicit knowledge is made explicit and thus available for further reflection or application, namely knowledge on the structural design process and on model-use and modelling as methods within it. With respect to structural design practice, this could help to interact with models in a way that makes use of their creative potentials or lead to the development of modelling tools that appropriately respond to the working practices of structural engineers. Methodologically, the dissertation contributes by providing an in-depth and detailed example case of how qualitative methods from the empirical social sciences can be applied in the structural engineering context to generate new findings. Overall, the dissertation thus contributes on several levels to the state of research on models and modelling and the generation of creativity in structural design.

Kurzfassung

Diese Dissertation befasst sich mit den kreativen Potenzialen der Modellnutzung und der Tätigkeit des Modellierens als Methoden im Tragwerksentwurf. Der Tragwerksentwurf wird dabei als kreativer Prozess verstanden, bei dem eine tragende Struktur für ein Bauwerk entwickelt wird. Bisherige Forschung zum Tragwerksentwurf basiert weitgehend auf Beispielen – ohne von diesen Methoden zu abstrahieren. Insbesondere fehlt das Wissen, welche Methoden zur Entstehung von Kreativität im Tragwerksentwurf beitragen. Kreativität ist jedoch nötig für die Bewältigung der Herausforderungen, die sich der Baubranche aktuell stellen, beispielsweise durch die nötige Transformation zum nachhaltigen Bauen. Bisherige Forschung suggeriert, dass die Verwendung oder die Entwicklung verschiedener Modelle, die den Tragwerksentwurf oder Teile dessen repräsentieren, eine zentrale Rolle für die Entstehung von Kreativität spielen. Allerdings mangelt es an einem Verständnis dafür, wie genau die Modellnutzung und das Modellieren zur Generierung von Kreativität beitragen.

Die Dissertation beleuchtet ebendiese Entstehung von Kreativität im Tragwerksentwurf. Dabei fokussiert sie auf die Modellnutzung und das Modellieren als zentrale Praktiken dieses Prozesses. Modelle werden als Agenten mit produktiven Fähigkeiten betrachtet, die aktiv zum Tragwerksentwurf beitragen. Ziel ist es, ein besseres Verständnis von Modellen, der Modellnutzung und dem Modellieren als Methoden im Tragwerksentwurf sowie von deren Beitrag zur Entstehung von Kreativität zu entwickeln. Die Hauptforschungsfrage lautet: *Welches sind die kreativen Potenziale*

der Modellnutzung und des Modellierens im Tragwerksentwurf und wie können diese konzeptionell in einer Methode des Modellierens erfasst werden?

Um diese Forschungsfrage zu beantworten, wurden qualitative Methoden der empirischen Sozialforschung mit einer interdisziplinären Literaturrecherche in einem Grounded Theory-Prozess kombiniert. Zunächst wurden qualitative Interviews mit Tragwerksplanenden durchgeführt. Die Interviews fokussierten den Tragwerksentwurf, die ihm zugrundeliegenden Methoden der Modellnutzung und des Modellierens sowie deren Beitrag zur Entstehung von Kreativität. Darauf aufbauend erfolgte eine teilnehmende Beobachtung von Modellierungspraktiken in einem Planungsbüro. Die empirischen Daten wurden mithilfe verschiedener Kodierungstechniken und vergleichender Analysen ausgewertet. Die resultierenden Erkenntnisse wurden mit den Ergebnissen einer interdisziplinären Literaturrecherche zu Modellen und der Tätigkeit des Modellierens in den Bereichen Tragwerksentwurf und Wissenschafts- und Technikphilosophie verglichen und mittels Triangulation, Expertenvalidierung und Peer-Debriefing weiter validiert.

Die Dissertation liefert zahlreiche Erkenntnisse zu den Methoden von Tragwerksplanenden im Tragwerksentwurf, insbesondere zur Modellnutzung und zum Modellieren. So werden erstens zentrale modellimmanente Mechanismen sowie deren Auswirkungen auf die Entwurfsentwicklung und Kommunikation, zwei Hauptziele im Entwurfsprozess, spezifiziert. Zweitens werden drei idealtypische Übersetzungsprozesse – inhalts-, kommunikations- und umgebungszentriert – identifiziert, die als Grundelemente der Tätigkeit des Modellierens betrachtet werden können. Drittens werden verschiedene Praktiken des Modellierens beschrieben. Als synthetisierendes Ergebnis wird eine Methode des Modellierens entwickelt, welche Tragwerksplanenden als Orientierung in Entwurfsprozessen dienen kann.

Anhand dieser Ergebnisse vermittelt die Dissertation ein besseres Verständnis von Modellen, der Modellnutzung und der Tätigkeit des Modellierens sowie von verschiedenen Kreativitätsstrategien im Tragwerksentwurf. Auf konzeptioneller Ebene wird implizites Wissen über den Tragwerksentwurf sowie über die Modellnutzung und das Modellieren als Methoden dieses Prozesses explizit und somit für weitere Überlegungen und Anwendungen verfügbar gemacht. Im Hinblick auf die Entwurfspraxis könnte dies zu einer Interaktion mit Modellen führen, die kreative Potenziale nutzbar macht, oder zu einer Entwicklung von Werkzeugen, die die Arbeitsweisen von Tragwerksplanenden unterstützen. Ein zusätzlicher methodischer Beitrag besteht in der Darstellung eines umfassenden und detaillierten Fallbeispiels, welches aufzeigt, wie qualitative Methoden der empirischen Sozialforschung im Kontext des Ingenieurwesens angewendet werden können. Insgesamt trägt die Dissertation somit auf mehreren Ebenen zum Stand der Forschung zu Modellen, der Tätigkeit des Modellierens und der Entstehung von Kreativität im Tragwerksentwurf bei.

Contents

Engineers ought to understand their work as creative because it requires choices.

–Eric Hines, *Understanding Creativity, 2012*

1 Introduction

Structural engineering is a creative profession. This becomes most evident in the task of structural design, which refers to the development of a concept of how loads are carried by a structure. Structural design is characterised by its conceptual nature and by the fact that it "connects seemingly contrasting fields such as art and science, intuition and empiricism" (Rappaport, 2017), and thus requires "not only logic and scientific but also creative and inductive ways of thinking" (Kloft, 2014). However, the creative and conceptual part of structural engineering receives little attention by the public, by engineers themselves, or by other professionals structural engineers collaborate with, such as architects (Addis, 1997). In the public, the engineer is often perceived as a "sharp thinker" (Lang & Hellstern, 2017), as a "problem solver" (Koen, 2009), or as being "narrowly focused on technical issues" (Petroski, 2011). The field of engineering is situated in a mathematical or empirical realm, while the creative potentials are undervalued (Rappaport, 2017). What is more, according to Addis (1997), "many architects [...] see their job as developing fully conceived structures for the engineer to 'make work' or to 'size' [...]. And it must be admitted that many engineers actively or inadvertently encourage this view of their role."

The author claims that it is important that structural engineers consider their work as creative for two main reasons. First, it highlights the fact that their work is not merely objective and subjected to boundary conditions and constraints, but that it requires individual and subjective choices (Hines, 2012). Thereby, understanding the structural engineer's work as creative sheds light on the responsibility every structural engineer has for the choices they make in everyday work life. In short, understanding structural design as a creative endeavour urges structural engineers to assume responsibility for how they fulfil their tasks. Second, understanding one's own work as creative is a prerequisite in order to be creative at all and to foster creativity, which is inevitably needed to address the multiple challenges the construction sector is currently facing.

With respect to the first aspect, the importance of structural engineers assuming responsibility for their work stems, for one, from its "central, civilizational significance" (Lang & Hellstern, 2017). By building bridges, tunnels, streets, and rail-way tracks, dams, wind parks, and power production plants, as well as buildings of every kind, structural engineers contribute immensely to the functioning of societies. Traffic infrastructure is needed to transport people and goods, power production plants satisfy the growing demand for energy, and buildings provide secure spaces to live and work in (Billington, 2014; Eibl et al., 2006; Hahn, 1996; Lang & Hellstern, 2017; Vossenkuhl, 2017).

Additionally, assuming responsibility is important as the work of structural engineers highly impacts the natural and built environment, and thus the everyday lives of present and future generations. This becomes most apparent in the fact that the construction sector largely contributes to the human-made climate change. For instance, the construction sector is responsible for approximately 37 % of the worldwide CO_2 emissions and for the consumption of one third of the worldwide produced energy (United Nations Environment Programme, 2022). What is more, structural engineers have the potential to influence these numbers. For instance, a recent study has shown that the decisions made by structural engineers in the design of structures can indeed greatly influence the global warming potential of their structures (Krinitzki, Kaczorowski, & Hartz, 2023).

Thus, the central significance and high impact of their work inflict a high responsibility on structural engineers towards society, something which has already been acknowledged in the Dresdner Moralkodex (Dresden code of ethics) from 1998. The code states that "Europe's engineers carry out their work with responsibility towards humanity, the environment and themselves. Their work serves the well-being and development of society" (Dresdner Moralkodex, as cited in Gebbeken, 2020). Today, particularly against the backdrop of climate change, it is more crucial than ever that structural engineers understand this responsibility and assume it through designing and shaping their structures accordingly. Hereby, neglecting the creative part of the profession, as outlined above, is hindering. In this respect, Hines holds that "engineers ought to understand their work as creative because it requires choices" (Hines, 2012). Conversely, it can be stated that understanding one's work as a creative endeavour that requires personal choices and decisions is a key prerequisite to assume the responsibility for one's work and its impacts.

With respect to the second aspect, understanding structural design as a creative endeavour not only urges engineers to assume responsibility for their work – it also empowers them to develop creative solutions at all. Such creative solutions are inevitably necessary to address current challenges, which are not limited to the transformation of the construction sector to meet sustainability goals. They further include population growth, urbanisation, migration, or the digitalisation of the whole value chain and the hereby inflicted changes in planning culture, professional responsibilities, execution and manufacturing processes, among others (e.g., Deutsch, 2017). In the light of these challenges, the structural engineering profession is experiencing significant shifts. One example is that the task of the engineer changes from planning new structures to building in existing contexts, which includes restorations, renovations, and refurbishments of structures, as well as 'design for disassembly' (e.g., Rios, Chong, & Grau, 2015) or 'design for re-use' (e.g., Baker-Brown, 2017). Additionally, structural engineers will need to deal with new construction materials that are locally available and exert a low global warming potential (e.g., Jones, Mautner, Luenco, Bismarck, & John, 2020). These shifts require structural engineers to adapt their planning approaches, from linear processes to circular ones. Overall, the current challenges result in a growing demand for sustainable structures, for innovative solutions that respond to the mentioned challenges, as well as in a need for revisiting established working methods (e.g., Deutsch, 2017; Ochsendorf, 2016). Therefore, the current challenges force engineers to be more creative, as creativity is needed not only to develop sustainable and innovative solutions, but also in order to adapt to changing circumstances, no matter what they are specifically (e.g., Addis, 1997; Eibl et al., 2006; Kloft, 2014; Langer & Böhrnsen, 2014).

In this dissertation, the hypothesis is that to assume their responsibility towards society, structural engineers first need to be aware of their own scope of action. This means that they need to understand the structural design process as a creative task with the possibilities to design and shape. Second, they need to know how to develop creative solutions that address current and future challenges. This means that they need to understand how creativity can be generated in structural design processes. Creativity, as understood in this dissertation, is hence characterised by two aspects. First, creativity means the ability to generate an individual and personal solution to a given problem. This solution cannot be objectively developed through mere deduction from given constraints or boundary conditions, but instead requires a subjective and inductive process. Second, creativity is not understood as the generation of an outstanding result, as it is the case, for instance, in the context of 'structural art' (Billington, 2014). Instead, creativity refers to the ability to adapt to changing circumstances, and thus to the proficient employment of approaches and methods that foster creative solutions in a structural design process.

In line with this, this dissertation aims to generate a better understanding of the structural design process as the creative part of structural engineering. To this end, it focuses on the underlying methods of structural design and their contribution to the generation of creativity. This focus on methods is emphasised by Duddeck, who states that as "it is impossible to teach future technologies which are yet non-existent," it is "fruitful to teach general ways of thinking and working, that will also be of value in the future" (Duddeck, 2002, p. 104). Specifically, the dissertation focuses on model-use and the activity of modelling as methods for creativity in the structural design process.

The role of models has been highlighted by many scholars and practitioners (e.g., Addis, 1988; Duddeck, 2001; Hossdorf, 1963; Schlaich, 1991). Duddeck even states that working with models can be regarded as the "core of the engineering profession" (Duddeck, 2002, p. 90). Structural engineers need models, first, because they deal with structures that do not yet exist, second, because these structures are too big and expensive to analyse directly, and third, because the behaviour of structures and their materials is often complex and partly unknown. In this respect, Schlaich states that without "models of abstraction and simplification, [the engineer] would be completely subject to trial and error" (Schlaich, 1991).

Due to their everyday use in structural design, models are often viewed as 'tools' (this is explained in more detail in Chaper 3.1.1). There are multiple publications that reproduce this notion, for instance, on the history of model-use in structural design (see e.g., Addis, 2021), or on specific types of models and their correct employment. In contrast, other disciplines, such as architecture or product development, see models in design contexts as artefacts that enhance generative capacities and creativity, and that are therefore much more than mere tools (see e.g., Gänshirt, 2020). Following this notion, this dissertation questions the understanding of models as tools and aims to develop a broader model-understanding for conceptual structural design, meaning the dissertation aims to re-define the perception of what models are and how they are used in the early stage of structural design. To this end, model-use and the activity of modelling are understood as methods, which can spur the generation of creativity in structural design processes. Hereby, model-use refers to the employment of already established models, while modelling refers to the development of new models. The dissertation analyses how creativity evolves in the interaction between engineer and model and how different types of this interaction shape the process of structural design. Hence, the model is not perceived as a passive object but instead as an active agent that contributes to the generation of creativity through interactions with the design engineer. Overall, the dissertation aims to develop an understanding of what characterises models in structural design, of their role within the process, and of the creative potentials of model-use and the activity of modelling. Thus, the main research question is:

What are the creative potentials of model-use and modelling in structural design, and how can they be comprehended conceptually in a method of modelling?

To answer this question, model-use and the activity of modelling in the structural design process were investigated from an external perspective. The aim was to detach implicit knowledge on modelling activities that happen in the mind or unconsciously from their performers and make it explicit. To this end, this dissertation combines different qualitative methods from the empirical social sciences with an interdisciplinary literature review in a grounded theory framework. First, to include the perspective of structural engineers, qualitative interviews with structural engineers were conducted. The interviews focused on the structural design process, its underlying methods, model-use and modelling, and their contribution to the generation of creativity. Second, a participatory observation of modelling practices in an engineering office was carried out, in order to directly observe the interaction between structural engineers and models. The empirical data was analysed using different coding techniques and comparative analysis. The generated findings were compared and contrasted with findings from an interdisciplinary literature review on models and modelling in the fields of structural design and philosophy of science and technology, and further validated using triangulation, expert validation, and peer debriefing.

The approach of this dissertation can be characterised as 'reflexive design research', which aims at a better understanding of the structural design process and the methods of model-use and modelling through an analysis and description of the process without influencing it. Hereby, the focus is on the process rather than on the final structure as its outcome. The reflexive approach can be differentiated from other forms of research on design processes, specifically the applied design research, which looks at the process from the perspective of its outcome and aims at optimised product development, and the practice-based design research, which uses design itself as a research method (Ammon & Froschauer, 2013). With its main focus on model-use, modelling, and the interaction between model and design engineer in the structural design process, the dissertation can be seen in the context of a number of other studies with a similar focus (see e.g., Gänshirt, 2020; Häußling, 2016; Henderson, 1999; Liptau, 2018).

The results of the research are presented in the main part of this dissertation. First, Chapter 2 presents a short characterisation of the structural design process as the context for model-use and modelling. Hereby, a special focus is placed on creativity as an outcome but also as an attribute of the process, as well as on the methods used in structural design processes.

Building on this contextualisation, Chapter 3 presents the state of research on the model as an object in the design process, on the activity of modelling, and on the question whether models have some sort of agency of their own. The chapter builds on literature from two distinct fields, structural design and philosophy of science and technology. Thereby, the chapter explores how philosophical perspectives might inform and improve the understanding of models and modelling within the context of structural design (see also Bucciarelli, 2002). From the literature review, three main conclusions are drawn: First, there is little empirical evidence on the relation between model-use and modelling as methods and creativity, even though the process of structural design is generally perceived as creative and model-use and modelling can be regarded as its central methods. Second, the creative use of models in early conceptual structural design remains vague and black-boxed. Third, the active potentials of models and the resulting role of the model in the structural design process are not explicitly dealt with.

Based on the theoretical fundament established in Chapters 2 and 3, the research gaps and the corresponding research questions of the dissertation are formulated in Chapter 4. It states the goals to shed light on models and the activity of modelling as well as to develop a better understanding of their role in the structural design process and of their contribution to creativity. The identified research gaps are specified, namely the general lack of conceptual research on methods in the structural design process and their connection to creativity, and the specific lack of research on models and modelling understood as methods in the structural design process. Further, the main research question as well as three sub-questions are presented, which refer to the model understandings of engineers, the embodied practices of modelling, and the method of modelling, respectively.

Chapter 5 introduces the qualitative empirical social science methods that were employed to answer the research questions of this dissertation. These methods were chosen to reflect the qualitative nature of both the research objects – the structural design process, model-use, and modelling – and the research questions. The first part of the chapter gives an overview of the overall research design and the specific methods that were employed. Furthermore, it delivers the methodological rationale for the research design. The second part describes how these methods were employed in the inductive research process of the dissertation. Lastly, the third part presents in more detail the context of a case study on modelling practices in an engineering office.

Chapter 6 constitutes the core chapter of this dissertation and presents the results of the empirical research in three sections and a synthesising forth section:

- The first section deals with the structural design process as the context for model-use and the activity of modelling. Based on findings from the qualitative interviews, it focuses on the design engineer and their contribution to the generation of creativity within this process. To this end, the task, skills, and influence of the design engineer, and the different working modes and strategies they employ in the structural design process are described. In an intermediate reflection, the interrelations between these aspects are made explicit and the model's role in the design process is highlighted.
- Tying in with these insights, the second section takes a closer look at the model, its use, and its contribution to the generation of creativity in the structural design process. This is done from the perspective of the design engineer that was obtained through the interviews. The section analyses the terminologies used by design engineers to describe their models, why and how models work and which effects and impacts they have on structural design processes, and how engineers critically evaluate the models they use. Based on this analysis, a qualitative definition of models in structural design is developed, and their role for the generation of creativity in the structural design process is assessed.
- In the third section, the focus shifts from the model as an object to the activity of modelling. This section largely builds on findings generated in the participatory observation. It conceptualises the activity of modelling as an interaction between the design engineer and the model, and analyses its contribution to the generation of creativity. Two different types of modelling practices are described, namely engaging with the model environment or with the model content. The section concludes with an intermediate reflection on the different

forms of interaction between engineer and model in these practices and the practical nature of modelling.

- The synthesising section establishes relations between the three previous sections and presents a conceptualisation of model-use and modelling as methods in the structural design process.

The empirical findings and the methodological approach that was employed to generate them are discussed in Chapter 7. In the first part, the creative potentials of modelling practices are debated, as well as how they can be strategically employed in the context of structural design. Secondly, building on the notion that modelling is a highly practical activity, the contribution and benefit of a broad model understanding and of viewing model-use and modelling as methods is assessed from a conceptual perspective. Lastly, the methodological approach employed in this dissertation is analysed. By reflecting on challenges and potentials, the contribution and relevance of a qualitative empirical social science approach for research in structural design is discussed, and research areas are identified in which a further application of this methodology would be fruitful.

The closing Chapter 8 presents a short summary of the findings and contributions of the dissertation, outlines its practical relevance and points to some limitations as well as to trajectories for further research. Furthermore, it refers back to the responsibility of the structural engineer that was emphasised in this introductory chapter, and puts the results of the dissertation in this more general and overarching context.

Structural engineering expressed through conceptual design means to combine knowledge with intuition, experience with fantasy and aims at inventing an efficient structure including a unique form.

–Jörg Schlaich, *On the Conceptual Design of Structures*

2 The Structural Design Process as the Context for Model-Use and Modelling

This chapter presents a short synopsis of the structural design process as the context for model-use and modelling investigated in this thesis. Its three sections each deal with one aspect of central importance to this dissertation: first, the nature and characteristics of the structural design process; second, creativity as an desired outcome but also as an attribute of the process; and third, the *how* of the structural design process, meaning its underlying methods.

2.1 Nature and Characteristics of the Structural Design Process

Design is an elusive word, which means that its meaning shifts with speakers, listeners, and context (Bucciarelli, 1988). In order to better understand the structural design process, this section summarises some overarching properties of design processes in general. On that base, the specificities of the structural design process are outlined.

First, in any design process, something is developed which has not been there before. In line with this, Morris states that "design is the power to create, to transform an idea from one's mind into something that is tangible" (Morris, 1999). Second, design processes have often been related to solving problems. Hereby, the problem is usually wicked (see e.g., Coyne, 2004; Rittel & Webber, 1973). This means that the problem is not objectively given but instead loosely formulated, subject to redefinition and re-solution. In consequence, the design process is usually open-ended and multiple solutions are possible that are better or worse rather than right or wrong (Parthenios, 2005). Furthermore, many researchers agree that design is not a formal process but instead a social one that is highly influenced by personal interactions (see e.g., Bucciarelli, 2002; Bucciarelli, 1988; Ferguson, 1993, p. 41; Schön, 1993). The process is further described as complex and defined by chances (Ferguson, 1993, pp. 41-45). Gerricke and Blessing summarise that design processes are characterised by mental processes, human interactions, iterations, constraints, and a co-evolution of problem and solution (Gericke & Blessing, 2011).

Despite the fact that "not two artefacts are designed in the same way" (Boulanger, Gelle, & Smith, 1995), there have been multiple attempts to describe the design process with process diagrams (Gericke & Blessing, 2011). Such diagrams are "non-exhaustive descriptions of the key elements of the design process and provide a framework of important design aspects" (Boulanger et al., 1995). The by far most common type of process diagram depicts the design process as a sequence of steps. Howard, Culley, and Deckoninck (2008) deliver an overview and comparison of different design process conceptualisations, and identify the four most common stages as "analysis of task, conceptual design, embodiment design, and detailed design" (see Figure 2.1). These steps are understood as iterative and cyclic (Howard et al., 2008).

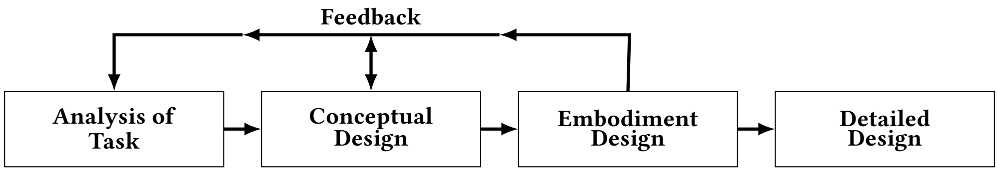


Figure 2.1. Example for a process model of a design process, adapted from Howard et al. (2008).

Another way to describe the structural design process is based on the activities designers perform or the strategies they employ (Gericke & Blessing, 2011). Hereby, an activity refers to a subdivision of the process that can reoccur several times in an individual designer's process, for instance, 'generating', 'evaluating', or 'selecting'; a strategy refers to a sequence in which design activities or stages are carried out (Gericke & Blessing, 2011).

The structural design process is a specific type of design process. The development of a load-bearing structure – or the birth of a structure, as Schlaich (2000) describes it – is a substantial part of structural engineering (Kloft & Hoyer, 2014). How the loads are carried by the structure as well as the concept, design, arrangement, and dimensioning of structural elements and joints have a high influence on the appearance, aesthetics, efficiency, economy, sustainability, and durability of a structure. Thus, several engineers, researching as well as practising, have described the nature as well as the process of structural design. Some attributes assigned to the the structural design process are, for instance, that it is a creative endeavour (see e.g., Kloft & Hoyer, 2014), or that it exerts an inductive nature and involves multiple decisions (Polónyi, 1987). These aspects are in convergence with the aforementioned general aspects of design processes. However, in order to describe the specific nature of structural design, the distinct features of design in this context have to be considered.

First, the structures that are developed are usually large in size, immobile, and fulfil a long-term function. Therefore, the relation to the context – both geographic and social – for which a structure is developed plays a special role in structural design.

Closely related to this is the fact that each structure is a one-off, a major and very specific aspect of design in the built environment context.

Second, the effects and impacts of a specific structural design usually cannot be tested or exactly preconceived for the unique configuration of a specific structure. This is closely related to the first aspect, the one-off character and the large size of the structures, and distinguishes structural design from other design contexts, such as automobile or furniture design. Not being able to test the future design products is particularly relevant with respect to safety issues. These play a crucial role in the structural design context, as failure often has grave or even fatal consequences. In this respect, Addis states that "to design a structure it is necessary to imagine every conceivable type of failure and then ensure that each one is prevented" (Addis, 1994, p. 14). Due to the one-off-character of every structure and the lack of testing opportunities, guaranteeing safety is a complex issue. A common means to ensure sufficient safety is, for instance, the application of norms that provide with standardised procedures, recommendations, and safety factors.

The crucial role of safety in the structural design context leads to the fact that even though engineers have to take into account numerous aspects such as the functionality, aesthetics, and economy of their designs, they often mainly concentrate on structural safety. This matter is also reflected in engineering education, which mainly focuses on developing expertise in mathematics, mechanics, or material sciences (Billington, 2014; Krafczyk, 2014). The focus on 'hard sciences' in engineering education and the use of standardised design procedures as prescribed in codes and norms is in contrast to the perspective provided by Duddeck that to achieve a good design result, the whole structure as well as the sum of possible effects on it have to be considered in one integral, creative design (Duddeck, 2002, p. 47). This statement introduces a new perspective on the design process, namely seeing design as a skill, which can be comprehended by examining the thought processes and actions that are needed to design, such as to analyse, conceive, propose, evaluate, choose, justify, and communicate (Addis, 1990, p. 73-74). Furthermore, this perspective poses significant requirements on the structural design engineer, such as experience, analytical skills, ingenuity, and communication skills (see e.g., Addis, 1994; Morris, 1999). As a result, structural design processes can further be characterised as highly individual processes that largely depend on the responsible engineer (Addis, 1990, p. 45).

Due to their individual nature, design processes have previously often been described based on specific examples of practice (see e.g., Bögle, Cachola Schmal, & Flagge, 2005; Flury, 2012; Stiglat, 2004). A comprehensive and more general account on the "nature and theory of structural design" has been delivered by Addis (1990). In this account, Addis puts forward that even though structural design can be described as a series of linked activities, including feedback loops to represent the trial and error nature of design (Addis, 1990, p. 37; Addis, 1994; Duddeck, 2001), each design process has to be developed according to the specific problem at hand by the engineer and there is not necessarily a causal connection between design procedure and output (Addis, 1990, pp. 44/46). Due to this contingent nature of the structural design process, Addis suggests to examine the input and the output of the process as well as the influences on it in order to understand it better (Addis, 1990, p. 37, see Figure 2.2):

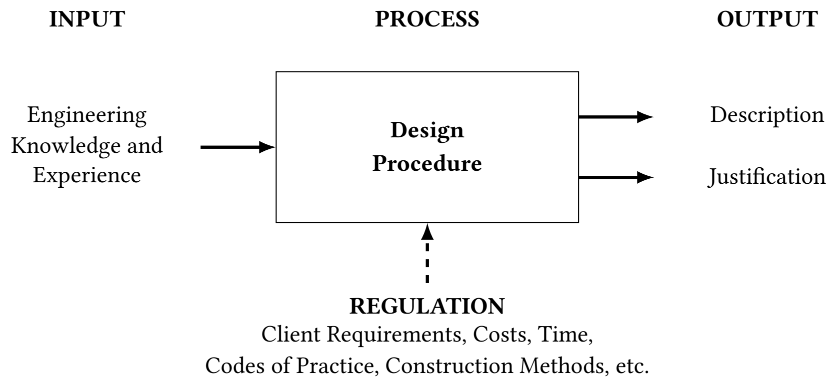


Figure 2.2. Scheme to conceptualise the structural design process proposed by Addis (1990): Instead of describing the process as a series of linked activities with iterations and feedback loops, the design procedure itself is black-boxed; instead, the input, output, and influences on the process are examined.

- The input can be described as the knowledge, experience, and intuition of the engineer (Addis, 1990; Schlaich, 2000). Examples of engineering knowledge are, for instance, physical laws, theories, data and rules, experiments, codes, or generally accepted practices (Addis, 1990, pp. 44/45).
- As the output and principal function of the structural design procedure, Addis names the description and justification of the proposed design (Addis, 1988; Addis, 1990, p. 37). The two outputs are interrelated, for instance, when the method of justification influences what is designed in the first place (Addis, 1990, p. 42).
- Aspects influencing the structural design are, for instance, the clients brief, the architects design, codes and regulations, the availability of materials, construction time and cost, workmanship availability, ground conditions, or the climate (Addis, 1990, p. 38; Addis, 1994, p. 14).

However, while the conceptualisation in Figure 2.2 helps to contextualise structural design processes, it also ultimately leads to the process itself being black-boxed.

To summarise, the structural design process can be defined as a type of design process with the aim to develop a load-bearing structure. The process can be compared to solving an ill-defined or wicked problem, for which multiple different solutions exist that are better or worse rather than right or wrong. Furthermore, it follows an inductive logic and requires multiple decisions of the design engineer. The multitude of objective as well as subjective dependencies, such as boundary conditions or the skills of the responsible engineer, make the process contingent and complex. In previous literature, the design process has usually either been described based on example cases, which results in a lack of methodological abstraction, or else been back-boxed or predefined, which leads to a neglection of its contingent nature.

2.2 Structural Design and Creativity

Design in general is often self-evidently associated with creativity. For instance, Howard et al. (2008) claim that creativity is an integral part of design processes and that it is the prerequisite for innovations. However, in the context of structural engineering, creativity is not as naturally acknowledged as an integral part. As Addis points out, engineers are often seen as technicians rather than creative designers, and that this role is promoted by many engineers themselves (Addis, 1997). This is why multiple researching and practising engineers stress the role of creativity in the structural design process (see e.g., Gavreau, 2019; Hines, 2012; Kloft & Hoyer, 2014; Schlaich, 1991). For instance, Jörg Schlaich formulates that "the appeal of structural engineering is that it combines rationality with creativity" (Schlaich, 1991). With respect to the contingent nature of the structural design process described before, Hines (2012) stresses that "if there is more than one way to do something, creativity comes into play".

Understanding creativity as a key characteristic of the structural design process leads to the questions of how creativity can be defined and how it can be achieved or promoted in structural design processes. While creativity in design processes is often black-boxed or circumscribed with the sudden emergence of a so-called "creative leap" (Dorst & Cross, 2001), in recent years, several publications in the field of design studies have contributed profoundly to a greater understanding of creativity itself and of the creative process.

In their review article on creativity in engineering design, Howard et al. (2008) summarise that most researchers ascribe two properties to creativity: for one, "originality" (also referred to with the attributes "novel" or "new"), and for another, "appropriateness" (also referred to with the attributes "useful", "purposeful", "value", "meaningful", "tenable", "satisfying"). Furthermore, most researchers identified a third property, for instance, "unobvious", "adaptive", "leap", "change", "unexpected", "transformation", "communication", "comparison", or "resourceful". These ascriptions converge with definitions of creativity in the structural design context. For instance, Gavreau states that creativity is "the ability to imagine meaningful new ideas" (Gavreau, 2019). However, as entirely new ideas are rare in the structural design context, "the creative effort tends to be focused on determining the best means to adapting existing structural systems to unique design requirements" (Gavreau, 2019).

With respect to the way creativity is developed, multiple publications based on empirical research methods such as observation suggest that creativity does not suddenly arise in an instantaneous act. Instead, it requires both divergent and convergent thinking (Sawyer, 2012) in multiple stages (Santamarina & Akhoundi, 1991). Particularly, four stages are considered to be necessary, namely preparation, incubation, illumination or insight, and verification or elaboration (Chan, 2013; Santamarina & Akhoundi, 1991). The first two stages highlight the importance of gaining specific knowledge relevant to the task and of deeply engaging with this knowledge.

Another important characteristic of creative processes is the co-evolution of problem and solution. This has been observed and reported by multiple researchers (see e.g., Akin, 1994; Christiaans, 1992; Dorst & Cross, 2001; Maher, Poon, & Boulanger, 1996). Instead of directly solving a design task given to them, designers usually spend a significant amount of time restructuring and reframing the task. From a study based on the observation of experienced designers who were each given the same design task, Dorst and Cross (2001) conclude that

> "creative design seems more to be a matter of developing and refining together both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis and evaluation processes between the two notional design 'spaces'–problem space and solution space."

On a more fine-grained level, researchers have identified mechanisms or procedures that provide for explanations how insight or illumination occurs in a creative process. Rosenmann and Gero distinguish between combination, mutation, analogy, and first principles (1993, see Figure 2.3). Another procedure can be described as emergence (Cross, 1997). Hereby, combination refers to combining features of existing designs into a new one, mutation refers to the alteration of one or more features of an existing idea, analogy refers to attributing abstracted features of existing designs to the new design, designing 'from first principles' assumes that the new design is developed in an abductive leap based on the requirements or desired functions of the design task, and emergence can be described as identifying new and previously unrecognised properties in existing designs (Cross, 1997). These procedures provide for useful descriptions of different ways in which a new idea can be created in a creative process.

In the context of structural design, creativity is often described as something that comes with experience. While experience is probably an important factor, this statement is of little help to designers struggling with the generation of ideas. Instead, it rather prevents a serious engagement with creative processes. However, as Hines puts forward, "understanding the principles of the creative process provides strength to see the process through" (Hines, 2012). Hines holds that the creative process includes the three elements imagination of an idea in the head, expressing this idea through a medium, and judging it (Hines, 2012). While intuition, talent, or wisdom – characteristics that one might relate to these three steps – cannot be taught, Hines emphasises that the skills to obtain or nourish them can be taught. This could be achieved, for instance, through inspiring students with stories of other engineers or

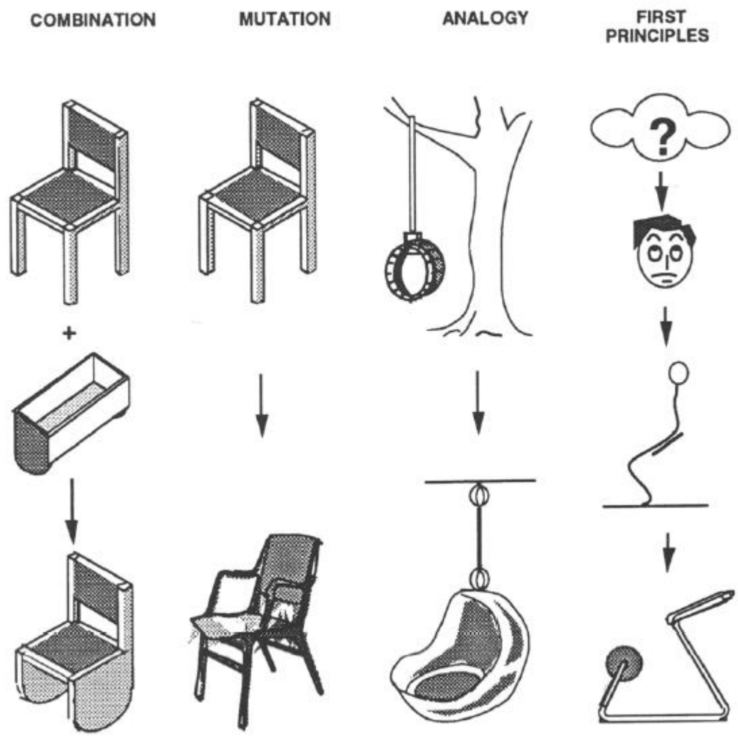


Figure 2.3. Visualisation of different procedures for the generation of insight in a creative process (Rosenmann & Gero, 1993): combination, mutation, analogy, and designing from first principles.

artists, teaching them fundamental languages to express their ideas such as drawing, or encouraging critical thinking (Hines, 2012). Hines further stresses that creativity requires iterations as well as a creative attitude, an aspect also emphasised in creativity research (see e.g., Santamarina & Akhoundi, 1991). Lastly, Hines underlines the importance of speed and courage in the process: "'speed' is necessary to ensure that the expression of ideas is uninhibited and that judgments are disciplined. 'Courage' is necessary to temper one's fears of expressing a bad idea or facing a tough decision" (Hines, 2012).

2.3 Methods and Approaches for Structural Design

In the previous two sections, the nature and process of design as well as creativity as a desired outcome and characteristic of the process have been described. However, at least in structural engineering, creativity is often black-boxed, which leads to the question which methods are actually used in structural design processes and how they relate to creativity, meaning how they promote or inhibit creativity. In order to establish a link between the *how* of the structural design process, meaning the methods employed in it, and the generation of creativity, this section presents a short review of methods employed in structural design processes. Hereby, a method is understood as a systematic way of doing something, “a concrete plan of action” (Gericke & Blessing, 2011), usually implying a procedure with a logical arrangement of steps.

In general, very little has been written on methods used in engineering design processes and particularly on methods for the generation of creativity in structural design. One possible explanation for this could be that structural design projects are usually one-offs, and that the path from the initial task to the structural design as the solution is perceived as individual, task-dependent, and contingent. However, as Kornwachs holds, “it does seem that there is something distinct and worth preserving about the methods used in engineering” (Kornwachs, 2012, p. 35). To this end, probably the most prominent attempt to define a method of engineering is the account of Koen, who defines the engineering method as “the use of engineering heuristics to cause the best change in a poorly understood situation within the available resources” (Koen, 1988). Hereby, what is a heuristic depends on the specific context and engineering task; some examples are rules of thumb, orders of magnitude, safety factors, and risk-controlling heuristics. This account shows that engineering design is not deterministic. Instead, it routinely requires to set priorities and select the best possible way forward from among multiple options knowing that there is no ‘right’ answer (Addis, 1997; Bulleit, Schmidt, Alvi, Nelson, & Rodriguez-Nikl, 2015). However, even though Koen’s account thus enables a better understanding of engineering practice, it is also a very reduced view and does not meet the criteria of a method described above, let alone provide engineers with guidance with respect to actual design processes.

With respect to the early stage conceptual design of load-bearing structures, the approaches or principles that engineers employ in design processes can be described as methods of the structural design process. For instance, to find an apt geometric form for a structure, an engineer might employ form-finding methods using soap or hanging models, design according to the flow of forces, or combine several ideal-typical structural systems in a new load-bearing structure (Burkhardt, 1995).

While such approaches or principles are very much linked to and dependent on the specific design task at hand, scholarship has testified to the importance of artefacts employed in the structural design process (for a detailed account, see Ruge, Dimitrova, Grubbauer, & Bögle, 2022). Artefacts, whether material or digital, are used as cognitive tools to push, probe, or evaluate design processes (e.g., Yaneva, 2009), and to trigger webs of inferences (Ammon, 2019). In this line, Henderson (1999, p. 200) stresses that artefacts “allow intangible ideas to become concrete – but still allow ideas to be reworked and renegotiated”, and thus act as intermediaries, which help to bridge between thought and final object. Employing artefacts is a way in which the design becomes gradually known to the designer. Furthermore, it enables designers to experience the future design in a tactile manner (e.g., Bucciarelli, 2002; Cross, 2006; Cuff, 1991; Yaneva, 2009). This is particularly relevant in the context of structural engineering, as the design outcomes are usually one-offs that cannot be tested before they are built.

Figure 2.4. The model as a central element in the structural design process. Design meeting with model for the Olympic Stadium 1968, from left: Gabriel, Bergermann, Leonhardt, Schlaich, Otto, Auer, Isler, ©Architekturmuseum der TU München.

With respect to artefacts in design processes, the important role of models is mentioned by several engineers, both in academia and in practice (see Figure 2.4; Addis, 1988; Duddeck, 2001; Duddeck, 2002, pp. 165-166; Hossdorf, 1963; Schlaich, 1991). Furthermore, not only their role but also the aspect of actively employing models or in general working with them in the design process – that is the activity of modelling – is specifically emphasised. For instance, Bucciarelli states that "to be good at design does not depend on mental images the designer may or may not have but rather on his or her mastery of specific skills and know-how such as sketching and modelling" (Bucciarelli, 2002). In the following, this thesis focuses on model-use and modelling as a method with the aim to contribute to a meta-discussion on the potential of these practices to incorporate more creativity into the structural design process. To this end, the next chapter presents the state of research on models and the activity of modelling in the structural design process.

A model or a set of models provide the way in which specialists, such as engineers, make sense of reality. To join a profession like engineering involves becoming so familiar with a set of models that the models provide the way in which someone orders their view of reality.

–John Monk, *The Book of Models, 1998*

3 Models and Modelling – Perspectives from Structural Design and the Philosophy of Science and Technology

The outcome of a structural design process is usually a one-off and cannot be tested as a whole before it is built and put to use. This is why the development and use of models that represent the structural design or parts of it are common practices in structural design. Duddeck even refers to working with models, meaning the translation of real-world problems into model-world problems, as the "core of the engineering profession" (Duddeck, 2002, p. 90).

This chapter summarises the state of research on models and modelling in structural design and serves as a theoretical base for the conducted empirical research. To this end, the three sections of the chapter each deal with a central aspect with respect to models and their use: first, the question of what actually constitutes models in structural engineering design and what the purposes for their employment are; second, the creative process of modelling; and third, the notion of the model as an agent that is interacted with in design processes instead of used.

However, while the use of specific models for set purposes is well established and documented, there is little fundamental research on the nature of models, their use, or their epistemological fundament (see e.g., Addis, 1988; Hossdorf, 1963). Thus, in addition to the perspective from the field of structural design, each of these aspects is complemented by a more theoretical, abstract, and synthesising perspective from the field of philosophy of science and technology.

3.1 The Model and its Purpose

> "When we say model, what comes to mind? Physical models, whether of a plane or a building? Mathematical models? Computational models?" (Deutsch, 2017)

In this section, the questions of what actually is a model and for what purposes it is used will be dealt with. To this end, the attempts to comprehend the nature of models and their purposes of use in structural engineering are contrasted with a more general account on these two aspects from the field of philosophy of science and technology.

3.1.1 The Model as a Tool for Representation in Structural Design

Builders have been using models at least for 2500 years during the design stages of construction projects (Addis, 2013). Since then, models in structural design have been used for a variety of purposes. These purposes of use include, for instance, to make assumptions regarding the loads acting on structures, to serve as simplified representations of the structural systems, to estimate the behaviour of the used materials, to calculate the designed structures with mathematical means, or to assess the safety of the resulting structures (Duddeck, 2001).

Considering their long history and their different purposes of use, it is not surprising that models are a common topic in literature from the field of structural design. Most of the publications focus on specific models and their development, field of use, appropriate employment, benefits, and limits. For instance, there are multiple research articles on the use of physical models by prominent architects and engineers such as Antoní Gaudi, Heinz Isler, Heinz Hossdorf, Pier Luigi Nervi, and Frei Otto. A good example for this are the multiple articles on physical models by Hossdorf (see e.g., Hossdorf, 1963, 1965, 1970, 1972, 1979), which focus on the area of application, the process of using physical models, new developments of this technique, and the benefits and advantages in contrast to other modelling techniques. Apart from physical models, also conceptual ones such as strut-and-tie models – promoted most prominently by Jörg Schlaich – have been discussed extensively in multiple publications with respect to similar aspects (see e.g., Schlaich, 1984, 1991, 1994, 1996, 1997; Schlaich & Schäfer, 1984, 1996). At present, there is a significant amount of publications on the topic of different types of digital models (see e.g., Aksamija, 2016; Andia & Spiegelhalter, 2015; Gramazio & Kohler, 2007; Kara & Bosia, 2016; Kolarevic & Klinger, 2008; Llach, 2015; Marble, 2012). Although most of these publications can be assigned to the field of architecture, they also touch on aspects of structural design. Recurring themes in these publications are, for instance, how to deal with the abundance of information in digital models, how to better work together with collaborators between planning phases or planning and construction, or how to optimise the design and manufacturing of structures.

These three examples (see Figure 3.1) already showcase that there is a broad variety of models used in structural design. The models can be physical, conceptual, or digital; they can represent different aspects, such as the structural behaviour, the flow of forces, or the sum of available information on a design; and they are used in different contexts, such as the exploration of structures with complex geometries and unexpected structural behaviours, the detailing of concrete structures and connections according to internal forces, or the management of different kinds of information regarding a design object and the communication about it with collaborators. The

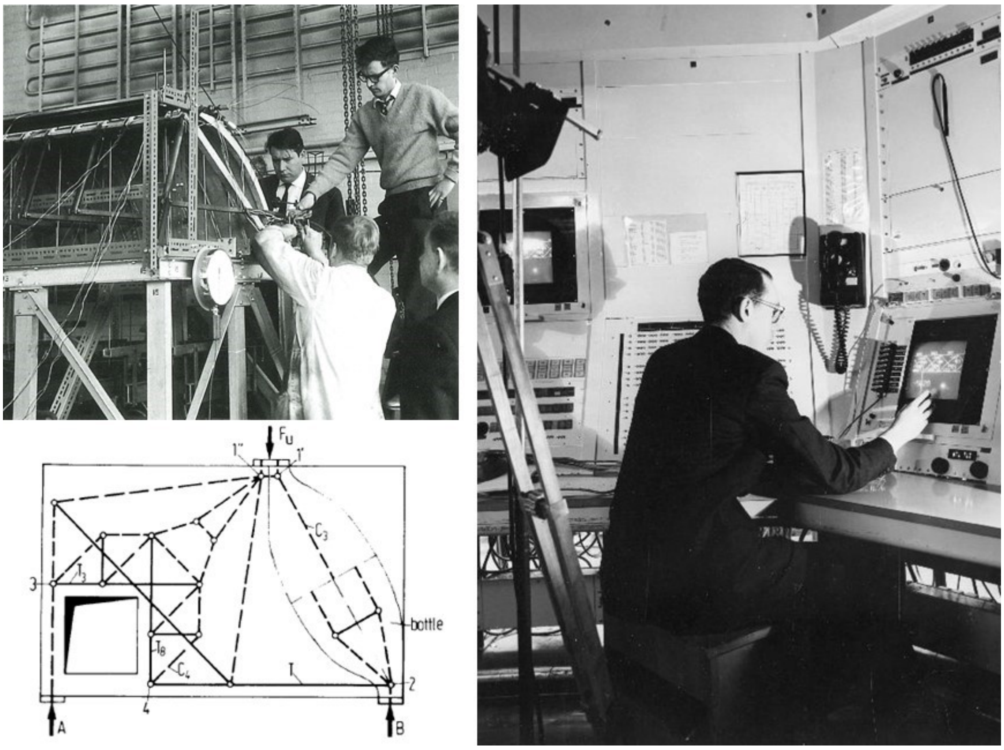


Figure 3.1. Examples of models in the structural design context. Top left: Employees with a 1:10 scale micro-concrete model of one bay of the Wangen warehouse roof (Hossdorf, 2003); bottom left: a strut-and-tie model for a deep beam with a void (Schlaich, 1991); right: Ivan Sutherland demonstrating the digital modelling tool "SketchPad" (courtesy MIT Museum).

range of model types, of what they are representing, and of the contexts in which they are used reflect the vital part that models play in the daily work of most structural engineers.

Beyond concentrating on specific models, some of these publications also contain reflections on models from a more general, conceptual, and abstract perspective. These reflections can be seen as attempts to capture the nature of models and define on a more general level what models are in structural design, for what purposes they are used, and what their role is. For instance, Hossdorf describes his physical models as "analogies", which are exact representations of the static behaviour of real structures (Hossdorf, 1972). As such, they already "contain the solution [of the to be solved structural problem] in them" (Hossdorf, 1972). In contrast, Hossdorf describes thought models such as theories as "structuring principles" that are applied to natural phenomena and hereby enable a partial understanding of these (Hossdorf, 1971). Similarly, Duddeck defines thought models in structural design as the "conversion" of a real situation into a mathematical representation. He further adds that this representation only assesses the relevant phenomena and leads to their predictability (Duddeck, 2002, p. 179). In contrast to Hossdorf, who thinks of models as "images of reality" (Hossdorf, 1963), Duddeck emphasises that reality is not really represented, but instead "translated" by means of reduction and abstraction into a state in which humans can assess it (Duddeck, 2001). He further characterises the nature of models in structural engineering as analytical and calculable (Duddeck, 2002). According to Addis, "the process of representing a real structure, load or material by a model consists in creating what is believed to be a valid and useful representation" (Addis, 1990, p. 66). And Schlaich describes the model as "a medium between the engineers capabilities and reality", which is characterised by abstraction and simplification (Schlaich, 1991). One common feature of these reflections is that models are seen as entities, which are in a specific relation to reality, or at least to those parts of reality that are of interest to the structural engineer.

As also described in the above cited publications, in the context of designing a structure the purpose of models is usually to predict the behaviour of the designed structures before they are built. For instance, Hossdorf views physical models as tools that aid the design of structures by delivering a realistic image of the static behaviour even of complex structures (Hossdorf, 1963; Hossdorf, 1971, p. 16). Duddeck states that the structural engineer translates the complete surroundings a technical structure is exposed to in reality to ideation and design models, in order to make predictions with respect to the structure's functionality, continued existence, and operation (Duddeck, 2002, p. 90). He particularly emphasises that models are not only used to understand the phenomena they represent, but also for design decisions. This is also acknowledged by Addis, who states that engineers not only use models to justify their designs but also to specify, to adapt, and to detail them (Addis, 1988, 1990). Similarly, Schlaich states that models enable the engineer to deal with complex phenomena (Schlaich, 1991).

The model as a representation or translation of reality with the purpose to draw conclusions for the design of a structure logically leads to the debate how 'well' specific models perform with respect to this goal. As both Schlaich and Addis claim, it is not possible to exactly represent all aspects of a structure (Addis, 2013; Schlaich, 1991). Usually, the structures design engineers deal with are too complicated to be modelled completely, an endeavour that would furthermore be too time-consuming and expensive (Addis, 1988). Hence, both Addis and Schlaich stress that multiple different models are needed to adequately solve a problem (Addis, 2013; Schlaich, 1991). This is in line with Duddeck (2001), who states that models are always characterised by a certain lack, an incompleteness, with respect to what they represent. According to Duddeck, a model is good, if the "right aspects of reality are left out in it and the right aspects are maintained", whereby the model becomes manageable. However, due to the fact that the structures are usually one-offs and are rarely tested with respect to the before modelled aspects after they are built, engineers usually don't get feedback on how well their models perform (Bulleit et al., 2015). Overall, Bulleit et al. hold that due to their incompleteness, their imperfect representation, and the lack of validation possibilities, models in structural design are always subject to uncertainty (Bulleit et al., 2015).

The topic of models for structural engineering design was and still remains a fast-evolving area of practice and research alike. New models are developed continuously, which is usually accompanied with both excitement and criticism, as they offer new opportunities as well as new dependencies. However, even though there is a significant number of publications that deal with models, only a few of them contain conceptual reflections on models on a meta level that try to capture the nature of models in structural design. The prevailing view of models as representations or translations of the to be designed structure used to understand and make predictions about its future behaviour ultimately leads to the debate how 'good' specific models are with respect to this goal. As a result, the status of models in the structural design context is reduced to being merely tools. However, with respect to the structural design as a creative process, the question arises if models also fulfil other functions. This is supported by a notable body of research on models in the field of architecture (see e.g., Gänshirt, 2020; Hillnhütter, 2015; Larsen, 2019; Liptau, 2018). As these publications make use of findings from the field of philosophy of science and technology on models, the next subsection presents some notions on models from the field of philosophy of science and technology that challenge the described view of models in structural design.

3.1.2 Philosophical Attempts at Defining the Model and its Purpose

Researchers from the field of philosophy of science and technology have been occupied with the question of the specific characteristics of models for multiple decades. An early and seminal work on models with a general claim has been provided by Stachowiak (1973). In the "Allgemeine Modelltheorie" (General theory of models), he assigns three main properties to models: mapping, which means that models are always representations of a target system; reduction, which means that models are not exact representations of this target system but reduce and abstract (some) properties of it; and pragmatism, which refers to the fact that models don't have an end in itself but rather are always pragmatically used for a specific task (Stachowiak, 1973, pp. 131-133).

Beyond these three properties, the debate on models in the philosophy of science and technology has centred mainly on four aspects of models in scientific contexts: what is the model's representational function, what are models ontologically, how does learning with models take place, and questions related to the general philosophy of science such as the relation between models and theory. Some comprehensive overviews can be found in Frigg and Hartmann (2018), Morgan and Morrison (1999), or da Costa and French (1998). With respect to what models represent, it can be distinguished between models of phenomena, models of theory, and models of data. In the structural design context, the first category is particularly relevant. More specifically, models can represent phenomena in different ways: through different scales, through the idealisation of the phenomena, or through analogies between the model and the phenomena. With respect to their ontology, models can be physical, fictional, structural, and mathematical or textual descriptions.

As philosophers of science and technology thus far were mostly concerned with models in scientific contexts, the main purpose of models has been described as to learn about the world (e.g., Frigg & Hartmann, 2018; Knuuttila & Boon, 2011; Swoyer, 1991). In this respect, Del Re (2000) refers to models as "the tools for scientific thinking." More concretely, the model is described as a vehicle that enables to generate knowledge about its target system, as this is usually either too big, small, or complex for direct observation (Del Re, 2000). Thus, one main focus in the literature is the topic of similarities or analogies between the model and its target system, which would allow to draw conclusions about the target system based on reasoning about the model (e.g., Del Re, 2000; Parker, 2009; Swoyer, 1991). Most prominently, Hesse has distinguished three kinds of analogies: the positive analogy, which refers to properties that can be found in both model and target system; the negative analogy, which refers to properties of the model that are not properties of the target system or vice versa; and the neutral analogy, which refers to properties of the model which may or may not exist in the target system (Hesse, 1966, p. 8). According to Hesse, the neutral analogy is the most interesting one, as it allows to make new predictions about the target system (Hesse, 1966).

A specification of the broad function of models to learn about the world is provided by Morgan and Morrison (1999). They hold that in order to generate new knowledge about the world, models usually either support theory construction, the exploration of implications of theories in specific cases, or the design of various technologies or artefacts and thus interventions in the world. The last function links towards models in the context of design and engineering. While models in this context have received fewer attention, three publications are worth a closer examination. First, in their article on engineering philosophy, Bulleit et al. (2015) state that the key goals of models in engineering are "explaining, predicting, and controlling the behavior of engineered systems; developing intuition and associated engineering judgment; instructing in both academic and practice settings; designing and evaluating engineered systems; and providing a context for experimenting and collecting data in order to develop models further."

Second, Currie (2017) analyses models in the context of engineering design and concludes that the purpose for their use in this context is not to learn something about their target system but to construct further models or to design the target system. For one, he observes that while the model is representing the target system, it is simultaneously involved in constructing it. For another, models used in design and engineering are preliminary: As one model is used to construct further ones, design processes are characterised by the abandonment of models. These two aspects lead to a dynamic relationship between the model and the target system, because the model as well as the properties of the target are continuously updated. He further ascribes models in design and engineering a procedural nature as not the representation of the target system is important, but the output of the model.

A similar account that is relevant to models in design contexts is the description of the "generative constructive use" of models by Peschard (2011). This conceptualisation refers to the use of models for the "generation of new models *and* new target systems" (Peschard, 2011, emphasis in original). Hereby, the new target is different from the target that was initially used to create the model and an extension or transformation of it. For this generative use, as Peschard emphasises, "not so much the model alone" is relevant but rather "the model in coordination with its target": The use of the model "is not directed at its target, but directed at other models in coordination with their own targets" (Peschard, 2011).

The "dynamic relationship between models and their target systems" that Currie (2017) has described, or the "model in coordination with its target", as Peschard (2011) puts it, refer to a dual purpose or role of models in design contexts. This aspect has also been observed by other researchers, specifically with respect to the use of models in the field of architectural design. For instance, Ammon and Hinterwaldner (2017) differentiate between the representativity of models and their productivity, which is their capability to enable something else.

One model definition that explicitly accounts for this dual purpose or role is the "model of model-being" introduced by Mahr (2011). In this concept, "a model is something as which something is being conceived of, and concretely, being a model is the content of a judgement in which something is being conceived of as a model" (Mahr, 2011). The concept is illustrated in Figure 3.2.

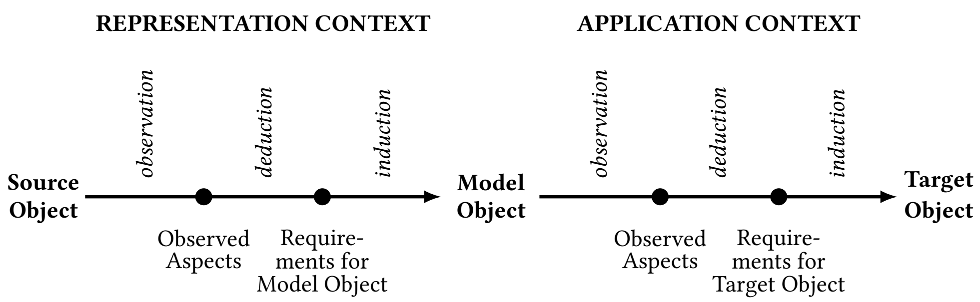


Figure 3.2. The model of model-being, adapted from Mahr (2008): The model is a representation of a source object and thus the outcome of an act of induction. At the same time, the model is also a source object for the generation of a target object and thus the premise for an act of deduction.

The model itself is a thought model, while the model-object is an entity that fulfils all the requirements of the model. There can be different model-objects for the same model. The model-object is perceived by someone to be both a model *of* a certain entity (source object; representation context) and a model *for* a certain entity (target object; application context). The model is thus placed in the middle of a process, comprising of the representation context and the application context. Mahr (2011) summarises that "the model functions not only as the target object, but also as the source object of a relationship of creation, which means that it represents at the same time the conclusion of an act of induction as well as the premise of an act of deduction." He puts forward that "this dual role seems to be one of the reasons why it is difficult to explain the nature of models; it is impossible to think, i.e., to be consciously aware of something which is not yet present but meant to be created and at the same time already available and meant to be used" (Mahr, 2011). This aspect of models has also been emphasised by Bulleit et al. (2015), who state that one "cannot avoid going from the known to the unknown" when working with models. The philosophical problem of induction, that "no series of observations can causally prove that a particular observation will follow", results in the fact that "there is always an assumption, 'an act of faith,' (Popper, 1959) in making such an inference" (Bulleit et al., 2015).

3.2 Understanding the Creative Process of Modelling

In the previous section, attempts to grasp the nature of models and their purpose in engineering have been summarised. In these attempts, mostly the use of models as tools, meaning the use of already existent models, was dealt with. However, taking into account the model of model-being, models do not only have an application context but also a generation context, and considering Currie (2017) and Peschard (2011), this is especially relevant in design and engineering contexts.

Although the process of developing models is essential to structural design, there do not exist explicit accounts of *how* this is done, of a method of modelling, so to speak. Furthermore, even though the structural design process is seen as a creative endeavour and models as the most prominent tools used in it, a connection between modelling and creativity has not been established. This section thus aims at a better understanding of modelling as a creative process.

3.2.1 The Development of Models in Structural Design: Example Cases

The development of models in structural design is a topic that is not properly acknowledged in engineering literature – in contrast to the use of models, which is well documented and discussed. The existing accounts often remain too general and vague to be of value for engineers who need to develop their own models in a structural design process. For instance, Addis describes the process of developing a physical model as making a scale model, subjecting it to loads, observing the behaviour of the model, and identifying the relationship between the model and the full-size artefact (Addis, 2013). However, as also pointed out by Addis, this process is not as straightforward in practice as it might seem in theory, because assumptions, simplifications, and approximations are necessary (Addis, 1990, p. 69). Similarly, Schlaich states that "the translation of a reality, which up to then existed only in [the engineer's] mind, into the right models, which serve (...) to predict the utility, durability, economy and beauty of [the] structure to be build, is one of the main challenges to the structural engineer, a semi-rational intuitive step" (Schlaich, 1991). Duddeck, too, acknowledges the difficulty and the accomplishment of capturing reality in an appropriate model by the activity of modelling (Duddeck, 2001). He describes this as the "art of leaving out the right aspects" (Duddeck, 2002, p. 161), and claims that this can only be achieved with heuristic means: "You can't find models through observation or deduction from axioms, but rather through luck. You invent them, through a creative act of fantasy" (Duddeck, 2002, p. 185). Duddeck names this 'thinking in models' and stresses that this is not self-evident (Duddeck, 2002, p. 182).

These few accounts of the activity of modelling render it as a creative and inductive endeavour. At the same time, the activity is black-boxed or even mystified as being a "semi-rational, intuitive step" (Schlaich, 1991), or an "art" that is related to "fantasy" (Duddeck, 2002). In the remainder of the section,[1] the goal is to analyse two examples of modelling practices provided in the literature as a first attempt to move beyond this black-boxing and mystification of the activity. The aim is to develop a clearer picture of how the activity of modelling is actually performed in reality in order to understand this practice better. The two examples are the development of physical models in the case of Frei Otto and the development and use of strut-and-tie models for the design of structural concrete. They were chosen for two main reasons. For one, they are both examples of developing one's own model for specific structures or problems. For another, they represent a variety of modelling approaches, one being a physical, material, and personal approach and the other being a conceptual, theoretical, and generalisable approach. The key aspects deducted from these two examples are highlighted in italics and will be summarised at the end of this section.

Frei Otto's modelling practices serve as the first example. In all of his projects, Frei Otto made extensive use of physical models. His daughter describes the eminent role of physical models in Frei Otto's work in the following way:

> "Our work and life were determined by thinking with models, thinking around models, understanding by models, feeling for models, discovering, researching and finding form with models, testing, verifying, proving and proofing with models, measuring and iterating in models, simulating, calculating and visualizing with models and convincing with models" (Kanstinger, 2018).

[1] The section is largely based on a previously published paper (Ruge & Bögle, 2021b).

The multiple publications on Frei Otto's way of working with models (e.g., Kanstinger, 2018; Meisner & Möller, 2015; Nerdinger, 2005; Vrachliotis, 2017) allow to draw important conclusions with respect to model-developing processes in general.

First, Frei Otto's work was characterised by a highly *experimental approach*, which can be compared to a fundamental research process, making use of experience, experiment, and mathematics (Meisner, 2005). In order to find geometries for the structures that would need minimal material resources (Kanstinger, 2018), he invented several techniques to build models. Furthermore, he used different form-finding processes, which were inspired by self-formation processes in nature (Barthel, 2005), and based on basic physical principles and forces such as surface tension (see Figure 3.3), adhesive power, magnetic or electrostatic forces, pressure differences, gravity, or friction (Kanstinger, 2018). Hereby, the aim was not only to identify and define the form of structures, but also to investigate the evolution process of the form (Kanstinger, 2018). The open experimental approach led to the discovery of completely new phenomena, which were the source for the development of many of Frei Otto's innovations.

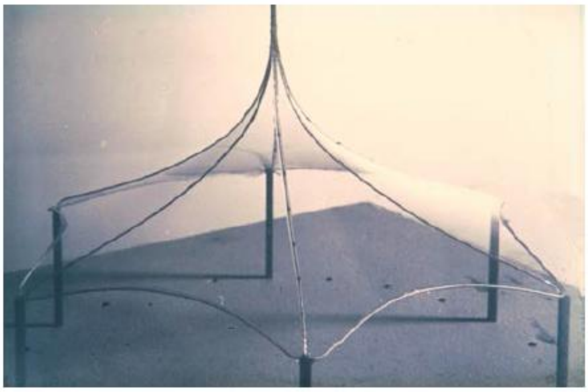


Figure 3.3. Making use of surface tension in a form-finding soap film model: Using soap-film models, a minimal and self-equilibrating surface – the smallest surface between any edges with equal surface tension in all areas – can be created in an easy, quick and exact manner (picture by Frei Otto 1963, published in Kanstinger, 2018).

Second, building physical models from scratch for each new project or idea was a rather slow process and required *deeply engaging* with the problem, the material, the geometry, and the structure. However, as already stressed by Hossdorf, this deep engagement enabled to integrate diverse aspects into one integral model (Kanstinger, 2018). This helped Otto to build an in-depth understanding of the problems he was working on (Brensing, 2005). Furthermore, the deep engagement was a way of making the design task tangible to himself, but also to his collaborators, to be able to subsequently solve it (Dickson, 2005, p. 111).

Lastly, multiple of Frei Otto's projects were not realised. Otto himself stated that he built little, but "constructed many castles in the air" (Meisner & Möller, 2015, p. 9). By *detaching* himself from the pressure to realise every idea, he was able to leave pre-defined ways, to follow his idealistic conceptions, and to develop and investigate radical and original visions, such as adaptable structures, eco-houses, convertible rooftops, the idea of dematerialised architecture, or of a "City in the Arctic" (Meisner, 2005, see Figure 3.4).

Figure 3.4. Project study of the never realised concept "City in the Arctic" (undated). In the concept presented by Frei Otto together with Kenzo Tange and Ove Arup & Partners, the city is spanned by a flat dome of 2000 m span and houses approx. 40.000 inhabitants. The pneumatic shell is made of two transparent plastic skins in between which a cable net is located that carries the tension stresses (Meisner & Möller, 2015, p. 101).

The second example is the development and use of strut-and-tie models for the design of structural concrete (see Figure 3.5). Strut-and-tie models are a generalisation of the truss model, which explains the internal forces in beams (see Leonhardt, 1965; Mörsch, 1912; Ritter, 1899). Hereby, the compressive stresses in the concrete are idealised with straight compression struts that form a framework with the tensile rods of the reinforcement. Through visualising the internal flow of forces in a clear, simple, consistent, and illustrative fashion, strut-and-tie models enable the design engineer to better understand the structural behaviour of concrete structures and to appropriately dimension their geometry and reinforcement on that base. The better understanding of the structural behaviour can help to prevent dimensioning mistakes. Additionally, the systematic methodology that is available for the development of strut-and-tie models makes dimensioning and detailing less vulnerable to the subjective influence of the structural engineer's personal experience or judgement, while also enabling systematic teaching and training (Schlaich & Schäfer, 1996; Schlaich & Weischede, 1981).

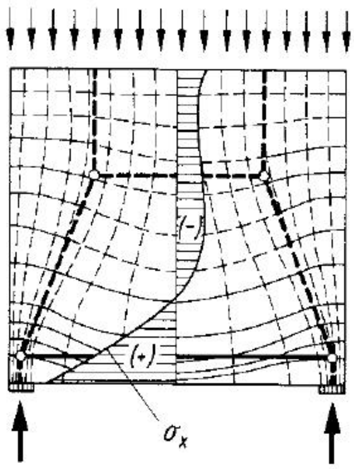


Figure 3.5. Example of a strut-and-tie model approximating linear-elastic stress trajectories. Based on the strut-and-tie model, the forces acting on the compression struts are calculated considering the equilibrium state and the struts are dimensioned accordingly. Then, the load-bearing capacity of the compression struts and of non-reinforced tensile struts is verified and the reinforcement is dimensioned (Schlaich, 1984).

The well-documented example of modelling with strut-and-tie models enables to draw conclusions for the activity of modelling on a more general level. First, even though there are general steps and rules to be followed when developing a strut-and-tie model for a structure, it always involves *transferring* these to a new context and developing one possible fitting model of the flow of forces that is appropriate to the respective structure. This transfer of already existent and available knowledge to a new context can be seen as characteristic for developing models in general.

Second, but closely related to the first aspect, Schlaich and Schäfer stress that when developing and using strut-and-tie models regularly, the understanding for the structural behaviour of the material concrete is not limited to the specific structure the strut-and-tie model is generated for (Schlaich & Schäfer, 1996). Instead, through *practising* this approach, the engineer gains a general understanding of different structural systems and their behaviour and trains their ability to transfer findings to new applications in a creative way (Schlaich & Schäfer, 1996). What is more, training this transfer on the rather detailed scale of a strut-and-tie model can encourage a form of 'thinking in models' also on other scales, for instance, on the scale of conceptual structural design. Thus, according to Schlaich, teaching strut-and-tie models and training to develop them is a suitable way to integrate the mindset of developing one's own models in engineering education (Schlaich, 1994).

As already mentioned above, both of the presented examples provide insights into what characterises the development of models. When comparing these two – at first sight very different – examples, several similar aspects become apparent:

Deep engagement: In both example cases, models are developed using a rather slow technique. In the case of Frei Otto, it is the building of physical models, in the case of the strut-and-tie models, it is the generation of an individual strut-and-tie model for a concrete member. These slow techniques force the design engineer to deeply engage with the task at hand. The structure or design becomes gradually known to the design engineer and can be thoroughly understood by them, which supports that the task of designing becomes accessible to the engineer and subsequently solvable.

Experimenting – practising: A central aspect of both examples is experimenting or practising. In the case of building physical models, this means experimenting in a literal sense with materials and structures on a small scale. In the case of the development of a strut-and-tie model, this manifests in the iterative generation of different versions in order to eventually find the best one out of multiple possibilities. In both cases, experimenting and practising can lead to the discovery of something new, for instance, new geometries of structures or a better general understanding of the behaviour of concrete structures.

Transfer: The aspect of transfer is also important in the described model development processes. In the case of Frei Otto's physical model building, the formation processes from nature were transferred to the laboratory context and applied to develop new geometries for structures. In the case of the strut-and-tie models, the rules for their development are transferred to a specific structure.

Balance between driving impulses and the detachment from them: Lastly, in both examples, the development of the models was shaped by a driving impulse. In the case of Frei Otto, this driving impulse was to use as little material for the structures as possible (Meisner, 2005). In the case of the strut-and-tie models, this driving impulse was to develop a way to detail and dimension concrete structures that was less dependent on personal experience and led to safer structures (Schlaich & Schäfer, 1996). However, in both cases, there is also a detachment from these original driving impulses during the activity of modelling, which is important for the generation of creativity. In the case of Frei Otto, it is the detachment from the idea that every project needs to be realised. In the case of the strut-and-tie models, the procedure enables a detachment from exactly predefined rules and encourages the creative development of one's own model.

To conclude, even though modelling in the structural design context is often black-boxed or mystified as an intuitive endeavour or even an art that requires fantasy, the analysis of the two presented example cases led to a number of possible general characteristics of modelling and thus suggests that there might be indeed a method of modelling.

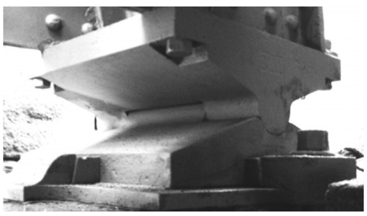
3.2.2 Epistemic Processes, How-Possibly Understanding, Model Terms

Similar to the field of structural engineering, also in the philosophy of science and technology the process of modelling is described mostly from a rather vague, abstract, and superordinate perspective. In the prevailing literature, the activity of modelling has been mostly described as an epistemic process consisting of three main stages comparable to the ones described by Addis (2013). These steps are establishing a representational relationship between model and target, investigating features of the model by manipulating it, and converting findings from the model context into claims about the target system (e.g., Frigg & Hartmann, 2018). In the model of model-being introduced in Section 3.1.2, this process is described in more detail. For the development of a model, the source object has to be observed, the observed phenomena have to be deducted to requirements for the model, the requirements have to be transformed from the real world to the model world, and out of these requirements a model has to be created in an act of induction. Similarly, the application of the model requires the observation of the model's behaviour in the model world, the deduction of the relevant aspects, the transformation of these aspects into requirements for the target object, and the design of the target object in the real world as an act of induction (see Figure 3.2).

These descriptions of the epistemic process assign significant importance to the relationship between the model and its target system, which has already been questioned in the previous section. In contrast, only few publications deal with the actual processes of modelling – yet these processes of constructing and manipulating models are the ones in which learning with models happens (Morgan & Morrison, 1999).

With respect to the construction of models, Morgan and Morrison have concluded from the analysis of several case studies on model building that models are typically constructed by "fitting together a set of bits which come from disparate sources" (Morgan & Morrison, 1999, p. 13). These bits can be "elements of theories and empirical evidence as well as stories or objects that form the basis for modelling decisions" (Morgan & Morrison, 1999, p. 15). Thus, models are often not constructed solely from elements related to their target system, but include additional elements. Morgan and Morrison argue that the presence of these other elements makes models separate from and partially independent of their target systems (Morgan & Morrison, 1999).

Similarly, the use of so-called "toy models" analysed by Reutlinger, Hangleiter, and Hartmann (2018) nicely illustrates that the model must not completely represent its target object truthfully in order to have an epistemic value. In their definition, a toy model is a highly idealised and extremely simple model. Such models often contain knowingly incorrect properties, meaning properties that are known to be incorrect for the target object. For instance, supports in structural design are often idealised as articulated, although in reality they do transmit moments (see Figure 3.6).



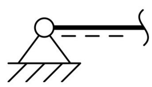


Figure 3.6. Example of a toy model in the structural design context. Left: the articulated support of the Most Mieszczanski Bridge in Wroclaw, taken from Wetzk (2010); right: the idealised depiction of an articulated support.

Toy models are usually not used for detailed predictions but nevertheless enable an epistemic access to the target system that leads to a better understanding. As analysed by Reutlinger et al. (2018), some toy models do not provide an understanding of how phenomena actually are in reality, but rather a so-called "how-possibly understanding", thus an understanding of how things could possibly be. This type of understanding gained from working with toy models can have at least three functions. First, it can engender a modal understanding that enables to understand "whether or why a phenomenon is the case". Second, it can fulfil "a heuristic function in the process of constructing less idealised models". Third, it can have a "pedagogical function, as the interaction with these models enables a quick and simple understanding of how to use a specific type of model" (Reutlinger et al., 2018). With respect to the design of structures, these functions can be spelled out as follows. First, in early stage conceptual design, the work with toy models can boost creativity by shedding light on possibilities or alternatives one might not have thought of otherwise. Second, a designer might start with a highly idealised toy model and will use it as a base to develop less idealised models throughout the process. Third, toy models allow to practice modelling, which is of high importance in structural design (see 3.2.1).

With respect to the process of manipulating models, it can be noted that this process can vary greatly depending on the type of the respective model. It can be done, for instance, by changing certain parameters of models and observing the outcome, by literally altering a physical model and observing the effects, or by performing calculations or thought experiments. Another way of manipulating models is described by Wendler (2016). He puts forward that assigning specific terms to models – and thus ascribing to them a certain status, purpose, usage, meaning, or impact – can transform the way a model is perceived. Model terms, as Wendler argues, can give impulses, establish boundaries, create tensions or imaginary safety, and thus influence the model itself and the process of modelling. Hereby, it is also important by whom a model is ascribed a certain term and who else is there to perceive this. Furthermore, different perceptions of the same model by different people can lead to interactions, misunderstandings, differences of opinion, or changes in perception, all of which play important roles in collective modelling processes and can foster creativity (Wendler, 2016). Therefore, as Wendler argues, model terms need to be treated not as outside of but as within the modelling process and as an active part of it (Wendler, 2016).

3.3 Models as Agents?

In the descriptions of model-use and modelling in the previous two sections, the engineer has been the central actor, either as the one using the model, or as the one developing it. However, the descriptions also provided some indications towards a more active role of models in the design process. These indications are explored in more detail in this section.

3.3.1 Interacting with Models through Digital Tools: New Workflows in Structural Design

In the context of structural design, seeing models not as objects that are used but as entities that are interacted with, and thus have a certain scope of action of their own is a notion that is most apparent in the discourse on computer-aided design (CAD) tools. For instance, in an article from 1979 on the changes CAD systems inflict on engineering offices, Hossdorf conceptualises the work with digital tools as an interaction between human and object, a “confrontation of the human mind with an object that is in the process of being created” (Hossdorf, 1979).

Today, digital workflows are predominant in the whole design process in most engineering and architectural offices. These digital workflows usually speed up the modelling process, as new models are continuously developed, adapted, altered, or dismissed. This implies that no longer the model as an object but rather the tool used to generate the model is in the foreground. Numerous publications deal with the question which impact new tools – particularly the ones related to parametric design, automated design, or informed geometry – will have on the outcome of design but also on its process (e.g., Marble, 2012). In this respect, Peters and Peters claim that “[computation] is not just a tool – there can be no doubt that it is fundamentally changing architecture” (Peters & Peters, 2013, p. 11). While this matter has mainly been investigated from the perspective of architectural design, most questions apply to the structural design context alike, especially since – also due to these new tools – the tasks of different designers involved in a project increasingly merge (see e.g., Deutsch, 2017). Furthermore, the discussion centres on tools rather than on models. However, as the tools are the means with which models are generated, the topic of tools is equally as relevant to this dissertation. Two main aspects of this debate are addressed in the following. The first one is how tools to build models influence and change the design process and its outcome. The second one is the question whether there is a real interaction with tools, meaning whether tools also exert a certain level of agency of their own.

With respect to the first aspect, the notion that tools influence the design process and its outcome is commonly acknowledged. Already early CAD systems have had significant impact on multiple aspects of design, for instance, through the transformation of a 2D drafting design process into a 3D model-based design process (Aksamija, 2016). These systems also required the designer to assign more time and invest more computational power towards the task of designing. More recently, the introduction of Building Information Modelling (BIM) tools inflicted further changes on the design methods used (Aksamija, 2016, p. 87). As Garber puts it, BIM is not only affecting how buildings are constructed, but also how they are designed (Garber, 2014, p. 13). Therefore, “no discussion of BIM should be complete without a reconceptualization of how new digital tools augment, challenge and change the authorial process of design” (Garber, 2014, p. 66). This implies that BIM as a tool impacts aspects such as the authorship of design, something that would attribute a completely new quality to ‘just’ a design tool. Another example for the influence of tools is that they change the approaches to design. For instance, with respect to computational methods that involve scripting, Katz, Krietemeyer, and Schwinn (2013) describe a change in design approaches from implicit intuition to explicit definition:

> “In many modelling tools, the designer will directly and intuitively interact with the model, as a sculptor might work with clay. In this process ‘rules’

> are implicit to the designer but are not explicitly defined in the model. In contrast, scripting requires designers to make these rules very explicit" (Katz et al., 2013, p. 81).

Another aspect that tools impact is the roles attributed to different designers in the design process. As new tools offer new possibilities they also lead to new questions to be dealt with and new tasks for the designers working with them. In this line, Aksamija has stated that "free-formed and complex structures [designed with computational tools] require a new understanding of engineering and redefine the role of the engineer in the design process" (Aksamija, 2016, p. 99).

The second aspect that is implicitly touched on in this field of literature is the question whether tools can have an agency of their own. For one, the example of generative design, which refers to "virtual geometric processes that are highly numerically controlled and constrained parametrically" (Garber, 2014, p. 124), shows that computer tools are acknowledged to have at least a logic of their own. As Garber recognises, "the most challenging problem is not to create the most novel geometric form, but rather how such forms could be rationalised and understood so they could ultimately be built" (Garber, 2014, p. 121). This implies that the tool inflicts a logic of its own onto the design, which the designer has to adopt. Similarly, in the case of informed geometry, which refers to informatically driven design processes (see e.g., Figure 3.7), one major aim is to grasp the complex and intuitive design processes in which the tools are not used but instead interacted with:

> "This process allows the designer other levels of interaction with the algorithm during calculation. (...) This synergy between the designer and the algorithm, the human intelligence and the artificial intelligence, makes the design smarter and allows to develop architectural, geometrical and structural aspects simultaneously" (Bergis et al., 2018).

Here, the tools are explicitly acknowledged a status of actors that are interacted with in design processes. Katz et al. even describe the interaction with the model as an "intimate design process" (Katz et al., 2013, p. 83). In his publication "Convergence. The Redesign of Design", Deutsch claims that "the contributions of individual [designers] – and the tools they are using – are converging" (Deutsch, 2017, p. 10). These reflections further fuel the debate on the authorship in design processes and the control over them. By asking "where in the design process is human input needed and where is it redundant? What role will our legacy tools play and to what extent are they holding us back?", Deutsch (2017, p. 14) challenges the roles of both designers and tools in the design process.

This short summary of literature concerned with a more active role of models – or the tools that generate them – makes apparent that this topic is of rising concern and importance, as it highly impacts the role of designers in the design process. While the

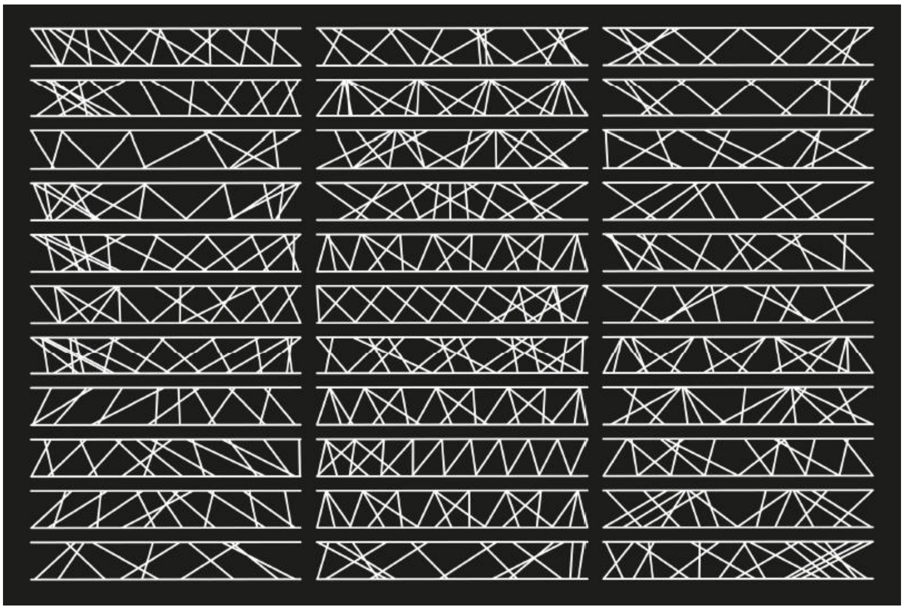


Figure 3.7. Octopus optimization of a structural truss by Robert Vierlinger, 2016. The machine learning algorithm rapidly generates concepts of repetition, variation, alignment and symmetry (Deutsch, 2017, p. 113).

first aspect – the fact that tools largely influence and impact the processes they are used in – is well acknowledged, the second aspect needs further elaboration.

3.3.2 Producing More Than They Contain: Active Potentials of Models

Several accounts on models and modelling presented in the last sections suggest that models do have a certain autonomy or independence – whether with respect to their source and target systems or to their users. Indeed, this autonomy or independence is commonly referred to as one of the most important properties of models. For instance, Hesse states that the neutral analogies of models, the aspects for which it is not known whether they are the same in model and target system, are the most interesting ones, as they can lead to fundamentally new findings (Hesse, 1966). Reutlinger et al. (2018) ascribe modal, heuristic, and pedagogical functions to toy models – models that are highly idealised, extremely simple, and thus often known to be 'incorrect' representations of their target system at least with respect to some aspects. And Morrison claims that the functional autonomy from their target systems is precisely what enables the models' function as instruments (Morrison, 1999, p. 40).

In his book "Das Modell zwischen Kunst und Wissenschaft" (The model between art and science), Wendler conceptualises this as the "active potential" of models (Wendler, 2013). He holds that as the model is a carrier of a thought process and not of the product of a thought process, it should be regarded as an active part of that thought process (Wendler, 2013, p. 27). Wendler supports this view with several other implicit descriptions of the active potential of models. For instance, Horst Bredekamp claims that models exert some sort of excess, which goes beyond their close purpose and stimulates the willingness to think and act of the person interacting with the model. These active potentials oscillate between "guidance and encouragement" and the "captivation of thinking and construction potentials" (Bredekamp, 2005, p. 14). Similarly, Wartofsky describes that a model produces "more than it contains" (Wartofsky, 1979, p. 144). Likewise, Knuuttila observes that "models often produce something unexpected and typically breed, in addition to new applications, new problems and lines of inquiry" (Knuuttila, 2005, p. 1267). In McMullins words, this "surplus content" of models allows for extensions, which may be both suggested and yet unexpected (McMullin, 1968, p. 391).

The notion of the active potential raises the status of the model from a tool to an active agent in modelling processes. With respect to the model of model-being that was introduced in Section 3.1.2, it is important to note that the status of the model also depends on what kind of role a modeller ascribes to the model. Oftentimes, as Wendler observes, models are denied this more active status and there is a certain inclination to ascribe "insights" the model produced to the modeller, or to portray certain modelling activities in retrospect as intentional actions of the designer, when actually they were largely led by the model (Wendler, 2013, pp. 39-40).

The influence, impact, or power models possess due to their active potential can be viewed both as positive and negative. For instance, models can define a "mode of action", meaning that they can predefine in fundamental manner what can be done or thought with them and what cannot (Wendler, 2013, p. 45). An example for this is the following statement by the architect Günther Behnisch on the impact of the modelling material: "Wooden blocks will produce a block architecture. Clay tends to soft shapes, paper and rods towards not corporally accentuated buildings" (Behnisch, 1989, as cited in Wendler, 2013, p. 30). This aspect of models to develop a life of their own and push into a specific direction is also described by Gänshirt (2020, p. 81) with respect to tools that are used to generate models:

> "All tools bear the danger of distorting our ideas; due to their own rules and modes of operation, their limits and possibilities, they push the person who uses them in a certain direction; if [the person] does not develop an awareness of this, [the person] runs the risk that the tools become independent."

The aspect of developing awareness is of high importance: Only by acknowledging and embracing the model's "self-will" or "stubbornness", as it has been described by Wendler (2013), one can profit from its active potentials and generative capacities – or in Wartofsky's words, from the fact that "they produce more than they contain" (Wartofsky, 1979).

The question of whether there is an 'engineering method' has been largely ignored. And yet, it does seem that there is something distinct and worth preserving about the methods used in engineering which cannot easily be reduced to simply applying science but includes design methods, methods applying engineering knowledge, methods for operating technical artifacts, production and manufacturing methods, and so on. (Kant & Kerr, 2019, p. 714)

4 The Need for a Conceptual Understanding of Models and Modelling in Structural Design

In Chapter 2, the structural design process as the context for model-use and modelling was described. From this, three main conclusions can be drawn. First, while there exist multiple descriptions of structural design processes, there is a lack of conceptual abstraction to the methods used in such processes. Second, while there is eminent research on creativity and the creative process, it is not explicitly dealt with how creativity can be incorporated in the structural design process and through which methods. Third, descriptions of methods employed in the structural design process often refer to the use of artefacts in the design process, particularly to models.

The in-depth literature review on models in structural design in Chapter 3 focused on three topics: the definition of models and their purpose of use, the creative process of modelling, and the model's role as an active agent in the design process. Each of these topics has been contrasted with perspectives from the field of philosophy of science and technology. From this comparison, too, some main conclusions can be formulated. First, models in design contexts are often understood as representations of reality and their performance is evaluated with respect to this aspect. Yet, literature from the field of philosophy of science and technology suggests that the productivity of models is another important function, particularly in design and engineering contexts. Second, the activity of modelling is seen as one of the most complex tasks of engineers. What is more, in the context of structural design, there are aspects that are not yet fully understood about models and that are to some extent black-boxed. Third, the fact that the tools used to generate models shape workflows in structural design is widely acknowledged; yet it is not made explicit if and how models participate actively in design processes. With respect to this question, Wendler provides with the notion of the active potential of models (Wendler, 2013).

This dissertation aims to shed light on models and the activity of modelling and to develop a better understanding for their role in the structural design context as well as of their contribution to creativity. To this end, this chapter summarises the identified research gaps and the research questions that will be answered in this dissertation.

4.1 Research Gaps

Through the review and analysis of the prevailing literature on structural design and models, two insufficiently dealt with areas of research can be identified, which are closely related. First and more generally, there is a lack of conceptual research on the methods used in structural design processes and how they relate to the generation of creativity. Second and more specifically, there is a lack of research on models and modelling understood as methods in the structural design process, and how these contribute to the generation of creativity.

With respect to the first gap, it has to be noted that the structural design process and its outcome in form of the description and justification of a structure are firstly dependent on the engineer's input and therefore highly subjective, and secondly subject to multiple influences and therefore also particularly unique (see Section 2.1). This is why the description of the design process on an abstract level usually fails to provide a clear picture of actual working practices in engineering. Instead, the work of structural engineers has mainly been described on the basis of concrete examples (see e.g., Bögle et al., 2005; Flury, 2012; Stiglat, 2004). However, many of these works are based on the experience of the authors and on examples of good practice rather than on empirical studies (Gericke & Blessing, 2011). Thus, they are often either too specific and subjective, meaning project-oriented or personal, or "too general to help project planning and guide daily decisions" (Gericke & Blessing, 2011). The literature does not sufficiently deal with the question of how engineers actually develop structural designs, meaning what methods are used in the process. Often, only the sequence of realised steps is described as opposed to how the designer works, meaning which actions or practices are enacted on-the-ground (Gericke & Blessing, 2011). According to Maffin, design "procedures usually address what is required to be done as distinct from how it should be done" (Maffin, 1998, p. 316). Yet, as Gericke and Blessing have pointed out, design processes could equally be described based on activities and strategies (Gericke & Blessing, 2011).

Furthermore, there are research works that suggest that there is something specific about the way design engineers work, a hypothesis also supported by Kornwachs (2012). For instance, Koen (2009) claims that "engineering is primarily defined by its art", and Bucciarelli (2002) holds that "to be good at designing does not depend on mental images the designer may or may not have but rather on his or her mastery of specific skills and know-how such as sketching and modelling". Therefore, it seems fruitful to base investigations not on abstract process descriptions or on individual project studies, but instead on the methods used in the process. This is a topic which has not been dealt with sufficiently (see Section 2.3). Yet, as Gericke and Blessing point out, research on methods could yield multiple benefits such as the rationalisation of creative work, the facilitation of planning, or the possibility to teach design and improve communication between different disciplines involved in design (Gericke &

Blessing, 2011). Motivated by the omnipresence of models in the structural design process and the emphasis on their role by multiple design engineers, researching as well as practising, this dissertation specifically deals with model-use and modelling as methods in the structural design process.

With respect to the second gap, models and modelling used as methods within structural design processes, previous research has mostly reproduced the notion of the model as a tool (see Section 3.1.1). Hereby, the representational function of models has been in the foreground, which inevitably leads to the question of how 'good' the model represents its target system. A second common notion from this field is that modelling is an intuitive endeavour or even an art (see Section 3.2.1). Both perspectives are not regarded as very helpful with respect to the creative use of models in design processes. The first perspective puts the focus on the model-object rather than on the interaction between the engineer and the model, which does not seem appropriate in the context of a creative development process of something new. The second perspective black-boxes the activity of modelling to an extent that prevents the further theoretical, conceptual, or methodological engagement with it.

The reflections on models from the philosophy of science and technology further suggest that both a more profound theoretical and methodological engagement with the activity of modelling and a shift of focus away from the model object towards the activity of modelling are fruitful research approaches. Particularly for the context of design and engineering, the literature in the field of philosophy of science and technology suggests that the focus should be placed more on the application context of models rather than on the representation context. This means focusing more on aspects such as the generative constructive use of models (i.e., to build better models, to design the target system), their preliminary character, the value of toy models and how-possibly understanding, the autonomy or agency of models, or the dynamic relationship between model, its target, and the modeller. An interesting starting point for further inquiry of these aspects is provided by Wendler, who has argued that what characterises models is their so-called active potential, meaning that models actively participate in our thinking and actions (Wendler, 2013, p. 10).

The above-mentioned aspects have thus far received little attention in the structural design context. Similar to the topic of design processes, previous literature on models is mostly based on reviews of historical cases of model-use and modelling. These only provide for either very specific or very general statements on model-use, in addition to being mostly object-oriented instead of process-oriented. Even though there are some hints towards a more active role of models, these aspects are only dealt with implicitly, for instance, with respect to the interaction or redefinition of roles between engineer and model. As a consequence, there are hardly any methodological abstractions to what actually constitutes the activity of modelling. Overall, the methodology and theory behind model-use in structural engineering has gained little attention so far, and a sound theoretical and empirical base is lacking to develop a conceptual understanding of models, the activity of modelling, and their contributions to creativity in structural design. However, especially the ongoing and profound restructuring of the way engineers work and interact with models due to digitalisation requires a completely new consideration of the topic for structural design. The aim of this thesis is to make these aspects explicit and thus contribute to a better understanding of the role of models and of model-use and the activity of modelling as methods for creativity in the structural design process. The hypothesis is that understanding model-use and modelling as methods in structural design is crucial for the creative design of structures, as it can enable to make direct use of the models' active potential.

4.2 Research Questions

The dissertation seeks to build a conceptual understanding of models and the activity of modelling as a method in structural design. It tries to shift the focus from models as tools to models as entities that the design engineer interacts with, therefore placing emphasis on the activity of modelling rather than on the model-object. To this end, this dissertation approaches the topic of model-use and modelling on three levels. First, it asks how models as well as their role and purpose can be defined in the structural design context. Second, it scrutinises the interaction processes between engineer and model and how they relate to the generation of creativity. Third, it conceptualises model-use and modelling as methods for creativity, which enables a grounded understanding of the practice and facilitates the teaching and transfer of the implicit knowledge embedded in it. Hereby, rather than deducting the insights with respect to these aspects from a literature review, a view 'from below' is adopted that focuses on definitions from practising engineers and on actual on-the-ground practices of modelling, and abstracts and theorises their relevant aspects. Thus, the dissertation focuses on making explicit the implicit strategies and activities of modelling in design processes, in order to generate knowledge on procedures, ways of thinking, and skills that are "learned mostly on the job and often possessed unconsciously rather than in codified form" (Bulleit et al., 2015).

With respect to the first level, it is important to explore which qualities and properties define models in structural design. The multiple tasks for which models are used and the different types of models used for the same task lead to a plurality of meanings assigned to the term model. Thus, it is essential to consider different model understandings of engineers, the different reasons to use models or engage in the activity of modelling, and their evaluations of specific models or the activity of modelling in general. Hereby, the aim is to make explicit characterising properties of models and to identify their inherent mechanisms. Based on these properties and mechanisms, an open understanding of what models are or could be in structural design is developed, which is adaptable to multiple possible futures and furthermore acknowledges their active potential in structural design processes.

The second level is the interaction between engineer and model. Keeping in mind that structural design is a highly practical process, the practices of model-use and modelling seem to be the key to the analysis. For what specific task, by whom, and how are models used in structural design processes? To analyse this, the activity of modelling needs to be considered in its respective context, with a clear focus on the *how* of the activity, meaning the specific actions, intellectually but also practically, that characterise the interaction between engineer and model. A further line of inquiry is the evaluation of the creative potential of model-use and modelling. Here, the dissertation makes use of Wendler's notion of the active potential of models (Wendler, 2013), which conceptualises the model's ability to participate in the thinking and actions of the modeller. It is not questioned whether models can exert agency of their own but rather how exactly models exert their agency in today's prevalent digital design processes, and how this conceptualisation can be made fruitful for the notion of model-use and modelling as methods for creativity. It is assessed under which circumstances the interactions between engineer and model lead to creativity in design processes, and if there are certain practices that facilitate or hamper creativity.

With respect to the third level, the dissertation aims to develop a general description of a method of modelling that acknowledges the characteristics and properties of models as well as the practices that constitute the interaction between engineer and model in the design process.

Considering the aim and the above-mentioned levels of consideration, the overall research question of this dissertation as well as three sub-questions (SQ) can be summarised as follows:

What are the creative potentials of model-use and modelling in structural design, and how can they be comprehended conceptually in a method of modelling?

SQ1 What are current model understandings in structural design, considering the context of model-use as well as the value assigned to models?

SQ2 What are the embodied practices of model-use and modelling characterising the interaction between engineer and model and how do they support creativity?

SQ3 How can the activities of model-use and modelling be conceptualised in a method of modelling?

Sie haben Recht – unser Schreibzeug arbeitet mit an unseren Gedanken.
(You are right – our writing tools work with us on our thoughts.)

–Nietzsche in a letter to the author Heinrich Köselitz

5 Methodological Preface

This chapter serves as a methodological preface for the empirical results. It is structured in three sections. In the first section, the research design is explained with a focus on the overall logic behind qualitative research and the employed methods. By describing the reasons that led to the specific research design of this dissertation, it provides with a methodological rationale for the qualitative approach to the topic, which is rather unusual in engineering research. The second section is an account of the actually realised research process. It makes explicit the single steps of the research process so it can be retraced by the reader and the way the findings were generated becomes transparent, comprehensible, and plausible. The third section describes the single case study of modelling practices that was conducted in an engineering office, hereby providing relevant contextual knowledge for the understanding of the empirical findings.

5.1 Research Design: Combining Qualitative Interviews and Participatory Observation in a Grounded Theory Framework

This dissertation makes use of several qualitative methods from the empirical social sciences. The research design was chosen for a number of reasons. Hereby, the overarching and main preposition was that the research design should reflect the research object as well as the research questions formulated in the previous chapter.

With respect to the research object, the structural design process, model-use, and the activity of modelling can be described as very complex activities that are dependent on multiple aspects such as the experience of the engineer, the engineering school, the philosophy of the office, and the complexity of the task. These aspects usually escape the analysis through more traditional engineering methods such as numerical simulations, experimental tests, or analytical methods. Qualitative methods, in turn, are data generation and analysis methods that respect the qualitative nature of the research object. Further, they yield for a holistic perspective and understanding, as they provide the space for understanding and interpreting the research objects in their entirety, as well as appropriately represent interdependencies of their diverse aspects (Strübing, 2013).

In order to understand what constitutes the activities of model-use and modelling, how to steer or improve them, and how to make productive use of their generative capacities and creative potentials, the context for these activities needs to be captured and made accessible for analysis. This includes aspects such as the attitudes and opinions of actors and the underlying reasons for actions. This aim corresponds well to the interpretative and reconstructive nature of qualitative methods. Through different analysis methods, the interpretation and reconstruction of situations and meanings, which can be either conscious or unconscious to the actor, is achieved.

Furthermore, qualitative research methods also provide the opportunity to adequately incorporate reflexive strategies into the research process. This is important, as the interpreted and reconstructed meanings cannot be attributed to the object of research directly. Instead, they constitute themselves only "in the referential relation" of context and statement or action with the research question (Reichertz, 2016). The conduction and analysis of data thus needs to be reflexive, for instance, with respect to the research interest and question, but also with respect to the researcher's ex-ante knowledge of the research object or their experiences during data conduction. In order to handle the resulting subjectivity in the data conduction and analysis, qualitative methods further promote that subjectivity is acknowledged, reflected, and comprehended by the researcher during the process, and that this subjectivity is further made explicit and transparent in the presentation of the results (Reichertz, 2016).

With respect to the research questions, it can be noted that they aim at making implicit knowledge (concerning models, their use and the values assigned to them) as well as implicit practices (of modelling and the interactions between engineers and models) explicit. Furthermore, they aim at synthesising this knowledge in a method of modelling. For these two purposes, qualitative methods from the empirical social sciences are particularly apt, as they usually follow inductive or abductive research logics, which aim at the development of theory and offer multiple ways to generate explicit knowledge out of implicit knowledge.

Furthermore, qualitative methods are particularly suited for answering explorative research questions such as the ones of this dissertation. In the case of a explorative research question, the knowledge on the researched object is usually not sufficient in order to pre-define the research process. Instead, the goal is often to achieve an in-depth understanding of phenomena and to become aware of aspects that were not known before, in order to formulate new hypotheses or theories with respect to the research object. In this sense, qualitative research can be described as both grounded and open. Grounded means that the process of research is strongly related to the object of inquiry with respect to the research question and that both data generation and analysis are tailored to its specificities. The openness of qualitative research implies that the methods employed and the steps taken are decided on in the process and tailored to what has been found out so far. The generation of data through interactions between the researcher and the actors of the field can be conceptualised as a communicative process. In a similar sense, the analysis of data takes place in a continuous interaction between researcher and the data itself in relation to the evolving research object.

Out of the variety of qualitative research approaches, the *grounded theory*, characterised by alternating phases of empirical work (data generation, data analysis) and theoretical work (literature review, theory development) was chosen as an overall research framework for this dissertation. The empirical data was mainly generated using *qualitative interviews* and *participatory observation*, and it was analysed using different *coding methods* and *comparative analysis*. Several *quality control methods* were used to validate the findings. The qualitative methods were complemented by an interdisciplinary literature review to formulate specific research questions in the initial stage of research, and to anchor and compare the generated data at later stages to conceptualise them into the findings. An overview of the employed methods is given in Table 5.1.

Table 5.1. Overview of the methods and approaches used and how they were employed in this dissertation.

Method/Approach	**Employment**
Grounded Theory	Research framework.
Qualitative Interviews	Data conduction.
Participatory Observation	Data conduction.
Coding and Comparative Analysis	Analysis of interview and observation data.
Quality Control Methods	Validation of the generated data and findings.
Interdisciplinary Literature Review	Guidance for the formulation of research questions; anchoring and comparing of the generated data and findings.

5.1.1 Grounded Theory as a Research Framework

Grounded theory is the name of both an approach to qualitative research and the outcome of it. It is a particularly open research framework, process, or style, which is used to generate theoretically generalised statements – a grounded theory – out of qualitative empirical data (see Knoblauch & Vollmer, 2019; Strauss & Corbin, 1996).

A grounded theory process is aimed for discovery. To achieve this, deductive, inductive, and abductive elements are combined in an open research process (Strübing, 2018, p. 32). Further, the grounded theory process is characterised by alternating phases of empirical work and theoretical work. Hereby, the three main steps data generation, data analysis, and theory development are conducted in parallel and influence each other productively in a recursive research design (Knoblauch & Vollmer, 2019). Analytical ideas during the data analysis influence the development of the object-oriented, grounded theory, whereby new findings are generated through the creative moment of abduction (Strübing, 2018, p. 32). Similarly, the development of the theory and the analytical ideas impact the process of data generation, for instance, by employing modified methods of data generation, producing different types of data, or adjusting the data sampling (Strübing, 2013, p. 113). In the course of the research process, findings are accumulated and result in an increasingly detailed understanding of the research object (Glaser & Strauss, 1967, p. 43). This interconnection of data generation, analysis, and theorising leads to a continuous refinement and concretisation of the research interest and questions during the research process, which is described for this dissertation in Section 5.2.

Overall, the grounded theory approach "is not a stiff method, but instead a problem-centred frame" (Pentzold, Bischof, & Heise, 2018, p. 3), which makes it flexibly adaptable to different areas of research. Prototypical applications are research questions that ask for reasons, causes, prepositions, processes, or consequences of certain practices. The use of grounded theory in this dissertation is in a tradition of other research works that were concerned with the use of artefacts carried out with this approach (Pentzold et al., 2018, p. 11).

As mentioned above, grounded theory not only refers to the research approach but also to a theory that is "derived from data and then illustrated by characteristic examples of data" (Glaser & Strauss, 1967, p. 5). The developed theory is never finished, but instead an interim result of a continuous process of theorising (Glaser & Strauss, 1967, p. 32). The aim is "not to provide a perfect description, but to develop a theory that is appropriate to the researched field and accounts for much of its relevant behaviour" (Glaser & Strauss, 1967, p. 237). A grounded theory which is readily understood by the laymen concerned with the respective area can be understood as knowledge to cope with practical problems in this area (Strübing, 2018, p. 47). For the people in the respective area, a grounded theory can sharpen their sensitivity to the problems they face, offer them new perspectives (Glaser & Strauss, 1967, pp. 30/240), give them a "broader guide to what they already tend to do, and perhaps help them to be more effective in doing it" (Glaser & Strauss, 1967, pp. 247-248), thus to better act and react in their environment (Strübing, 2018, p. 35).

5.1.2 Data Generation through Qualitative Interviews

The research questions aim at making implicit knowledge and practices explicit. This concerns knowledge on model understandings, the context of model-use, the evaluations of models, and the interactions with models. Thus, mostly interpretational knowledge and process knowledge was needed to answer the research questions. Hereby, interpretational knowledge can be described as knowledge that is not simply factual but includes normative dispositions, interpretations, and valuations. Process knowlegde, in turn, is knowledge on sequences of action, interactions, events, or based on experience (Bogner, Littig, & Menz, 2014, p. 18). Both types of knowledge are usually bound to an expert as the carrier (Kaiser, 2014, pp. 31/42; Rowley, 2012). Therefore, in order to gain such knowledge, qualitative expert interviews are a common and widely acknowledged method (Helfferich, 2019).

In general, being an expert is not a personal attribute but an ascription. It is defined by the specific research interest but also by the status of the person. As such, being an expert is a construct of the researcher as well as of society (Bogner et al., 2014, p. 11). Experts are further defined through the knowledge ascribed to them, which needs to be relevant to the specific research topic and question, and to a special extent affecting the practice of the field (Kaiser, 2014, p. 38). Furthermore, experts are characterised by the ability to make conjunctions to other areas of knowledge and to reflect on the relevance of their knowledge (Bogner et al., 2014, p. 14).

The expert interviews conducted in this dissertation were guided, semi-structured, and qualitative interviews. A previously prepared interview guideline was used to structure the interviews and ensure that they stayed focused and that data was generated that is useful for answering the research questions (Helfferich, 2019). To ensure efficiency but also an explorative and narrative character, the interview guidelines contained an invitation for narration, explicitly pre-formulated questions tailored to the research interest, as well as notes for further follow-up questions that could be formulated in the situation if applicable.

The method of expert interviews was used at several points in the research process of this dissertation for both explorative and exploitative purposes. Among these were, for instance, the general exploration of the field of structural design, gaining orientation in the field, specifying the research gaps and questions, generating hypotheses throughout the research process (Bogner et al., 2014, pp. 23-24; Kaiser, 2014, p. 29), and developing theory. The interviews were further used as an empirical base and a comparative data set for the data generated through participatory observation.

5.1.3 Data Generation through Participatory Observation

Even though qualitative interviews are a suitable way to gain interpretational and procedural knowledge on models, model-use, and modelling, these topics withdraw themselves to a certain extent from the analysis through interviews. As model-use and modelling can be described as routine and everyday practices in the structural design context that are performed subconsciously, most engineers do not actively think about these activities. And even when thinking about these everyday practices, they might be subconsciously remembered differently than they actually happened (see also Wendler, 2013). Often, only malfunctions draw awareness to the significant share of such everyday practices or uses of artefacts (cf. Schubert, 2019). Also, the routinised use of artefacts often happens non-verbally and the subtleties are difficult to communicate in interviews (Schubert, 2019). Instead, the significance of artefacts is more likely to be revealed in the actions performed in relation to these artefacts (Strübing, 2018, p. 34; Woolgar, 1991), more specifically, in the context of their development and use (Star, 1999). To capture the actions in relation to models directly, a participatory observation was conducted additionally to the interviews.

Participatory observation "can be defined as a process, in which the presence of an observer in a social situation is maintained for scientific purposes" (Schwartz & Schwartz, 1955). The goal of an observation is to unobtrusively follow a complete field over a longer period of time (Reichertz, 2016). Hereby, the precise research question does not have to be specified in the beginning. Instead, the participatory observation is loosely structured and evolves around the research object, through the forming, extension, and modification of hypotheses throughout the research process (Girtler, 2001, pp. 55-56; Knoblauch & Vollmer, 2019).

Participatory observation is aimed at the understanding of others, their actions, and objectivations. Common research questions answered with this method ask for the properties, causes, and consequences of the observed phenomena (Knoblauch & Vollmer, 2019). As the participatory observation deals with the research object directly, a research situation is created which allows for insights that correspond well to the social reality of the field. This is due to the fact that the individual is not artificially drawn out of its natural field, as would be the case in an interview (Girtler, 2001, pp. 55-56). By participating in the social actions of the field, overhearing conversations and taking part, the researcher becomes a research instrument themselves (Knoblauch & Vollmer, 2019), and can at least partly understand common knowledge and value propositions in the field (Girtler, 2001, p. 65). Through the observation of actions as they happen, mainly procedural knowledge is generated, which makes the method particularly suited to scrutinise unconscious, non-verbal behaviour or implicit, corporal knowledge (Thierbach & Petschick, 2019).

Participatory observation is characterised by its relatively small degree of standardisation and by its distinct subjectivity. However, it is not an arbitrary method but instead systematically planned and conducted (Thierbach & Petschick, 2019). Data is generated in multiple forms, for instance, in the form of field notes, protocols, and reports (Thierbach & Petschick, 2019). Events, behaviour, or properties are received and documented. Additionally, interviews can be used to make sense of prior findings and to test their plausibility (Kaiser, 2014, p. 34). Due to its flexibility and proximity to real life situations, participatory observation has a strong capacity to adapt to its respective object of research.

In this dissertation, an open and focused observation was conducted. This means that the observation was communicated to the observed people and that it focused on a specific aspect of the field (Reichertz, 2016, p. 204), namely the practices of modelling or model-use and the interactions between engineer and model in the context of early stage structural design.

5.1.4 Data Analysis through Coding and Comparative Analysis

Qualitative material in the form of interview transcripts, field protocols, and field notes is usually analysed using interpretative approaches and methods (Kaiser, 2014, p. 3). In this dissertation, the conducted material was mainly analysed through coding and comparative analysis, two methods which are commonly employed in grounded theory approaches (Knoblauch & Vollmer, 2019; Glaser & Strauss, 1967, p. 72).

Coding The fist main strategy, coding, can be described as the process of conceptual abstraction by assigning general concepts – 'codes' – to singular incidences in the data (Vollstedt & Rezat, 2019). Strauss and Corbin (1996) distinguish three forms of coding, namely open, axial, and selective coding.

Open coding can be described as a line by line analysis of important sequences that is used to break up the data and to explore its multiple meanings. It focuses on the conceptualisation and categorisation of phenomena with the overall goal to develop a wealth of codes that describe the data (Vollstedt & Rezat, 2019). In this dissertation, for instance, different influences on the structural design process were coded and sorted into different categories. To develop a grounded theory, the relationships between the developed categories need to be integrated into an overarching framework by axial and selective coding.

Through axial coding, relationships between the categories that were developed in the open coding process are established (Vollstedt & Rezat, 2019). To do so, a central category is picked out and material which relates to this category is coded. This could be, for instance, propositions, temporal or spatial aspects, causes and effects, means and purposes, context, or boundary conditions related to this category. Through the analysis of the resulting codings, a network of relations around the category can be developed. Thus, by coding data which concerns the propositions, the temporal or spatial aspects, causes and effects, means and purposes, context, or boundary conditions in relation to the central category, an explanatory network of meaning for the categories is created. In this way, concepts are developed that can serve as hypotheses to answer the research question or explain the relations between the developed categories. For instance, the previously identified influences on the structural design process were put in relation to each other to develop a qualitative scheme of the process (see Section 6.1.4).

Through the subsequent process of selective coding, the material is coded again with the lens of the developed concepts. This is not a test of hypotheses; rather, the concepts are evaluated with respect to their robustness (Bischof & Wohlrab-Sahr, 2018, p. 94). Thus, through selective coding, further elaboration and validation of the concepts can be achieved in order for them to be integrated into a cohesive theory (Vollstedt & Rezat, 2019).

In general, systematic coding activities take place at every step of the research process as categories emerge and are reformulated and concepts are developed and integrated into a the grounded theory (Glaser & Strauss, 1967, p. 72).

Comparative Analysis The second main strategy that was employed to analyse the generated data was comparative analysis. This is the constant and systematic comparison of single 'cases' with respect to conceptual similarities and differences. Hereby, a case refers to data that can be seen as a case for a phenomenon that has been observed or a concept that was developed (Glaser & Strauss, 1967, p. 49). By constant comparing and posing of questions, both "conceptual categories and their properties, and hypotheses or generalised relations among the categories and their properties" are generated (Glaser & Strauss, 1967, p. 35; Pentzold et al., 2018, p. 5). Through comparing each incident that is coded for a certain category (or concept) with the previous incidents in the same category (concept), theoretical properties of the category (concept) are developed (Glaser & Strauss, 1967, p. 106). Hereby, as Glaser and Strauss (1967) explain, "the analyst starts thinking in terms of the full range of types or continua of the category, its dimensions, the conditions under which it is pronounced or minimized, its major consequences, its relation to other categories, and its other properties."

Through comparisons with similar but also different cases, the categories and concepts can be defined more precisely and sub-categories or sub-concepts evolve. It can then be analysed, which category (concept) or sub-category (sub-concept) can be found in which case and why. Later, contrasting comparisons are made, to test out the boundaries and reaches of a certain category (concept) and to define, what its characteristic and most important properties are. For instance, in this dissertation, the model definitions by the interviewees were compared to each other to identify general aspects of what defines a model in structural design. When new cases that are compared do not result in any new categories or concepts, theoretical saturation is reached. This means that this part of the theory is saturated and there is no need to further analyse new cases with regard to the saturated aspects. As in these cases, all possible 'types' have been identified, the statements valid for these types are valid for all cases and the findings can thus be generalised (Krotz, 2018, p. 67).

5.1.5 Quality Control and Validation

In general, there exist three ways to control the quality of qualitative research and validate it: communicative validation, which means the validation through involving observed or interviewed persons or experts; procedural validation, which refers to validation through explaining the research procedure; and argumentative validation, which is the validation through the search for common aspects and contradictions using triangulation. All three types of validation were incorporated in the research process of this dissertation.

First, communicative validation was achieved through peer debriefing (Flick, 2009). This means that the raw data collected in the interviews and the participatory observation was discussed with the supervisor and colleagues, as well as with other professionals in the field of structural design research. Furthermore, the findings were subject to expert validation. This was realised through regular presentations of intermediate results at research colloquia and conferences (see e.g., Ruge & Bögle, 2019a, 2019b, 2021b).

Second, procedural validation was ensured mainly through explaining the research design in this section and the research process in the following section. This includes the description and explanation of the choice of methods and the goals, as well as the approach and the research procedure.

Third, argumentative validation was mainly achieved through triangulation, a method of taking on different perspectives in the research process (Flick, 2011, p. 12). Hereby, the researcher has to widen their view continuously to obtain new perspectives on the examined phenomena and capture them in sufficient sophistication (Thomas, 2019, p. 51). In this dissertation, both data triangulation, meaning the incorporation of different kinds of data – interviews, field notes, field protocols, field reports – as well as methodical triangulation, meaning the use of different kinds of methods to generate the data – qualitative interviews and participatory observation – were used.

5.2 Research Process

This section is an account of the research process of the dissertation, from the forming of the research interest to the final integration of the findings into a method of modelling. The detailed description of the research process fulfils three purposes. First, it enables the reader to comprehend the generated results and put them in context. Second, it ensures procedural validation as explained in Section 5.1.5. Third, it serves as a data base for the evaluation of the methods in Section 7.3.

The grounded theory research process of this dissertation can be roughly divided into three stages: an exploratory stage, a focused stage, and a case study (see Figure 5.1). The research activities can be described as an interplay between theoretical work, empirical work, and process steering decisions. These decisions and the evolution of the research object were motivated by the theoretical and empirical insights that were gained from the interdisciplinary literature review in the fields of structural design and philosophy of science and technology, and from the conduction and in-depth analysis of the empirical data. This process was further supported by regular meetings with the supervisors and colleagues. In these meetings, ideas and developments with respect to the content and structure of the dissertation were presented, critically discussed, and documented in protocols. The specific methodological steps used in this process are made explicit in the following detailed descriptions of the three stages.

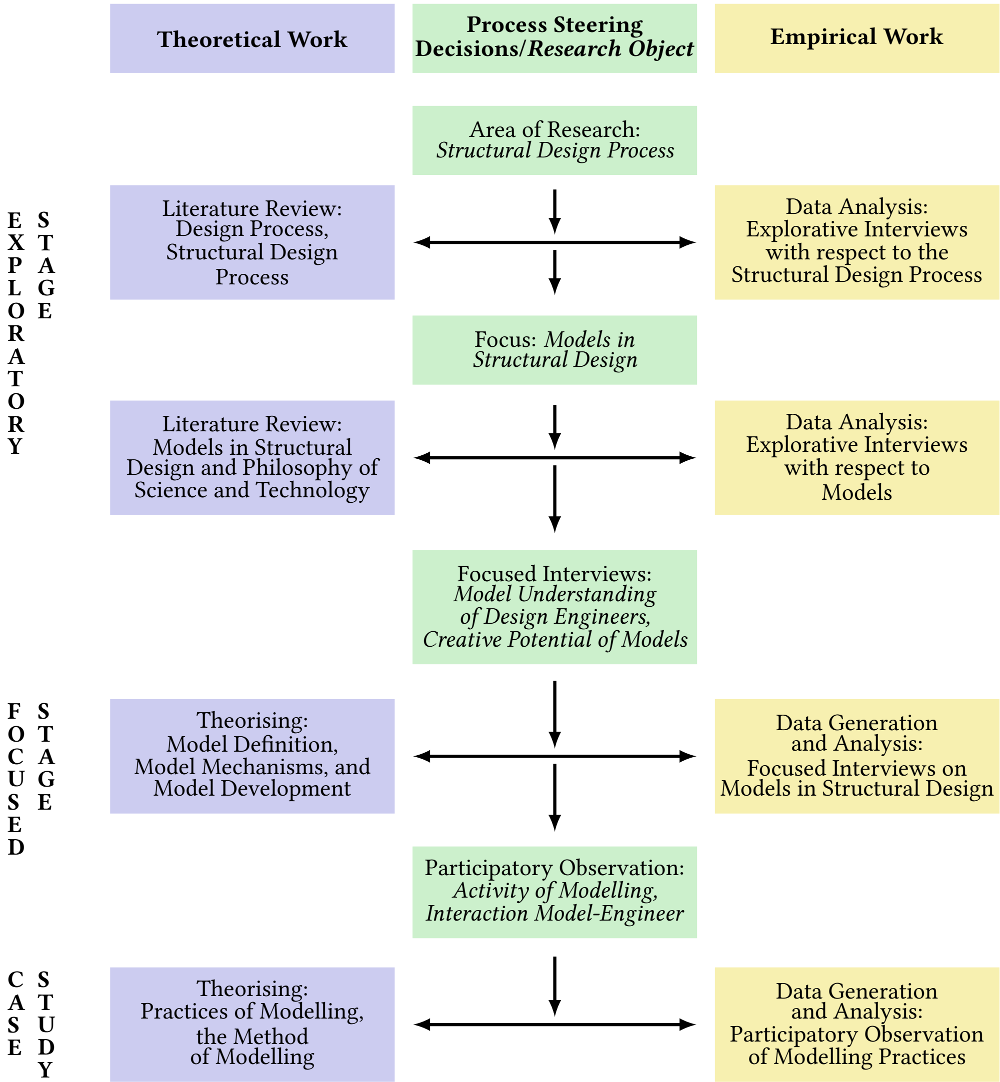


Figure 5.1. Overview of the research activities in the three stages of the research process. The research activities can be described as an interplay between theoretical and empirical work. This interplay was coordinated through process steering decisions, which influenced the next steps of theoretical and empirical work as well as the evolution of the research object throughout the process.

5.2.1 Exploratory Stage: Defining the Research Agenda

The research started out from the researcher's interest in the structural design process. Even though trained as a structural engineer, the researcher did not have practical experience in structural design processes, as university courses mostly evolved around the calculation and verification of structures (Billington, 2014; Dimitrova, Grubbauer, Ruge, & Bögle, 2021; Krafczyk, 2014). The idea that structural engineers engage in design processes was interesting for two reasons. First, it seemed counterintuitive to the subjection to physical laws and constraints inherent to structural engineering (Ruge & Bögle, 2021a). Second, it seemed to contradict the common public perception of engineering tasks (Addis, 1997; Dimitrova et al., 2021).

Thus, the first step of the research process was an extensive literature review on structural design processes, the results of which can be found in Chapter 2. This led to the insight that even though there are many reports on the structural design process of specific built examples, there is a lack of abstraction to the underlying methods or strategies used in it (Gericke & Blessing, 2011; Kant & Kerr, 2019; Kornwachs, 2012; Maffin, 1998).

In parallel to the literature review, the researcher conducted and analysed qualitative interviews with structural engineers in the context of a research project on innovation in large-scale construction projects. These were guided, semi-structured interviews of explorative and narrative character with people involved in large-scale construction projects in Germany. The interviews centred around the question which features the interviewees perceived as innovative in the respective projects. They further aimed to acquire process knowledge on how these innovations had been implemented (see the interview guideline in Appendix A.1). The relatively long duration of the interviews of approximately 60 to 90 minutes assured that both exploratory findings as well as explanatory reasons could be collected. The interviews were conducted in teams of two or three researchers with different disciplinary backgrounds and transcribed by student assistants. Then, the material was opened up by a process of group coding, in which codes were inductively generated and then discussed in the interdisciplinary research team leading to a deep familiarisation with the interview material.

For the dissertation, the interviews conducted with structural engineers who were involved in early stage structural design processes were selected as an exploratory data set. Even though generated in a different context, they provided a fruitful base to explore the topic of design processes, as innovation processes in the field of structural design can be closely related to structural design processes. Furthermore, developing innovative structures usually constitutes a challenge to the design engineer and provokes the employment of multiple methods and tools, which makes it suitable to represent a broad spectrum of working approaches. Additionally, as a consequence of the often high identification and engagement with innovative projects due to their representational value, complexity, and challenges, there was a high chance of the engineers remembering the structural design process or parts of it.

A first preliminary analysis of the interview transcripts revealed the omnipresence of models in structural design. The subsequent literature review (see Chapter 3) showed that in most cases, either the specific model-use of single engineers (Hossdorf, 2003; Vrachliotis, 2017), or the different types of models, their applications, limitations, and evolutions was described. However, there were hardly any general or conceptual reflections of models and their use in the structural design process (see Section 3.1.1). This motivated to also look into other fields of research concerned with models, specifically the philosophy of science and technology. In this field, multiple different attempts to define models and to describe their epistemological and creative potentials exist. This led to the question, what actually is the model understanding of practising structural engineers, and whether there is such a thing as the creative use of modelling as a method in structural design. At this point, a first take on the research questions was formulated (Section 4.2).

As the structural design process as the context for model-use was still relevant to the research questions, the author decided to systematically analyse the explorative interviews with respect to two units of analysis: first, the descriptions of structural design processes, and second, the model understandings of structural engineers. For the analysis, interviews with structural engineers who were involved in the structural design of the projects and who explicitly talked about its process were selected. In total, 18 interviews with 24 engineers were identified (see Appendix A.2). For the first unit of analysis, these interviews were coded using codes that were partly inductively motivated by the material, partly deducted from the research questions (see Appendix A.3). The coding process included the highlighting of all relevant passages in the interviews, the writing of a short synopsis of each passage, the identification of categories in the passages and synopses, and the assigning of one or more categories to each highlighted interview passage. Then, for each category, all assigned passages were again analysed to identify the properties of the categories and the relations between them, and to develop overarching concepts that explained the phenomena.

The interview analysis with respect to the model and its use within the structural design process followed a slightly different procedure. The same 18 interviews were analysed. However, in this case, a word search for the term 'model' was performed, including all declinations of the word. Additionally, the context of these terms, i.e., the passages before and after the term, was acquired as output. The retrieved segments were analysed in a process similar to the one performed for the first unit of analysis (code-set see Appendix A.4).

The analysis of the exploratory empirical data led to two main results. First, the interviews delivered valuable insights on the structural design process. These enabled a better understanding of its character and influences, of the structural engineer's role in the process, and of the strategies to manage the process. Second, the interviews also delivered first insights into the model understanding of structural engineers. For instance, there were virtually no hints to the rather broad model definition from the field of philosophy of science and technology (see Section 3.1.2). The most common association with models were digital 3D-Models, BIM, or physical models. In this respect, it was also observed that most interviewees perceived models as rather complex entities, which contradicts the notion of models being pragmatic, idealised, and simplified reductions (see Section 3.1.2). The results from both units of analysis were condensed in conference papers that were read and commented by two reviewers each; the paper on structural design processes was also presented at a conference (Ruge & Bögle, 2019a).

However, to answer the research questions on model understandings and creative potentials of models, the exploratory interviews proved to be an insufficient data base. Reasons for that could be that the interview guideline as well as the sampling of the interviewees was tailored to another research focus, namely the generation of innovation in large-scale construction projects. Thus, it was decided to conduct a second round of qualitative interviews specifically tailored to the research interest.

5.2.2 Focused Stage: Systematic Data Generation with Qualitative Interviews

The decision to systematically conduct further qualitative interviews marked a new stage in the research process. The second round of qualitative interviews was aimed to specifically answer sub-question 1 of the research questions (see Section 4.2), and thus to generate data on model understandings and valuations of engineers as well as on the context of model-use.

As a preparatory step, an interview guideline for semi-structured qualitative expert interviews was developed. The guideline was structured by introductory questions and structuring questions (Kaiser, 2014, pp. 63-65). The introductory questions gave the interviewees an opportunity for a longer statement in the beginning of the interview, which allowed the researcher to judge whether the interviewee had understood the goal of the interview as well as how much steering would be needed. The structuring questions were used to introduce new topics in the course of the interview. They were formulated with respect to the operationalised research questions but also informed by the findings from the exploratory interviews. These structuring questions were arranged in such a way that the interview followed a plausible line of argumentation for the interviewee (Kaiser, 2014, p. 53). The final guideline can be found in Appendix B.1.

After the development of the guideline, the process of interview partner selection and acquirement started. This was guided by the main questions of which expert possesses information relevant to the research questions, and who would be capable of conveying these information in an interview (Rowley, 2012). As a result, the following criteria for interview partner selection were developed:

1. The interviewees should be structural engineers who are actively involved in the early stage conceptual design of construction projects or competitions.
2. The interviewees should have at least a few years or projects of experience.
3. It would be favourable if the interviewees worked on ambitious projects, as these potentially require special practices and approaches with respect to creative structural design. Furthermore, such projects usually entail a higher level of engagement and thus it is more likely that interviewees remember the work process in detail.

Based on these criteria, the strategy of interview partner selection consisted of requesting engineering offices that had won or been nominated for engineering awards in the last 10 years (2011–2021) in the German-speaking area. The considered engineering prices were the Deutscher Brückenbaupreis (German Bridge Engineering Award), the Deutscher Ingenieurbaupreis (German Engineering Award), the Ulrich Finsterwalder Ingenieurbaupreis (Ulrich Finsterwalder Engineering Award), and the Balthasar Neumann Preis (Balthasar Neumann Award). In total, 26 offices and if possible, the responsible engineers, were identified (see Appendix B.2). The contact was established via an E-Mail that explained the context, aim, and scope of the expert interviews and included a hand-out with additional information on the topic and relevance of the dissertation as well as the added value of the interviews (see Appendix B.3). Out of the 26 offices that were contacted, 19 engineers from 17 offices were interviewed.

The interviews were conducted personally by the researcher via video-conference (zoom) from May–August 2021. In most cases, a previous telephone contact had taken place, to further explain the nature, content, and scope of the interview. The interview atmosphere can be described as uncoerced but still concentrated. In most cases, the interviewees were pleased about the interest in their working practices and talked openly about their approaches to structural design and their model understandings. There was only one case in which the interview had to be cut short (30 instead of 60 minutes) due to other obligations of the interviewee. This resulted in the skipping of some of the introductory questions and a hurried atmosphere on the side of the researcher, and subsequently led to misunderstandings regarding the focus of the interview that influenced the statements greatly. Otherwise, some common reactions included the question what kind of results these qualitative interviews could deliver. Furthermore, some interviewees reported that the topic was hard to grasp as it was very theoretical, or that the open approach to the term model would lead to an infinitely broad terrain. In total, 22 hours and 14 minutes of audio material were generated in the 19 interviews (see Appendix B.4).

The first step of the interview analysis was the complete orthographic transcription of the interviews (Misoch, 2019). This was done by the author herself using the programme MaxQDA and completed in September 2021. The further steps were the reading of all transcripts and the highlighting of important passages. Then, an initial code-set was developed based on notes taken during the conduction and the first reading of the interviews. Using this code-set, half of the interviews were coded to test whether the code-set was adequate to capture the gist of the interviews. During this first round of coding, the code-set was iteratively adapted. Then, all interviews were coded with the final, robust code-set (see Appendix B.5).

With respect to the content, the analysis focused on several aspects. These included, for instance, descriptions of the structural design process and strategies, approaches and tools used in it, model understandings of the interviewees, descriptions of specific modelling situations, functions and reasons behind modelling or model-use as well as its effects and potentials, and model evaluations. However, even though the material proved to be adequate to answer the first research question, the need to conduct a participatory observation to directly observe the actual practices of modelling became increasingly evident.

5.2.3 Case Study: Participatory Observation in an Engineering Office

The motivation to conduct a participatory observation in an engineering office in form of a case study was the need for direct observations of actual modelling practices, in order to uncover potentials, impacts, and effects of the activity of modelling that could not be conveyed in the interviews. The aim was to gather material that could be used to answer the remaining research questions of the dissertation. These focused on the embodied practices of modelling and model-use, the interaction between engineer and model, the relation of model-use and modelling to creativity, and a method of modelling (see Section 4.2).

As there do not exist other examples of studies on this topic conducted through participatory observation, a single case study was conducted (Flyvbjerg, 2006). The aim was to undertake a first explorative venture with a method new to the field and therefore highly probable to deliver new insights, both in content and type. This would allow conclusions with respect to the suitability of this methodology for engineering research. Furthermore, it could be used as a reference and inform future studies in the field (see Section 7.3).

The conducted observation was open, which means that the observation was communicated to and acknowledged by all observed people (Knoblauch & Vollmer, 2019). Hereby, the researcher took on the role of an observer as participant. This means that the researcher was present in the field, but followed it mainly through observation (Thierbach & Petschick, 2019). Furthermore, the observation was focused, meaning that specifically the actions related to model-use, modelling, and interactions between engineers and models were observed. The observation period was four weeks. This decision was based on both content-related and pragmatic aspects. One content-related consideration was, for instance, how long structural design phases of the potentially observed projects would last. The pragmatic aspects related to the process and progress of the research endeavour as a whole, for instance, how long would it take to get oriented in the field, how much data could be generated in this time period, and which amount of data could realistically be analysed in the remaining project time.

The engineering office selected for the participatory observation was Bollinger und Grohmann ZT GmbH in Vienna. This choice is explained in more detail in Section 5.3. The field entrance was managed through a contact with the heads of both the engineering office and the Vienna branch office, which had been established by the supervisor. In an online meeting a few weeks before the observation, the overall motivation of the dissertation as well as the specific goal and the planned procedure was presented and questions from both sides were dealt with.

The participatory observation was precisely planned and prepared. The overall approach was to follow the course of at least one project in the structural design stage or one competition project, thus to be assigned to the engineers involved in this project and to follow their actions through the field. Situations that were expected to be valuable to answer the research question were meetings related to the observed project and modelling activities in the observed project but also in other projects. An observation guideline was developed, which also served as a structure for the field protocols. This guideline was informed by the research questions and the planned focus for the observation, but also by Latour's four analytical approaches to artefacts (Schubert, 2019, see Appendix C.1). Furthermore, a structure for daily field diary entries was developed to prepare the documentation of the observed situations (see Appendix C.2). Lastly, a presentation explaining the overall aim of the dissertation and the specific added value of the participatory observation was prepared.

The observation took place from 01.03.–25.03.2022. In this time, mainly the course of one project and the engineers working on it were followed (see Section 5.3). Furthermore, due to the presence of the researcher in the open-plan office, many other situations could be observed that were not in direct relation to the project. These included, for instance, spontaneous consultations between colleagues on a certain subject or online workshops by employees. The researcher herself was assigned a free table and a desktop computer in one area of the open-plan office. On the computer, the researcher had access to Microsoft Teams, which was the main communication channel of the office, as well as to all project files of ongoing and past projects from the office.

The field entrance was facilitated by the fact that the professional socialisation of the researcher was similar to the one of the observed people and the researcher already had acquired significant knowledge on design processes and modelling through the interviews. Through 'speaking the same language', it was easy to understand what was happening in the observed project. At the same time, the constant reflection after the field stays ensured that the necessary distance to the field could be upheld. For this purpose, the writing of the daily field diary entries was particularly helpful. Furthermore, this routine helped to reflect on the challenges and opportunities during the observation. Frequent referring to the observation guideline helped to stay focused and to ensure that actions relevant to the research questions were documented. Situations that were protocolled were, for instance, meetings the researcher observed from her desk, meetings with respect to the observed project, or presentations and workshops that were organised by the office on topics related to modelling. While observing these situations, the researcher made notes on what was said and done as well as on her reactions. Furthermore, striking features, contradictions, problems, routines, what was emphasised and what was not articulated, the everyday practices, and seemingly irrelevant details were documented. After returning from the field each day, these notes were digitised into field protocols and a field diary entry was written. By also documenting the researcher's personal impressions, ideas, and feelings towards what was happening in the field, the inherent subjectivity of the method of participatory observation could be made controllable and useable.

The observation period can be roughly divided into three phases. For each phase, the aims and the respective actions to achieve these are summarised in Table 5.2.

Table 5.2. The aims of the three stages of the participatory observation and the respective actions that were taken to achieve them.

Phase	Aims	Actions
1	Get to know daily routines, identify valuable situations for observation	Describing the surroundings, the office, the social hierarchy, and the recurring processes in the field.
1	Introduce researcher to the field, explain her presence, get approval from all observed people	Engaging in personal conversations; explaining the research focus in personal conversations and in presentations; distributing additional information (see Appendix C.3).
2	Observe relevant situations remote	Directly approaching employees to get included in relevant situations remote.
2	Generate additional data	Conducting additional interviews; getting acquainted with the tools and programmes used in the observed project.
3	Observe relevant situations at the office	Observing of relevant situations at the office; direct observing of modelling activities.

The first phase was of mainly exploratory nature. The two main aims in this phase were to get oriented in the field and to introduce the researcher to the field. Furthermore, the previously developed templates for the protocols and diary entries needed to be adapted to what was actually being observed. In the first few days, the researcher stayed fairly passive. This meant that she observed every situation she was offered to participate in to get a feeling for the routines and procedures of the office in general as well as of the project she was assigned to. After a few days, situations important to the research questions could already be better identified. For instance, meetings with externals were not ideal with respect to the observation of modelling practices. In contrast, individual modelling work or internal meetings focusing on the project's model were much more relevant. The researcher thus started to actively approach employees and ask them to be integrated in these situations. The observation thus slowly transformed from an exploratory to a focused observation. A day-by-day overview of this phase of the observation can be found in Appendix C.4.

On Day 7 of the observation, the researcher tested positive for Covid-19, and had to stay in isolation for ten days according to the then valid regulations in Austria. The researcher was met with much sympathy, which is exemplified in the fact that the secretary of the office sent over groceries and a company laptop, thereby enabling that the observation could continue remote. Due to the isolation, the observation shifted into a focused phase: Situations could no longer be observed ‘by accident’, as the researcher had to either know about a situation in order to request to be integrated via Microsoft Teams, or rely on the observed employees to invite her from their own initiative. This required the researcher to take on a more active role than in the exploratory phase, planning and organising situations herself. It also became increasingly evident how much working time in the office was actually spent in meetings, and that most of the concentrated modelling work was either done in meetings, or late in the evenings and during the weekend. This resulted in little real observation time during the remote phase. The time of remote work was instead used to conduct additional interviews, to complete the descriptions of the office space, the observed project and engineers, the tools, programmes, and modelling techniques used in the project, to reflect on what was already observed, and to get more acquainted with the tools used in the project. A day-by-day overview of this phase of the observation can be found in Appendix C.5.

During the last week of the observation, the researcher was again present in the field. In contrast to the first week of the observation, the researcher took on a more active role. Additionally, in this phase of the observation, the researcher felt more comfortable in the field. These circumstances enabled the fruitful observation of several interesting situations within and outside of the project context. A day-by-day overview of this phase of the observation can be found in Appendix C.6.

Following up on the observation, the researcher conducted additional interviews with the four engineers she had observed the most. These were the three engineers who were the main actors of the observed project, and one engineer who had just started at the office at the time the observation started, and who thus had a fresh perspective on the office as well as the approaches and methods employed there. Guidelines for these interviews were specifically designed for each interview and consisted of open questions with respect to the observed situations but also of questions adapted from the interview guideline used in the previous stage of research (see Appendix B.1).

In total, 17 field diary entries, 34 field protocols, 7 additional descriptions of the office, the project, the tools, and the observed employees as well as 6 interviews were conducted during the participatory observation (see Appendices C.4-C.9 for detailed information). The data was analysed in an iterative process. This process included several rounds of coding and interpretation, which were informed by concepts gathered from the literature review and from previous empirical stages.

Already during the field stay, a reflection of what had been observed happened every day, supported by the writing of the daily reports. After returning from the field, the researcher transferred the conducted material to MaxQDA and read everything cohesively multiple times. The aim of this was to reach an in-depth understanding of the data as well as recall everything that had been observed and experienced in the field. While reading, multiple thoughts, possible concepts, cross-connections, and ideas emerged, which were directly documented in memos in MaxQDA. From this first round of analysis, the most prominent aspects were discussed with the supervisors and colleagues.

After discussing the first insights stemming from the grounded engagement with the material, the material was read again through the lens of the research questions. Hereby, everything that was perceived to be relevant to the research question was coded with 'important' to be made available for further analysis. These passages were then jointly analysed and an initial code-set was developed. The process of in-depth reading of the protocols and writing memos was repeated several times, alternately focusing on single protocols that were seen as especially relevant to the research questions, and on segments coded with the same codes. The categories and concepts that emerged during this process as well as their properties were structured and related to each other using mind-maps. This led to an iterative adaptation and concretisation of the categories and concepts. Regularly, the preliminary findings were presented and discussed with the supervisors. Overall, this process led to the grouping of the concepts into two main categories: practices that are related to the *environment* of the modelling activity, and practices that are related to the *activity itself*. These two main categories inform the structure of the section on modelling practices in the empirical findings (see Section 6.3).

5.3 Case Study: Modelling Practices in the Engineering Office B+G Vienna

In this section, the case study on modelling practices in structural design, which was conducted using participatory observation, is explained in more detail. The goal is to provide the relevant contextual information for the interpretation and understanding of the findings presented in Chapter 6. The section makes use of the descriptions and the interviews that were conducted during the participatory observation (for the reference guides, see Appendix C.8 and C.9).

The participatory observation of the modelling practices can be regarded as a single case study of a paradigmatic case (Flyvbjerg, 2006). The main criterion for the selection of the engineering office was that it should have an accounted expertise in digital modelling. The selected office was Bollinger + Grohmann Vienna (B+G; about this office, see Cachola Schmal, 2001, 2004; Schittich & Cachola Schmal, 2013). B+G is an international and highly recognised medium sized engineering office with head-quarters in Frankfurt and branch offices in different cities in Europe, Australia, and Asia. Their main areas of expertise are structural design, the development of complex geometries, and digital design. Their general focus on innovation in all of their projects and their special expertise in the development of digital and parametric tools (e.g., the parametric design tool Karamba) were regarded to be particularly suitable to answer the research questions on creative modelling practices in structural design. Specifically in the Vienna office, where the design tool Karamba was and still is being developed, there are many interesting projects with a strong focus on complex geometries and digital and parametric modelling.

5.3.1 The Setting: The Office B+G Vienna and the Observed Project

The office B+G Vienna is an open-plan office. Around 35 people work there in four interconnected areas with 8–12 desks each. The atmosphere in the office is familiar, employees address each other informally. The office also offers social events to the employees. For instance, during the observation period, a joint ski-trip took place, as well as joint lunch breaks or office events such as barbecues. In general, a strong work ethic was observed in the office: Employees feel responsible for their tasks and when necessary, work long hours to meet deadlines, or work from home while in isolation due to a Covid-infection (Description-office).

Due to the still ongoing pandemic in March 2022, employees worked partly remote, partly at the office. A significant time of the work day was spent in meetings, most of them via Microsoft Teams. Especially the project leads regularly spent 5–6 hours per day in online meetings. But also for project engineers, who were usually engaged in individual work, such meetings made up for a considerable amount of time on a regular working day. Employees consulted each other when questions or problems occurred. These questions or problems were often related to the input of certain parameters into a programme or the output and visualisation of certain results within a programme. This happened both between employees working on the same project and between employees working on different ones, although it has to be noted that at the time of the observation, about half of the employees were engaged in a number of similar competition projects.

The observed project was also a competition project. The task was to design a building complex which included residential housing, everyday infrastructures such as kindergardens, cafes, and grocery stores, as well as office, hotel, and leisure spaces for about 5000 inhabitants. Hereby, the main design criteria were to exploit potentials of natural light and ventilation, to connect internal and external spaces with each other and with the surrounding nature, to utilise state of the art technology and empower digital transformation, to embody sustainable and environmental design, and to sustain the surrounding environment as much as possible. For these criteria, an overall master plan should be developed, which included the exploration of constructability constraints and opportunities and modular construction strategies. Apart from B+G Vienna, an architectural office and five other specialist planners were involved.

In the project, B+G Vienna was responsible for constructability, modular construction strategies, and sustainability. Essentially, the task for the structural engineers was to develop a concept for the load-bearing structure of the architectural design.

As the project was actually a prototype of a much bigger project, the overall architectural concept was clear. However, the specificities were still being developed by the architects in parallel to the development of the structural concept. One of the involved engineers described their situation as follows: "We did not have a clear concept from the architects, but already needed to evaluate it with respect to potential structural systems and constructability" (Int-observation-06). As it was not a standard project but geometrically complicated, the specificities such as the structural axes or the connections between the different building parts needed to be decided on in an iterative process. In this process, the structural engineers made proposals that were evaluated by the architects with respect to the compatibility with their design ideas. Thus, the engineers had a lot of freedom and co-determined important parameters with the architects. In that sense, one of the engineers named the role of the engineers "co-designers" (Int-observation-06), and another described the task as the "mapping of a working structure onto the architectural design, but with a lot of freedom" (Int-observation-04). Furthermore, the team from B+G also supported the architectural office in the organisation of the project.

The observation period covered the last four weeks leading up to the original deadline for the submission, which was then postponed last-minute for a week. At the beginning of the observation period, three employees from B+G Vienna were involved in the project; at the end, a fourth person joined the project team (see Appendix C.9). In the beginning of the observation period, the project members were still involved in other projects, and thus had little time for the observed project. Furthermore, as described above, the engineers also depended on the progress of the architects in order to adapt and detail their structural concept. In the second and third week of the observation, the project engineers were able to dedicate more time towards the project, which resulted in significant progresses with respect to the structural design. As a result, this time period yielded for more interesting situations to observe with respect to modelling practices. During the last week of the observation, the project moved into an intense phase, as it was the week prior to the planned submission of the competition. The project lead was continuously in exchange with the employees working on the project, checking in with every one of them several times a day to discuss the progress and the next steps, and address problems that had surfaced.

5.3.2 The Main Actors: Tools and Observed Employees

In the observed project, the tools that were employed to organise the project and develop the structural models and the people using these can be identified as the main actors with respect to the modelling practices.

With respect to the tools, most project work was supported by two distinct types of tools. First, tools to support the organisation of the project within the structural design team but also among all collaborators in the competition project. Second, tools used primarily for content-related purposes, that is to develop the structural design and generate models for it.

For the organisation of the project, mainly two tools were used (see Table 5.3). The first tool was Microsoft Teams, which was also used as a general organisational and co-working tool in the office. Almost all meetings, external and internal, were done using this tool. The second tool was Miro, which is an online whiteboard for collaborative work. Especially the work with Miro was seen as beneficial for the speedy process of the competition project and the intensive collaboration with the architects (Int-observation-04, Int-observation-06).

Table 5.3. The tools used for the communication within the observed project and for its organisation.

	Microsoft Teams	**Miro**
Purpose	General office organisation and communication tool; organisation of the project and the collaboration within the whole design team and internally at B+G.	Online whiteboard as base for the project meetings and to protocol them; representation of the current state of the architect's and consultant's work; communication object.
Content	Meeting organisation; links to documents; chat-discussions on organisational and content-related topics; distribution of work.	Inspirational pictures; intermediate results of the architects and the consultants; protocols of the design meetings.
Users	All members of B+G and of the project's design team, including architects and all other consultants.	All members of the project's design team, including architects and all other consultants.
Frequency of Use	Every day, constantly open; frequency of use higher and discussed tasks more specific toward the end of the project.	During the project meetings (twice a week); prior to the meetings to prepare them; afterwards to recollect what was discussed.

For the development of the structural design, different tools were used in the different phases of the competition project. In the beginning, a lot of the conceptual work also happened with Miro, which was used to collect and discuss inspirational pictures (Int-observation-04). At the time of the observation, the competition was already in a more advanced phase, and modelling work happened mostly with two tools (see Table 5.4): Rhino 3D, a CAD-Programme, and the Karamba-Template, a tool that was developed in the office and allows people without coding skills to use Karamba, a plug-in for Rhino 3D for structural analysis. Occasionally, the Snipping Tool was used to generate quick concepts on top of already existing models.

During the time of the observation, the primary goal was to develop a geometrical model of the structure with Rhino 3D, and to develop a calculation model for the same structure with the Karamba-Template. The Rhino 3D model represented the

Table 5.4. The tools used for the development of the structural model in the observed project.

	Rhino 3D	**Karamba-Template**
Purpose	CAD-Programme; drawing of the structural model; same programme as the architects use for their design; initially: geometric representation of the structural system; later: geometry for the structural model in combination with the Karamba-Template model.	Parametric set-up linking Rhino 3D geometry with structured data in Excel to create a Karamba model that can be dimensioned and optimised; definition of materials, cross-sections, loads, and load-cases.
Content	Geometrical model of the structure divided into layers: architect's geometry, different parts of the structural model, work layers, layers to support the work in the model, i.e., with reference grids, lines, etc.	Made up of multiple parts in different programmes: a geometry in Rhino 3D, a Grasshoper-file with a Karamba plug-in, an Excel-file that connects the geometry with the Grasshopper file.
Users	All employees at B+G; employee-05: generation of the geometrical structural model; employee-06: generation of the simplified geometric model to connect with the Karamba-Template.	Employee-06, supported by employee-04.
Frequency of Use	Whenever there is time to get into modelling; initially: sporadically a few times a week; later: every day.	Initially: sporadically to get the Template working; later: intense and more frequent use to perform calculations and iterative optimisations.

exact geometry of the structure as outlined by the architectural geometry. In contrast, the Karamba-Template model contained all structural elements, parameters, loads, foundations as well as the structural relations between them, but had a much more simplified geometry and did not exactly represent the structural system geometrically. The two models were developed in parallel by different employees. Towards the end of the project, these two models were combined, resulting in one complete and geometrically exact model that could be calculated using Karamba.

The choice to use the combination of Rhino 3D with the Karamba-Template was a very deliberate one. The main reasons were the parametric set-up and the possibility to work on the geometrical model and the structural model at the same time:

> "The benefit was that the model could be adjusted in the process very easily due to the parametric set-up, which was good as the concepts and design of the architects changed a lot during the process and otherwise, we would not have been able to get started with our own concept for a long time" (Int-observation-06).

Another engineer involved in the project further stressed the great flexibility of Rhino 3D:

> "In the project, we used Rhino for multiple different modelling steps: We developed a concept model and a geometrical model of the structural concept, we also used it as a base for the Karamba-model, as a communication model to communicate our structural concept to the architects, and later for the visualisation of the concept for the report" (Int-observation-05).

The use of the Karamba-Template was furthermore a strategic decision with the goal to test it with employees who had not used it before, and thus to assess the added value of the Template in terms of speed and usability.

During the observation, four employees from B+G Vienna worked on the project: one project lead who had the overall responsibility, and three project engineers. As described above, the task of developing the structural design had been divided into two sub-tasks: to develop the geometrical model of the structure with Rhino 3D, and to develop the calculation model of the structure with the Karamba-Template. Each of the two tasks was assigned to one of the project engineers who were involved in the project from the beginning. Later in the project, a forth employee joined the project team to support the modelling work in Rhino 3D. Thus, already through the set-up of the project and the distribution of the work, a high necessity for communication arose. The different responsibilities, experiences, and tasks of the project employees are summarised in Table 5.5.

Table 5.5. Overview of the employees involved in the observed project and their roles (see also Appendix C.9).

Employee	Responsibility	Experience	Tasks in Project
Employee-04	Project lead, overall overview and main responsibility for the project.	Trained architect, working experience as structural designer in early stage conceptual design, experienced in Rhino 3D and Karamba (Template).	Project organisation (supporting the architects); decisions on further approach, next steps, and work distribution among employees; guidance and instruction with respect to Rhino 3D and Karamba-Template; consultation for decisions on the model development.
Employee-05	Main responsibility for the geometrical model in Rhino 3D.	Trained architect, working experience as structural designer in early stage conceptual design of structures, experienced in Rhino 3D and Karamba.	Proposals and decisions regarding the geometrical realisation of the structural concept; development and refinement of the geometrical model; guidance and instruction with respect to Rhino 3D and Karamba.
Employee-06	Main responsibility for the development of the calculation model with the Karamba-Template.	Trained engineer and architect, little experience with Rhino 3D, no experience with Karamba.	Set-up of the calculation model with the Karamba-Template; analysis of the results and iterative adaptation of the calculation model.
Employee-07	Supporting role.	Trained architect, experience in Rhino 3D and Karamba.	Support for the generation of the final report through modelling and rendering in Rhino 3D in the last two weeks of the project.

So the model is actually a playground where I make up my little blocks, my construct, my simple thought construct, which can then ultimately be played back into a real building or into a construction. So it's actually my little playroom. (Int-models-07)

6 Towards an Understanding of Model-Use and Modelling as Methods for Creativity in Structural Design

This chapter presents the findings from the empirical research. Thematically, it is divided into three main sections, which are synthesised in a concluding forth section.

The first section deals with *the structural design process* as the context in which model-use and the activity of modelling are embedded in and thus influenced by. Hereby, it focuses on the role of the *engineer and their contribution to creativity* in this process. To do so, the task, skills, and influence of the design engineer in the process are analysed. Furthermore, different working modes and focal points of the process as well as strategies the design engineer engages in are described. The section ends with an intermediate reflection that presents a qualitative scheme of the structural design process and the design engineer's role in it.

On this base, the second section takes a closer look at *the model and its contribution to creativity in structural design.* The aim is to develop a better understanding of what constitutes models in structural design as well as of the effects and impacts of their use. The section focuses on three main aspects: first, model-terminologies, second, model-use and the questions of why and how models work and which effects and impacts they have on the design process, and third, model evaluations by engineers. In the intermediate reflection, a qualitative definition of models and their role in structural design is developed.

In the third section, the focus shifts from the model as an object to *the activity of modelling and its contribution to creativity.* Two practices of modelling are distinguished: first, practices that can be described as engaging with the model environment, and second, practices that can be described as engaging with the model content. The section concludes with an intermediate reflection on the different types of interaction between engineer and model in these practices and the practical nature of modelling.

Finally, the last section of the chapter synthesises the findings by describing *model-use and modelling as methods for creativity in structural design.*

6.1 The Structural Design Process and the Engineer's Contribution to Creativity

The structural design process is a creative process with the aim to generate the design of a structure as its result (see Section 2). This section presents findings on how the structural design process is perceived and described by structural engineers involved in the early stage design of structures. Hereby, the focus is on the role of the design engineer in this process, and specifically on their contribution to the generation of creativity within it. Thus, the findings can be regarded as empirical first-hand insights into how personal motivations, attitudes, and reflections shape the structural design process, the generation of creativity within it, and the structural design as its end result.

The findings from the interviews largely confirmed the aspects that were described in Section 2. Hereby, two aspects were particularly emphasised by the interviewees.

The first aspect is that most engineers described the structural design process as an open, creative, and individual process that cannot be predetermined. This means that the outcome as well as the way to achieve it are not known in the beginning – the process starts with the famous blank paper:

> Planning means you sit in front of a white paper and you need to have an idea. Usually under relatively high time pressure and other constraints. (Int-process-04)[1]

This perspective on structural design renders the design engineer with a high responsibility with respect to the process of structural design and its outcome.

The second aspect that was highlighted by the interviewees is that while being open, creative, and individual, the structural design process is subject to a multitude of boundary conditions, constraints, and requirements that are oftentimes conflicting.

> The problem was that we had a lot of geometrical constraints for the placements of the struts. We could not place them in the elevator or staircase areas, and we needed to ensure that all walkways remained free. That was one thing. But the other thing was the static aspect. The struts needed to make sense from that perspective as well, the distribution of forces needed to make sense. (Int-process-08)

Additionally, a good structural design should reflect the specific task, the client's aspirations and requirements, the architectural design, and the location of the structure defined by the surrounding natural and built environment.

[1]Overviews and reference guides of the interview transcripts, field diary entries, field protocols, and descriptions used in Chapter 6 can be found in Appendices A.2, B.4, and C.4–C.9. All of the used excerpts have been translated from German to English by the author.

> Designing bridges and doing it right, also for the site. That is very important. Bridges must actually be designed for the respective site. (Int-process-10)

Additional influences that should be taken into account with respect to each structural design are, among others, constructability, economic constraints, the timeline of the project, local specificities (climate, location, ...), or existing structures. Furthermore, a multitude of general boundary conditions, constraints, and requirements that apply to all structural design projects need to be respected, such as the legal frameworks in which the design process happens that manifest in norms, regulations, or the HOAI planning phases (see also Addis, 1990, Figure 2.2).

Depending on the project, the specific configuration of these boundary conditions, constraints, and requirements varies. Likewise, whether all of these can be successfully fulfilled is largely influenced by the specific project context. Furthermore, luck or chances can play decisive roles in the process or even determine success or failure of the whole project. For instance, one of the interviewees explains for the case of a bridge renovation:

> And then we got lucky! And our luck was that the structural deficits we had calculated were compensated by the new material values we obtained in the empirical tests. This could have also been different. It could have also been the other way around, and then we would definitely have had to stop the project. (Int-process-19)

There is an inherent tension between these two aspects. For one, structural design, as any design process, is an open, creative, and individual endeavour that is influenced greatly by the design engineer. For another, there are a multitude of oftentimes conflicting boundary conditions, constraints, and requirements that usually cannot all be met. This dichotomy has become apparent also in the descriptions of structural design presented in the Introduction and in Chapter 2. For instance, structural design has been described as a field that "connects seemingly contrasting fields such as art and science, intuition and empiricism" (Rappaport, 2017), and thus requires "not only logic and scientific but also creative and inductive ways of thinking" (Kloft, 2014). In consequence, the interviewees characterised the process as difficult, intense, exhausting, and full of friction. One of the interviewees describes that often, multiple aspects need to be considered simultaneously requiring an integral approach:

> It always flows into each other. Because when you design, you need to think in networks and simultaneously integrate multiple aspects into your considerations. (Int-process-06)

This integral approach however, requires that the structural design engineer is able to concentrate and deeply engage themselves into the task and develop new ideas for the structural design while at the same time keeping in mind and respecting the multiple boundary conditions, constraints, and requirements, an aspect already acknowledged by Duddeck (2002, p. 47). To better understand how this can be achieved by design engineers and what their contribution to creativity in structural design processes is, the following analysis focuses on four aspects: 1) the engineer's task, skills, and personal influence on the process and its result, 2) the different working modes the engineer engages in that facilitate the rapprochement to the structural design as its end result, 3) the strategies engineers employ to steer the process, and 4) the interdependencies between these aspects.

6.1.1 Tasks, Skills, and Personal Influence of the Design Engineer

In order to better understand how a structural design is developed, it is important to assess the role of the design engineer in this process and to understand how they can influence it. To this end, the design engineer's task in this process, the skills needed to fulfil this task, and the design engineer's influence on the structural design process and its outcome are analysed.

Task

In general, the structural engineer's task is to *develop the structural design.* Hereby, often the apt solution for a problem does not yet exist. Thus, the design engineer needs to creatively develop concepts for the structural design. One usual approach would be to conduct variant studies in order to find a solution for the specific case, while identifying and assessing possible risks for each variant. Making something feasible further implies uniting different requirements and boundary conditions. However, as emphasised by the interviewees, the task of the design engineer cannot be reduced to making something technically feasible and constructible. Instead, it further encompasses the design of the load-bearing structure, meaning the definition of its form in such a way that it is elegant and no parts of it can be taken away without impacting its function. Another aspect the interviewees mentioned in this respect was the pushing of the boundaries of feasibility, and thus the creation of something new and innovative.

Aside from developing the structural design, another general task of the design engineer is to *navigate the process of its generation.* Navigating the process of structural design includes collaboration and communication. As construction projects are highly interdisciplinary endeavours and the structural design has multiple interfaces to other parts of the project, collaboration and communication happens, for instance, with architects, clients, construction companies, specialist planners, and regulation authorities. Recurring topics are, for instance, the explanation of the structural design and if necessary, its defence against opposing arguments.

Skills

To fulfil the described tasks, structural engineers need to have a broad spectrum of diverse skills. On an abstract level, the interviewees stressed that the design engineer should possess of analytical skills as well as the capability to work conceptually and recognise connections, to transfer findings, results, or experiences from one context to another, and to be creative. As one engineer describes, structural designers need to have the ability to "think outside of boxes. That means we should not only concentrate on our discipline, but also need to identify interrelations" (Int-process-06). Among the multitude of skills named by the interviewees, four categories were identified[2].

First, the structural engineer must possess of *fundamental and specific disciplinary knowledge*. The specific knowledge needed depends on the respective project context and can range from knowledge on statics and dynamics, to knowledge on parametric design tools or FE-calculation, to knowledge on specific construction materials. This type of knowledge can be attributed as explicit knowledge that can be gained during university education. However, as the knowledge that is required for the realisation of projects usually exceeds what has been taught at universities, a key asset of structural designers stressed by the interviewees is the continuous willingness for further study.

Second, in addition to this explicit disciplinary knowledge, the interviewees emphasised that the design of structures also requires *implicit disciplinary knowledge*. This includes, for instance, knowledge on the behaviour of materials under diverse conditions, on construction and materialisation processes, or on the overall feasibility and reasonableness of structural systems. The interviewees referred to this kind of implicit knowledge with terms such as "a feeling" (Int-process-05; Int-process-08) or "deep and first-hand knowledge or experience" (Int-process-04). In the opinion of most of the interviewed engineers, this implicit knowledge is derived naturally from experience and can be characterised as a kind of tacit knowledge. This refers to a non-codified, unarticulated knowledge which is tied to senses, physical experiences, intuition, or implicit rules of thumb. Tacit knowledge is acquired via informal take-up of learned behaviour and procedures, but also in processes of subception, meaning learning without awareness (Howells, 1996; Polanyi, 1966). This is illustrated by the following interview statement:

> If I say, 'I don't believe that', then it's usually true, there is a mistake [in a calculation]. You develop a gut feeling for statics. … So, you have to have some kind of physical access to the material as well. … But there is no point in just saying 'That's wrong', [the young engineers] have to learn for themselves: What is a weld seam? How much space does it consume? Where are the obstacles? And then you will learn to design. (Int-process-05)

[2] This subsection largely builds on findings previously published in Ruge and Bögle (2021a)

Third, the interviews revealed that there is a certain way of thinking necessary for structural design, in the following referred to as *engineering thinking*. In the interviews, three overlapping aspects of engineering thinking were identified:

1. There seems to be a general understanding to *approach* structural design in a *conceptual* way. Several structural engineers emphasised that structural design means developing concepts, one of them stating that “many aspects need to be considered simultaneously by lateral thinking that tries to combine all sides of a problem” (Int-process-06). In this context, one engineer described how this conceptual approach can lead to a “sudden emergence of an idea or solution” (Int-process-05).
2. Structural engineers should possess a “*solution-oriented mind-set*” (Int-process-04), as well as a certain confidence that the structural design will be feasible and solutions will be found in the end. This becomes tangible, for instance, in an attitude to “always look and enjoy looking for solutions to problems” (Int-process-05). As one structural engineer stressed, rejecting challenging designs by stating they won’t be feasible is not an option: “I can’t say – that’s not possible, that’s not possible, and that’s not possible – I have to state how it works” (Int-process-21).
3. Engineers often focus on a *clear aim*. One structural engineer stated that to find a good solution, they need “an existing and somehow pressing problem” (Int-process-05). Then, as the interviews revealed, these problems can be tackled by a “systematic approach” (Int-process-20): By picturing the desired outcome, engineers validate it by asking about the significant points of the structure, for instance, the potential risks of a specific structural design or the potential problems in the construction process.

These three aspects of *engineering thinking* – conceptual approach, solution-oriented mind-set, and clear aim – are closely related to each other. Further, they are driven by the same desire of engineers to stretch the boundaries of feasibility that are given in the form of norms or built examples, and to do “something new which hasn’t been done before” (Int-process-11). Several structural engineers agreed that this is what essentially makes a good engineer. One structural engineer stressed that engineering thinking is rather the opposite of looking in the literature or norms, but begins when you “have to think about a problem for yourself and generate your own solution” (Int-process-12). In a similar stance, another engineer states that

> Instructions are great, but the engineer needs to be above them. He can use them for orientation, but should always apply common sense and engineering sense. We need to evaluate, does this instruction apply to our case? And if not, we need to think of something else ourselves. (Int-process-04)

This converges with Addis, who states that structural design processes are highly individual, dependent on the responsible engineer, and have to be developed according to the specific task at hand (Addis, 1990, pp. 44-46).

Last but not least, *collaboration skills* are needed, meaning communication and interpersonal competences. The design engineer needs to show interest in the issues of other participants of planning processes and be open and understanding towards them. This means they should be willing and flexible enough to react to their proposals and learn from them.

> If I don't want to think about what the [project partner] does, then I also can't evaluate for myself what consequences my decisions will have on the tasks of others. (Int-process-04)

For collaboration to be productive and fruitful, it is necessary that all partners want to collaborate. Hereby, openness, interest, and curiosity with respect to the propositions of others are needed. Asking for background information to be able to understand the boundary conditions of the architects, specialist planners, or other project partners is crucial to avoid long discussions, frictions, and misunderstandings (Int-process-15).

Personal Influence

The above-mentioned skills vary from engineer to engineer. For all four categories – *explicit* and *implicit disciplinary knowledge*, *engineering thinking*, and *collaboration skills* – this can be attributed to the differing education and specialisation from engineer to engineer, as well as the differing experience gained from past projects and collaborations. Thus, a structural design process and its result can be completely different depending on the individual engineer engaged in it. With respect to this personal influence of the design engineer on the structural design process and result, specifically three aspects were stressed by the interviewees.

First, *knowledge and experience can both enable but also hinder creativity.* Thus, it is important to be aware of how the own experience shapes how one approaches structural design.

> For me, when it comes to a building, I think about the difficulties already in advance – that's normal, when you have seen a lot. The student on the other hand is completely free. And this sometimes leads to better designs, I would never have thought of something like that. But later, maybe not everything is feasible the way the student thought it would be. But you can't change that. I can't say, I am completely free now like I was 30 years ago. But I am aware of that. (Int-process-11)

Hereby, it is also of importance whether an engineer specialises in a specific kind of projects or makes experiences in different domains.

> Our employees always work on different projects. This leads to a broader experience and lateral thinking. And I think this is a beneficial approach, not to train specialists that are only competent for one thing. We want to avoid that. (Int-process-17)

Second, the interviewees emphasise that structural design is shaped by multiple decisions a structural design engineer needs to make in the process, many of which depend on the *personal perception and preferences* of the design engineer. For instance, design engineers influence the structural design through their specific take on structural design, through how they interpret the design brief, through the level of security they prefer with respect to the final design (or else through their decision to break out of known and predefined structures), or by an attitude or philosophy of what defines a good structure. In this respect, it is important who the design engineer has worked with in previous projects. As decisions based on such aspects cannot be justified objectively, sometimes a specific structure can be the result of the engineer's (and architect's) arbitrariness – an aspect that further underlines the structural engineer's responsibility for their structures.

> We needed to induce the horizontal force from the struts into the three ceilings, via a steel construction. And I was sitting there with the architect, and then we designed and designed, and we decided to go with this thunderbolt shape. That is pure engineering or architectural arbitrariness. (Int-process-06)

A third aspect stressed by the interviewees is the *personal aptitude* to engage in the creative process of structural design. Factors that were named are whether an engineer possesses a sense for aesthetics, an understanding for architecture, or the capacity to develop new concepts. The professional education and experience largely shape these aspects. In this line, several interviewees stated that there is a gap in the professional education regarding creative designing or structural design in general.

6.1.2 Working Modes and Focal Points

As emphasised by the interviewees and confirmed by the literature (see Section 2), the structural design process is a complex and individual process that varies from project to project and from engineer to engineer. However, it is still beneficial for design engineers to have an understanding of some overarching characteristics. While previous attempts to grasp the structural design process tried to identify the steps of the process by distinguishing their respective aims or goals (see e.g., Addis, 1994, p.14), in this dissertation, the aim is to concentrate not on the what but rather on the *how* of the process, a gap identified by Maffin (1998). Hereby, the section largely builds on a previously published paper by the author and her supervisor (Ruge & Bögle, 2019a).

Through the interview analysis, two different working modes were identified. The first mode is focused on the creation, meaning the forming and designing of something, in the following referred to as the mode of creation. The second mode is focused on proving and verifying what has been created, in the following referred to as the mode of reviewing. Furthermore, in the interviews, a third crucial element of the design process was identified, namely focal points that consitute important moments in the design process, which interrupt the working modes and structure the process.

Mode of Creation

In the mode of creation, the aim is to generate, to develop new things, to experiment, in short terms to create. However, it is not clear yet what the outcome will be – it is an open as well as opening process that is hard to grasp. The vague, fuzzy, and diffuse nature of the mode of creation also becomes apparent analysing the use of language in the corresponding interview segments: The descriptions are vague and cautious, the word 'something' is used a lot. One aspect that multiple interviewees raised is the development of concepts and ideas. This usually engenders the manifestation of a first idea or a rough concept.

In the context of the design process, the mode of creation can be described as a mode in which a foundation for further design activities is established. This can manifest in multiple activities, for instance, in the pre-dimensioning of a structure, the calculation of an initial concept, the creation of variants and alternatives, or in a concept being further detailed. Thus, in this mode, the progress of the design is in the foreground. Usually, a continuous improvement of the design is aimed for.

The mode of creation can happen in collaboration or alone. According to the interviewees, collaboration in this mode can include, for instance, discussing ideas with others, communicating background information, convincing partners of a developed design, get more information, or get expertise one does not possess oneself.

Furthermore, the interviews suggest that the mode of creation is influenced significantly by the tools employed. For instance, several interviewees agreed that when engaged in creating new concepts, working with computer-aided tools can limit their creativity, because these tools have their own logic and several aspects are predefined (Int-process-04; Int-process-05; Int-process-07). In contrast, most interviewees described sketches as their preferred tool in this mode:

> First, it is a lot by hand with sketches (Int-process-10).
>
> When you develop something, you start on paper (Int-process-01).

Mode of Reviewing

In the mode of reviewing, the aim is to test and verify what has been created. The mode can be described as goal-oriented. As there is a clear picture of how the design should be like as an outcome and how to get to it, the mode of reviewing follows a closed as well as closing approach. It is not about the development of something but about the reviewing of already developed concepts. Thus, this working mode is directed towards understanding rather than towards creating.

One way this mode manifests in activities is in the reflection of constraints, boundary conditions, the task itself, or other influences such as the project constellation with respect to the already developed designs. This reflection helps to develop an integral understanding, for instance, of one's own task within the project, the structural design, the flow of forces, or of the architect's ideas.

> That's actually one of the first drawings or considerations we made, the load balance of this storage. And we then saw that you can actually add on to it. (Int-process-05)

In contrast to the mode of creation, in the mode of reviewing a clear aim is pursued. The outcome is already known or at least anticipated, yet it still has to be proven. For instance, the interviewees talked about "defining the values of the forces acting on the building" (Int-process-01), "getting a single-case approval" (Int-process-04), "verifying results" (Int-process-04), "seeing if something is feasible" (Int-process-09; Int-process-14), or "proving that we have it under control" (Int-process-10). Another aim of this mode of working is the preparation of decisions. This can mean defining boundary conditions for oneself to be able to frame the task of design, deciding to follow a certain thought or idea, but also discarding what was developed so far: "We were three engineers, deciding how to proceed, by discussing and exchanging sketches on paper" (Int-process-10).

Similar to the mode of creation, according to the interviewees, a lot of different tools are used in the mode of reviewing. These ranged from mathematical and digital models to experiments on one-to-one models (Int-process-08; Int-process-09). Several interviewees stressed the significance of using "the right tool or model" for the respective tasks. Compared to the mode of creation, the interview statements suggested that the choice of tools for the mode of reviewing were more rationally than personally justified. However, the input for these models as well as the interpretation are highly influenced by personal preferences and skills of the respective engineer.

Another common activity in the mode of reviewing is the processing of results to be able to communicate them. This can mean translating the results into another format, abstracting, simplifying, or reducing them in order for other project partners to understand them. Hereby, one interviewee emphasises the importance of communicating results:

> Not only to have an idea but also to communicate it: I personally find sketches very important to transport an idea, so that the other person says, yes, we could do that. (Int-process-07)

Particularly in an interdisciplinary context, the tools used for communication must be chosen appropriately, as illustrated by the following statement:

> The base for the collaboration was the visualisation, using images and scale models. The technical planners had to give presentations on a specific topic. Every four to six weeks. It was a regular routine. And everything was in colour. We were not used to this. It was due to the visualisation and due to the understanding. (Int-process-01)

Focal Points

The interviews furthermore suggest a third element of the design process, the focal points. These focal points are crucial to the development of the structural design, as they direct or initiate the modes of creation and reviewing and thus partition and structure the design process. A focal point marks an emergence, for instance, of an idea or a decision. Hereby, it interrupts the current working mode, which is at that point frozen to its current state. Focal points can emerge during collaboration, both disciplinary and interdisciplinary, or during individual work alike.

The interviewees mostly talked about instances in which focal points were planned and consciously undergone, for instance, when results were reviewed and evaluated, collaboratively or individually, to force decisions. The interviews further revealed how these planned focal points can be triggered in meetings, e.g., with presentations of data, models, or simulations. However, as also reported by several interviewees, focal points can equally occur spontaneously, unconsciously, unplanned, or chance-like. This happens mainly within a creation or reviewing mode, for instance, when ideas emerge in the process or decisions are made unconsciously while sketching, modelling, or evaluating.

The focal points are moments within the process that direct it, therefore enabling the development. The more focal points emerge, consciously or unconsciously, the more movement and development happens in a shorter period of time, which implies a more creative process. Hereby, the interviews suggest that anything can trigger this emergence, from the models employed in a creation or reviewing mode to random circumstances. An interesting line of further inquiry would be thus to analyse how exactly focal points emerge during or in between the different working modes.

6.1.3 Strategies to Navigate and Progress the Structural Design Process

Aside from the rather rough differentiation between the working modes of creation and reviewing, a more fine-grained analysis of the interviews allowed to additionally identify specific strategies. These strategies can be used in either of the two working modes. The analysis suggests that the interviewees employed these strategies in order to navigate and progress the structural design process, in other words, to spur the emergence of focal points. The following paragraphs provide with anecdotal examples that illustrate the possible ways in which these strategies manifest in specific actions in the structural design processes. Thus, the description of these strategies can be related to the description of design processes based on “activities and strategies”, as proposed by Gericke and Blessing (2011, see Section 2.1). The identified strategies can be categorised into three types: strategies for orientation, strategies for ideas, and collaboration as a strategy.

Strategies for Orientation

The interview analysis revealed several strategies design engineers engage in to find orientation in the structural design process.

First, one common strategy that was named by multiple interviewees is to *react to or find orientation in previous similar designs, structures, or projects.*

Similarly, a second strategy is to *find inspiration in the boundary conditions of the present project.* Hereby, a very close investigation of what these boundary conditions actually are can lead to a more thorough understanding (Int-process-02), and also provide hints as to how these boundary conditions can inspire the structural design.

With respect to both strategies, to *idealise or simplify* the problem or the boundary conditions can also be a fruitful strategy. As one engineer describes in the following statement, the final structural form of an arch was found by idealising it using existing typologies and simple mathematical functions:

> So this somehow formed arch is idealised as a basket arch, which is of course a simplification in the end. But also the course of the cross-section we did not optimise arbitrarily, but rather we said: Where are we at the beginning, where are we at the end? What do we do in between? And then we said we would make a gradual transition with a sine function. (Int-process-18)

Third, several interviewees also described the benefits of using *guiding principles* for orientation. This could be to detail an initial overarching idea or concept by deductively developing the design from this starting point. Such a guiding principle could be, for instance, to only have identical structural members in a design system:

> The idea was to create a lens on these supports. And the question we asked ourselves was: If you have a lens and you want all the same rods, what should the shape be? ... And purely analytically you come up with such a shape. And that was actually still interesting. (Int-process-05)

In a similar stance, another strategy named by the interviewees was to *follow rules of thumb, or routines and procedures* that have worked in the past, and hence to employ a more systematic approach. This could, for instance, be done by asking the same questions for every structure – or in the case of this interviewee for every bridge – one designs:

> That you simply ask yourself: What does the bridge look like? ... How is it going to be built? And what... what are the engineering difficulties here or what difficulties could arise? Simply from the flow of forces, from the systems that exist. (Int-process-20)

Strategies for Ideas

With respect to the generation of new ideas within the design process, the interviewees named the following strategies.

First, in contrast to following rules of thumb or finding orientation in previous designs or overarching principles, one engineer reported that *deliberately breaking rules* can be a fruitful strategy in order to come up with new ideas for interesting structural designs:

> Any reasonable engineer would put the diagonals like this [inclining in opposite directions]. But this is totally static and not dynamic. So we decided to tilt both [into the same direction]. This is not so bad for the load-bearing behaviour, not quite optimal, but it is very important for the dynamics that are then created. (Int-process-06)

Second, as one of the interviewees emphasised, a strategy to spur the generation of new ideas and concepts is to *create an atmosphere between freedom and pressure*, and to deeply immerse oneself in the design task:

> My way of working is like this: When I have a problem, I have it in my head. And then I somehow go out into nature or lie down in the bathtub and suddenly it 'clicks', and then I have an idea and then I pursue it. And I think if you want to have ideas like that, they don't come on command. You need a little bit of pressure, but you also need space to somehow deal with it and think about it. (Int-process-05)

This can be related to the detachment from driving impulses and deeply engaging that were identified as characteristics of model developing processes in Section 3.2.1.

Another common strategy is to *take on different perspectives*, such as the one of the architect, the checking engineer, or the construction company. Questioning what was developed so far from a new perspective or combining multiple ideas or concepts can be a first step to the development of alternative variants.

> And then we thought about: What might a pure concrete solution look like? And that's how this picture came about. (Int-process-10)

Similarly to changing one's perspective on a design, multiple interviewees also reported that they usually *develop and investigate multiple different designs in parallel* and compare these to each other so that the results can inform the further progress of the project.

Another strategy for new ideas reported by the interviewees is to *change the methods or tools of design or analysis.* These range from sketches, rough estimate calculations, 2D and 3D digital modelling, physical modelling, to computational fluid dynamics or complex simulations of the dynamic behaviour of structures. For instance, switching from a 2D to a 3D model or vice versa can have surprising effects. In this line, one of the engineers described that after a first round of generating structures with computer algorithms, they took the output and adapted it manually to then again use the result as the new input for the algorithm (Int-process-06).

Collaboration as a Strategy

Last but not least, the analysis of the interviews made clear that collaboration can also be a strategy for designing. As was revealed in the interviews, when working in a team, the different members can each take on different perspectives and thus speed up idea generation as well as validation. Hereby, collaboration can happen within the structural design team but also with architects, clients, construction companies, checking engineers, other project partners, or even people not involved in the project. Explaining one's ideas, asking for feedback, listening to others, being curious, interested, and open in conversations – according to the interviewees – are essential to cultivate this strategy.

> Be curious. Talking to people in the early stages, why do you actually do it that way? And then open discussions. Because then... I've always found that if you discuss things openly with people, if you understand what the other person wants, if you present your arguments, then you always find a good solution. And in the end, everyone is satisfied. (Int-process-04)

In this line, interviewees stressed that verbalising one's own boundary conditions and constraints or trying to understand the work of others often works best face to face and that hereby, different objects play a significant role:

> That is perhaps another point that is important, we do have plans on the table now. We could have left that alone, we could have talked like that, but that's not right. That is, plans are important (knocks on the table). So with respect to your question: We had plans hanging on the wall, lying on the table, and we talked about them. (Int-process-23)

What is more, collaboration can also be productive in the sense that it can guide the joint development of the structural design, be the source of mutual inspiration, or help to estimate the feasibility of an idea. For instance, another interviewee described that

> The idea didn't come from the architect alone neither from us. It's really a collaboration, and that's how it works: You sit down together, discuss a

> problem, make suggestions. The best thing is when everyone prepares at home, they bring a few suggestions and then in the conversation it crystallises out where everyone says, 'Ah yes, that's the direction to go in.' (Int-process-17)

In this respect, one interviewee stated that the architects challenged them to think beyond their usual constraints and limits (Int-process-02). Similarly, another interviewee emphasised that working closely together with architects in a project has widened their horizon and led them to approach new projects with a more free and open mind-set (Int-process-23).

Summary

Overall, usually a combination of different strategies takes place in the context of a design process, as only thereby and in multiple iterations and feedback loops a holistic result can be achieved. This aspect has also been emphasied by the interviewees, as illustrated by the following statement:

> I have penetrated it analytically, the bridge. And empirically. But only the sum of both is then the real deal. So that's what it comes down to. (Int-process-19)

6.1.4 Intermediate Reflection: A Qualitative Scheme of the Structural Design Process

The insights from the previous sections on the structural design process and on how the structural engineer engages in it are synthesised in a scheme of the structural design process in Figure 6.1. As described before, the design process itself is characterised by its individual nature, as is the design result. Hence, the scheme will never look the same for any two structural design processes. Instead, its aim is to illustrate basic aspects and interrelations and to serve as an orientation.

The scheme shows the structural design process from the perspective of the design engineer and thus focuses on the aspects in the sphere of influence of them. Other aspects that influence the structural design process and its result, which cannot be influenced by the design engineer during a project, are implicitly referred to as the context of the design process. These aspects are norms and regulations, the project constellation, or general boundary conditions such as climate conditions and expected loads, among others. The key elements of the scheme are the design engineer, the two working modes of creation and reviewing, the strategies, and the focal points:

- The **design engineer** is both influenced by the context of the structural design process and the process itself and influencing them themselves. For this relation, the design engineer's tasks to deliver the design result and steer the design process and the design engineer's skills and personal influence, as described in

Section 6.1.1, play an important role. These interactions highly depend on the specific case, and are thus in this scheme only visualised in abstract manner.

The open, creative, and individual rapprochement process from the blank paper towards the structural design as its result is illustrated in the scheme by different types of arrows.

- The bold arrows represent the **two working modes of creation and reviewing** described in Section 6.1.2. In the scheme, these two modes alternate, however, in reality they cannot always be clearly delineated from each other, as they are not always undergone consciously, the boundaries are blurry, and the elements coalesce.
- Within the working modes, the design engineer employs diverse **strategies** to navigate and progress the structural design process. These different strategies – some examples have been described in Section 6.1.3 – are illustrated by the circular arrows within the working modes.
- The **focal points**, illustrated as dots, structure the design process and constitute points during the process, at which decisions are made and ideas emerge. This could happen either within a working mode directing it, or in-between two kinds of modes initiating the new mode.

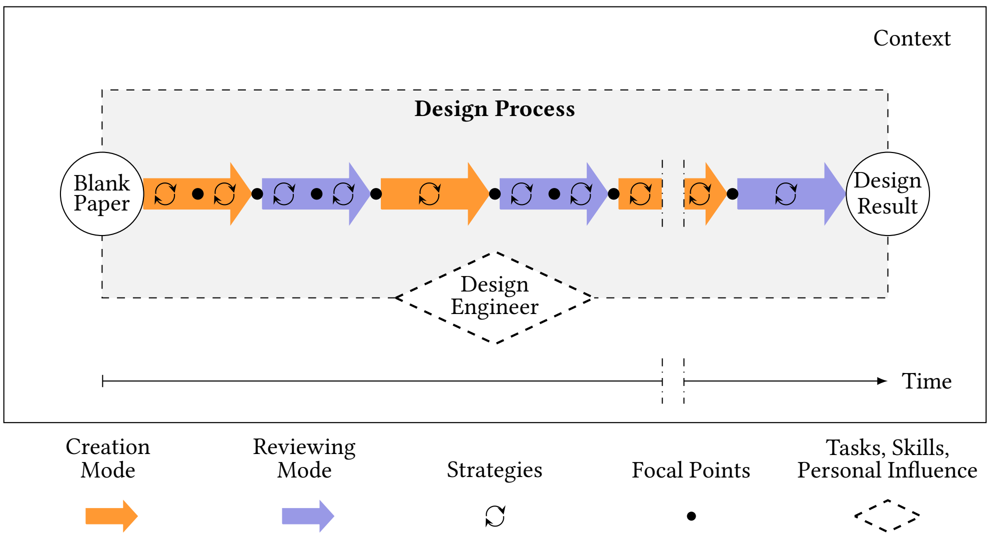


Figure 6.1. A qualitative scheme of the structural design process. The process from the blank paper to the design result is steered by the design engineer. The process consists of alternating modes of creation and reviewing, in which the design engineer employs different strategies. Furthermore, the process is structured by focal points that mark important insights, states of the design, or the change of a working mode or strategy. Overall, the design process, the design engineer, and the context the design process is embedded in influence each other.

Due to the purely qualitative and illustrative character of the scheme, the number and length of all arrows representing the working modes or strategies, as well as the number and location of the focal points within and in between the modes are only exemplary.

The Scheme in Figure 6.1 serves to qualitatively describe the nature of the structural design process. By visualising the interrelations of different aspects described in this section, it provides an understanding of the complexity and interdependencies of the creative conceptual design process and the structural engineers role in it. This understanding is ultimately necessary to better comprehend how creativity can be incorporated into the structural design process. However, in its very abstract form, the scheme does not yet allow a more detailed understanding of how engineers actually perform their task on-the-ground, of how their skills influence the specific and material actions and practices that manifest in the two working modes and in the strategies, and that lead to the emergence of focal points and consequently the design result. Hence, the question arises what exact actions or practices are contained in the bold and thin arrows showcased in the Scheme and how do these relate to the generation of creativity?

In this respect, one aspect stands out in the evidence presented in this Section: Most of the descriptions on the *how* of the design process, meaning the working modes, focal points, and strategies, included references to specific tools, models, or other objects (in the broadest sense) that engineers use in their design processes. These descriptions ranged from the mere mentioning of the used tool, model, or object to detailed narrations including advantages and disadvantages. The dominance of the subject of tools, models, and other objects demonstrates their significance in the design process and converges with previous findings (i.e., Addis, 1988; Duddeck, 2001; Schlaich, 1991, see Sections 2 and 3). The next section analyses what actually defines a model in structural design (as opposed to tools and other objects) and thus focuses on the nature, properties, and characteristics of models. On that base, it assesses their role in the context of structural design more closely in order to comprehend the generation of creativity in structural design processes from this stance.

6.2 The Model and its Contribution to Creativity in Structural Design

The aim of this section is to explore what actually is a model in structural design and what its contribution is to the generation of creativity in structural design processes. The goal is to develop a grounded understanding of models in structural design. Hereby, grounded means that the understanding is based on the interview statements and thus rooted in everyday practices of model-use within structural design contexts, and that it reflects the diverse possible functions, roles, and contributions of models in the structural design process.

To achieve this, based on the broad understanding by Mahr (2011) that "being a model is the content of a judgement in which something is being conceived of as a model" (see Section 3.1.2), this section starts out with some illustrative examples of model definitions the engineers provided in the interviews:

> Well, of course I'm stuck in this classical way of thinking of an engineer, in which a model is primarily supposed to represent a certain reality. In specific terms, I have a bridge here that is supposed to go from point a to point b, and I need a model for it, and if there are only two supports, then the simplest model is the so-called single-span girder. (Int-models-03)

> So a model to me represents something, which is not yet there. And I have to somehow develop an idea for it, how it looks, how it can be, how it interacts with the circumstances, and so on. (Int-models-04)

> For me, a model is first of all a tool to somehow simulate the later building. It is nothing more than a calculation tool or a geometry tool. To simply help me determine the dimensions of the structure or the load-bearing system or something else, so it's really just a tool, a mental tool. (Int-models-05)

> So basically I condense the complexity of a task into a simple model, which is actually the essence of the model, it is actually always a simplification, a strong, sometimes a very strong simplification. (Int-models-09)

> So for me, a bridge design that I imagine, that I can then draw with paper, with a pencil, is also a visualisation of a model. (Int-models-13)

> So I think basically the model describes for me first of all an image, image of the geometry, image of the volumes, which I use as a basis, so to speak, for further considerations. (Int-models-19)

Even though each of these statements provides only a personal and incomplete notion of what a model is, taken together they hinted towards three aspects that would be crucial to analyse in order to adequately define models in structural design and to assess their role for creativity. First, the different objects that the interviewees described to use in their design processes. Based on a summary and systematisation of these into the three categories models, other artefacts, and tools, Section 6.2.1 analyses which objects used in the design process are judged to be models and why. Second, the questions why models are employed at all, why and how models work and what effects and impacts model-use has (Section 6.2.2). And third, how model-use is evaluated by the engineers as well as what role models play for them in the design process (Section 6.2.3). These results are synthesised into a qualitative definition of models in structural design, and further analysed with respect to the role of models in the structural design process (Section 6.2.4).

The results presented in the following sections rely on interview statements by individual engineers that reflect their personal experiences and opinions. The analysis showed that each interviewee had a professional understanding of what a model in structural design is. At the same time, these understandings varied to a certain degree: The same definition was not shared among all of the interviewees. Instead, different explanations, interpretations, or biases of what makes an object a model could be identified. Thus, it can be concluded that what constitutes a model in engineering is at least partly a personal ascription, which converges with the model of model-being by Mahr (2011). Furthermore, the interviews suggested that professional education and experience largely shape the personal model-use and consequently also the model understanding of engineers – similar to how they influence the skills of structural design engineers, as discussed in Section 6.1.1. Thus, before diving into the four subsections, it is important to reflect the influence of the professional education and experience on the model understanding of engineers.

Digression: How Professional Education and Experience Shape the Model-Understanding of Engineers

Similarly to influencing other skills, the professional education and experience can also lay the foundation for the understanding how different tools that are used to develop models work, and how specific models can be used or developed. Consequently, which tools and models someone got to know in university or the first job defines what tools this engineer chooses to work with in practice, and further which tools and models this engineer can sensibly, meaning correctly, employ. One interviewee explains this as follows:

> I've been working for 25 years, and the engineer I learned with still had a thick pencil and the scale and the sheet of paper. I learned it that way, and I think that also shapes the way you work. (Int-models-04)

The interviews also revealed that the longer the education dates back or the greater the amount of experience is, the less open an engineer is to learn new tools or the application of new models and the more this engineer tends to keep using the same as before. The interviews showed that this is partly due to routines that engineers adapt in the course of their work experience. Furthermore, a certain respect for 'new' tools or models plays a role, as this can result in a reluctance to employ these tools or models personally, even though their benefits are indeed recognised:

> So I am – or at least I feel like I am almost too old to learn all these tools. I must confess, I also have respect for these tools and also for the possibilities they bring about. In this moment, I look around and there is again one of us working on a bridge, and [this person] has built the model parametrically, with a Grashopper tool, which is great, because it creates many possibilities, but it also makes it extremely difficult for me to continue to use what is produced with the tool. Because ultimately I can't handle the tool because I don't know how to. (Int-models-19)

According to the interviewees, aside from the engineer's knowledge and capabilities gained through education and experience, also the personal understanding and preferences, i.e., on how a design process should be undergone, and personal aptitudes influence the engineer's choice of tools and models. For instance, as one interviewee pointed out, the ability to imagine and visualise structures in the mind can make certain tools or models redundant while potentially creating the need for other ones. Another interviewee expresses that approaches are always very individual: "I think that's a good thing. You should use the tools, which you are actually creative with" (Int-models-08). In this respect, the interviewees suggested that the professional education should enable each engineer to get to know a wide variety of tools and models to be able to find the one that allows them to be creative.

6.2.1 Models, Artefacts, and Tools in the Structural Design Process

Design engineers employ a variety of different objects in their design processes. This subsection aims to analyse what differentiates models from the other objects used in design processes, thus to better grasp their properties, characteristics, and qualities. To this end, an overview of different objects the interviewees described to use in the structural design process is presented. Some of these objects are referred to by the interviewees as models, some of them are not – these are in the following referred to as artefacts – and some of them are described as tools used to develop models or other artefacts. The different terms for models, artefacts, and tools are summarised in the following. The aim hereby is not to provide with an extensive list of all possible objects used in design processes, but instead to illustrate the diversity of them. By analysing what the terms referring to models, other artefacts, or tools have in common and what distinguishes them, the qualities that make a model a model – in the eyes of the interviewed engineers – can be deducted. Thus, by assessing the interdependencies between the interivewees' use of the term model, "situations and arguments are analyzed, by which judgements of model-being are justified" (Mahr, 2011).

Models

First, with respect to the terms the engineers used to describe models, three different types of terminologies can be identified in the interview statements. These are terms referring to the model object itself, terms referring to what the model is representing, and terms referring to what the model is used for. The results of the terminology analysis are summarised in Table 6.1, including some examples for each category that were named by the interviewees. Some of these examples can be allocated to more than one category.

Table 6.1. Summary of the terms the interviewees used to describe models. With respect to what the terms indicate for models and their use in the structural design context, three categories were identified: first, terms that refer to properties or qualities of the model as an object; second, terms that refer to what the model is representing; third, terms that refer to what the model is used for. Some model terms can be assigned to more than one category.

	Examples for Model Terms Named by the Interviewees
Term refers to the model as an object	*Materiality:* 6B-pencil-model; acrylic model; built model; cardboard model; computer model; digital model; hand-made model; haptic model; sofistik-model; paper model; physical model; polystyrene model; virtual model; wood model. *Scale:* 1:1 model; 1:50 model. *Dimension:* 2D-model; 3D-volumetric model; 3D-calculation-model; 3D-model. *Conceptual Nature:* analytical model; associative model; concept model; geometrical model; mathematical model; mechanical model (i.e., cantilever, single span girder, single mass oscillator); numerical model; theoretical model; thought model. *Additional description or valuation:* basic model; classic model; complex model; continuous modelling; critical model; monster-sofistik-model; mother-model; preliminary model; real model; simple model; temporary model; true model.
Term refers to what the model is representing	Acoustic model; architectural model; building model; BIM; building services model; concept model; complete model; detail model; function model; load model; model of the surroundings; mechanical model (i.e., cantilever, single span girder, single mass oscillator); node model; statical model; structural model; survey model; terrain model.
Term refers to what the model is used for	3D-calculation model; analytical model; association model; communication model; continuous modelling; cooperation model; FE-model; interdisciplinary exchange model; planning model; preliminary model; presentation model; research model; statical model; temporary model; test model; working model.

The first category contains all terms that directly refer to the model object itself, that is the terms that belong to this category describe what and how the model is. It includes terms that refer to the materiality of the model, terms that refer to the scale or dimension of the model, terms that refer to the conceptual nature of the model, and terms that include an additional description or evaluation of the model. The second and the third category include terms that refer to what the model is representing and what the model is used for, respectively. Thus, depending on the model terminology chosen by the interviewees, one of these aspects is placed in the forefront. The question hence arises, whether this has something to do with what defines a model in the context of structural design.

First, through the analysis of the terms that refer to the model object, it becomes clear that the models described are very diverse: Their materiality ranges from purely conceptual thought models to digital and physical ones; some models have a specified scale or dimension or both, others don't; some models are described as critical or complex while others are described as simple. This diversity suggests that the ontology of the model object, be it its materiality, scale, dimension, conceptual nature, or other attributes, cannot really be decisive for the judgement if something is a model or not.

Second, the analysis of the terms that refer to what the model is representing similarly delivers a range of different 'things' that can be represented by models. This range spans from acoustics to architecture, loads, the mechanical behaviour, or the load-bearing structure. However, all of these 'things' have in common that they are usually connected to the design outcome. This means that they either represent parts of the design outcome and the behaviour of it, or other entities that are in relation to the design outcome, as in the case of the "model of the surroundings".

Lastly, the analysis of the terms that refer to what the model is used for suggests that models fulfil a wide range of purposes, such as calculation, analysis, association, idea generation, or testing. Furthermore, the terms reveal that the described models fulfil the aim to get to know more about the design outcome, meaning the models employed by the interviewees in the design process are usually employed for epistemic purposes. More specifically, the terms do include a reference to the future, in the sense that they specify what actions can be performed with these models or what can be found out with them.

Artefacts

The interviewees also mentioned several other objects that they did not explicitly refer to as 'models', but that are still relevant in the structural design process. By not referring to them as models, whether consciously or unconsciously, the interviewees do not ascribe these objects the status of a model (see Mahr, 2011). These objects are in the following referred to as artefacts. An overview of the terms used by the interviewees can be found in Table 6.2. In order to derive model properties, characteristics, or qualities from these ascriptions of what is a model and what is not, the artefact terms by the interviewees are compared and contrasted with the model terms.

The artefact terms can be sorted into the same three categories as the model terms. With respect to the terms referring to the artefact object itself, the same diversity exists as in the model terms. Similarly, with respect to what the model represents,

Table 6.2. Summary of the terms the interviewees used to describe artefacts other than models. With respect to what these terms indicate about artefacts and their use in structural design, three categories were identified: first, terms that refer to properties or qualities of the artefact as an object; second, terms that refer to what the artefact is representing; third, terms that refer to what the artefact is used for. Some artefact terms can be assigned to more than one category.

	Examples for Artefact Terms Named by the Interviewees
Term refers to the artefact as an object	*Materiality:* hand sketch; physical object; pictures in the head; rough concept; sample; visual mock-up; visualisation. *Dimension:* 2D-sketch; 3D-animation; 3D-sketch; floor plan; perspective; section; site map. *Conceptual Nature:* comparison; data collection; geometrical concept; synoptical comparison. *Additional description or valuation:* exact representation. *Type:* aerial photographs; drawings; drone shots; FE-calculation; norms; photographs; plans; presentation; sketches; specialist books.
Term refers to what the artefact is representing	As-built-plans and data; built references; construction records; data collections; exemplary projects; example collections; FE-calculations; floor plan; geometrical concept; plan of the site; rough concept; section; site measuring; site plan; pre-dimensioning.
Term refers to what the artefact is used for	Comparison; decision matrix; demonstrator; FE-calculation; mock-up; pre-dimensioning; presentation; sample; site plan; visual mock-up.

the terms also referred to all kinds of different entities that relate to the design outcome. With respect to the model-use, however, a difference can be observed: Rather than being used for finding out more about the object it represents, the terms referring to the artefact-use suggest that artefacts are more centred on representing or demonstrating existing knowledge about entities. Thus, they included a reference to the past (representing what has already been found out) rather than to the future (gaining additional knowledge). This difference in the quality of use associated with artefacts versus models suggests that the question of the use of models is crucial for the development of a model definition in structural engineering.

Tools

The interviews further illustrate the strong relation between models or artefacts and tools. As stressed by several interviewees, often a specific model or artefact requires the respective tool to be generated with and vice versa, the tool shapes the model or artefact that can be generated with it to a certain extent. Thus, not only the mentioned models and artefacts but also the specific tools to develop models or other artefacts that were named by the interviewees were analysed. Examples of tools named by the interviewees are, among others, BIM-capable programme, CAD-programme, Civil3D, communication tools, computational fluid dynamics, databases, Excel, FE-programme, graph paper, Grashopper, InfoGraph, Karamba, parchment paper, pencil, Powerpoint, Revit, Rhino, Rstab, self-written programmes, Sketch-Up, sketching paper, Sofistik, three-dimensional tools, and VBA.

Analysing the context in which these tools were named, they can be further specified with respect to four aspects: 1) whether and to what extent a tool defines the structure of the content that can be generated with it, 2) whether and to what extent the tool defines the accuracy of the content that is generated with it, 3) the barriers to start working with the tool, and 4) the actions that can be performed with it.

First, one example for the aspect whether and to what extent a tool defines the structure of the output generated with it is that using pen and paper instead of a CAD-programme has implications for the structure of the resulting sketch. As one interviewee explains, in early stages, it is often not advisable to use CAD-programmes that structure the sketch into straight lines or bows predefined by mathematical equations:

> In this case, the pencil was the tool. Of course, you can also start right away with CAD, or with any programme. And actually one must say quite clearly, in the very early phase – in my experience and I think also in the experience of many specialised colleagues – it does not make sense [to use a CAD programme], it is not about every centimeter. A programme always wants to have a line or an arc or some geometric form and this only disturbs me, I have to define something, I don't even know what the arc looks like yet. And intuition, the quick stroke, is still the easiest and gives the best feeling somehow, yes. (Int-models-09)

This is closely related to the aspect of the accuracy that is predefined by the tools. For instance, the roughness that is inherent to hand-drawn sketches was often described by the interviewees as a desired quality in a first sketch. On the other hand, having a drawing in a precise scale also has advantages, as one engineer emphasised:

> I think a very big problem is that we lose the scale. So I think in scales, I can also, if I draw a hand sketch, and it should be 1:20, then it turns out 1:20 ... and that helps, because that means there is more information contained in the sketch, which does not have to be described or thought of additionally ... and if the sketch is, let's say, 1:25, I am already completely irritated. (Int-models-14)

Thus, it depends on the context and on the preferences of the engineer which degree of accuracy – and consequently which tool – is perceived as appropriate for a certain task.

Third, the choice to use a certain tool for a specific task can be limited due to individually perceived barriers that complicate the use of the tool. For instance, as one engineer observes,

> Drawing is not easy for many engineers – you notice the ideas always remain very two-dimensional, and there are only a few who can quickly sketch their ideas three-dimensionally. (Int-models-13)

The barriers that exist with respect to getting started with a new tool are related to the professional education and experience of the respective user, their personal preferences and perception as well as their personal aptitudes, as outlined in Section 6.1.1 and in the Digression in 6.2.

Lastly, also the actions that are possible with one specific tool are defined by the tool as well as the engineer's knowledge about it. Hereby, some engineers favour to use different tools for different tasks, others prefer 'all-in-one' tools that encompass multiple actions and can be used throughout large parts of the design process.

Summary

To summarise, the aim of this subsection was to differentiate between the multiple objects design engineers employ in the design process and to thereby deduct properties, characteristics, or qualities of models. Three kinds of objects were identified: models, artefacts other than models, and tool that are used to generate models or artefacts, respectively. From the analysis of the different terms the interviewees used to refer to these objects, several conclusions with respect to the nature of models can be drawn.

- First, the multiple terms that are used for models emphasise the plurality of meanings assigned to the term model. At the same time, they highlight the large spectrum of different types of models that are all relevant in the design process.
- Second, a model term can be used to describe a variety of objects, and further, these objects can represent a variety of other objects (in this context an object in relation to the final design outcome).
- More specifically, it was analysed that the terms that referred to the use of models suggest that models are oriented towards the future. This implies that model-use has an epistemic purpose, which can be specified as to produce further knowledge on the design.
- In contrast, the terms that referred to the use of artefacts indicate that artefacts are mainly used to represent knowledge about the design that is already existent.

Due to this difference between models and artefacts, it seems fruitful to further approach the definiton of models by a more thorough analysis of model-use, including explanations why and how models actually work. This will be done in the next section. The exemplary statements with respect to the tools used in design processes, in turn, showcased some aspects with respect to which tools can be categorised. Furthermore, they highlighted the aspect of the engineers' evaluations of different tools to develop models or other artefacts in the structural design process. This aspect will be dealt with in more detail in Section 6.2.3.

6.2.2 Model-Use: Why and How Models Work

Building on the anecdotal overview of different models, artefacts, and tools used by engineers in the structural design process presented in the previous section, this section focuses on the topic of model-use. The analysis of the interviews revealed that there are basically two overarching objectives why design engineers employ models in the structural design process. The first objective is the design development, meaning that models are used for content-related purposes with respect to the structural design process. This can be both the judgement of what was developed so far and the development of new ideas, elements, or design features. The second objective is communication about the design, meaning that models are used for communication-related purposes. These two objectives converge with the tasks of the engineer described in Section 6.1.1, namely to deliver the design result and to navigate the process of structural design.

The question that is dealt with in this section is why and how models succeed to fulfil these two overarching objectives for model-use – in short, why and how models work. To this end, the first part concentrates on the why and identifies model mechanisms and their effects, and discusses how these impact the objectives of design development and communication. The second part, then, focuses on the how, and describes different processes of translation that are either motivated by the objective of design development or communication.

Why Models Work: The Mechanisms of Models, and their Effects and Impacts on Design Development and Communication

With respect to the question of why models work, the analysis of the interview segments led to insights on two aspects: 1) the analysis led to the identification of three mechanisms that are inherent to all models in different extents, and 2) it led to the assessment of the mechanisms' effects that in turn impact the overarching objectives of model-use, namely design development and communication.

Model Mechanisms The three mechanisms that were identified are a) externalising and capturing, b) visualising and uncovering, and c) simplification and abstraction.

First, *externalising and capturing* means the detachment of an idea, a thought, a concept, or an intuition from the originator and the documentation of it. As ideas can be fleeting, the model can be used as a medium to conserve them (Int-models-06). The interviews reveal that this is both relevant in early stages of the design as well as throughout the whole process.

> You have, let's say, this process to grasp your idea, which has to become haptic. And in the end, it also has to– well, I can't hold it in my head. I have an idea, and you know, a day later you don't remember it anymore. I have the idea, and then I sketch it on paper, and then I can look at it again a day later and reflect on it. And this is the start of the process, an entry into a real model. (Int-models-01)

As becomes apparent in the interview statement, the externalising and capturing of an idea enables that it becomes tangible, both for the originator and others. At the same time, this mechanism enables that the idea becomes available for observation and reflection, again both for the originator but also for others. Certain details of the idea can be looked at from an outside perspective, be revisited, and further developed. The interviews reveal that only the externalising and capturing of an idea or thought with respect to the design in a certain state through the model can eventually enable the further development of the design: As long as the idea or thought stays in the imagination of the originator, it is not challenged and thus stays fixed and cannot be improved or refined. Another important aspect of this mechanism is that through it, the model helps to dissect the processes of developing an idea or thought and the processes of reviewing them, which takes away ambiguity from the task. This can be related to the two working modes of creation and reviewing identified in Section 6.1.2, and indicates that the model can support alternating between the modes frequently and easily. Furthermore, through externalising and capturing, the comparison of ideas or in general the discussion of them becomes possible:

> I think when you see a model, whether physical or digital, it's something else than when you create it with your brain. You can check scales, proportions, these things much better with the help of models than in your head. ... And these models and drawings enable us to talk about it at all. I can't talk about what [someone] has in their head because I don't see anything and I don't hear anything. (Int-models-18)

Furthermore, things that remain unchanged in the design process such as boundary conditions can be fixed in the model, resulting in the design engineer not needing to spend brain power to recall these information throughout the design process. The model enabling the comparison or discussion of ideas, or the fixation of boundary conditions showcases how it supports some of the strategies for structural design identified in Section 6.1.3.

The second mechanism can be described as *visualising and uncovering*. While externalising and capturing also has a certain visualising effect, this mainly refers to a change of medium, from inside the head to some kind of physical entity, i.e., a sketch, physical model, digital drawing, or any other kind of model. In contrast, the mechanism of visualisation and uncovering refers to two different aspects. First, implicit aspects of a structure, design, or idea are made explicit. These aspects can be the flow of forces, the deformations, the mechanisms of the structure, the appeal of certain forms, or the strengths and weaknesses of a design in general.

> There are two office floors, then a column-free event floor, then a technical floor, and then a five-story underground parking garage exactly in the area of where the entrance spindle is. You can imagine that there is nothing on top of each other, and then we actually made the flow of forces visible, so to speak, with strut-and-tie models. (Int-models-16)

Second, future states of the design can be made visible and thus available for reflection already in the present. This includes aspects such as the possible problems that might occur in the building process or other future states of the project.

The third mechanism that was identified is *simplification and abstraction*. Ideas, design concepts, or thoughts are often complex, unorganised, either too specific or too vague. Models usually represent these ideas, concepts, and thoughts in some kind of simplified or abstracted structure. This enables that these can be analysed or further evaluated. This mechanism has also been prevalent in the literature on engineering models (see Section 3.1.1). Hereby, simplification refers to reducing the complexity of an idea, concept, or thought to be able to summarise it in a model and hence to make it explainable or understandable. Such a simplification can either be more or less specific than the initial idea, concept, or thought. When being more specific, the simplification takes away ambiguity and thus enables the concentration on specific aspects. When being less specific, the simplification creates a leeway for interpretation, so that new ideas, concepts, or thoughts with respect to the design can evolve out of the engagement with the model. Simplification can manifest in different degrees, for instance, in trivial measures such as selecting a different scale, but can also engender reducing the design idea to a minimum of aspects. As one engineer explains,

> For me, a model is simply the reduction of a complicated or more or less complicated issue to something very simple. Let's take the [name]-Bridge again. Basically, there are only two lines. In the end, it's a bridge, but the model we used to describe how we'll build the bridge is basically one line, that's the upper chord, and another line is the lower chord, and then an idea of how it might look to clamp the abutments. Basically, I can show you with ten, twenty lines, that's how the bridge works. Although, of course, it is a bit more complicated. But this is a model. (Int-models-09)

The abstraction refers to the fact that the model transforms aspects of the ideas, concepts, or designs in such a way that they can be dealt with through the available means, for instance, through geometric tools such as CAD or through Finite-Element models.

> I have an amazing team that translated the physical model really quickly into a Rhino-model and then into a Grasshopper model and then into a Sofistik model, and managed to map this incredibly complex geometry into Sofistik. These are all model steps. Different models, from the model in the head to the physical mesh to Rhino to Sofistik, these are all abstraction steps that someone has to do. So in the end we can calculate it. (Int-models-17)

Hereby, only the information relevant for what the design engineer wants to know about their idea, concept, or design is translated into the model, for instance, only the structurally relevant aspects of a geometric form. This way, the engagement with the model to find answers to the questions is not clouded with too much information and the relevant aspects can be comprehended faster.

Effects and Impacts on Design Development and Communication Through these three mechanisms – externalising and capturing, visualising and uncovering, simplification and abstraction – model-use can achieve three kinds of effects that in turn have an impact on the two main objectives in structural design processes, namely design development and communication.

First, as was already mentioned and partly exemplified in the interview statements above, these mechanisms can *support or assume imagination.* With respect to the objective of design development, having a model at hand frees the designer from the need to imagine what it represents. Instead, the model can simply be looked at, the brain is less occupied with imagination tasks and can concentrate more on other tasks such as the perception and evaluation of what is already there or the development of new ideas. In general, by supporting or assuming imagination, models can help to create a better spatial feeling, a better perception of the proportions, scales and the overall appearance, a better judgement of the context of a structure and its relation to it, or a deeper understanding of how the structure will be once it is constructed. On that basis, models enable to pose new questions with respect to what can be seen.

> Ultimately, [models] serve to create a more precise spatial perception. I can indeed imagine something three-dimensionally in my head, but it's something else when I see it in front of me on a table or on the screen from different sides. I believe that one grasps proportions and appearance much better with, with the help of models. (Int-models-18)

With respect to the objective of communication, by supporting or assuming imagination, the model can also act as a common ground in collaboration processes. This is especially useful as people have different capabilities of imagination. One common example are different capabilities of three-dimensional imagination: "When I build a model, everyone sees it three-dimensionally. Because many people have a hard time imagining it three-dimensionally" (Int-models-10). But also for other aspects, such as the structural behaviour of a system or the appearance and haptic quality of certain materials, models can provide with a common ground that can be used as a base for collaborative work.

Second, model-use can also *facilitate understanding*, either of the design itself or of what is communicated about it. A better understanding of the design itself is crucial with respect to the objective of design development. This understanding encompasses, for instance, geometric aspects such as the proportions, form, scale, and dimensions, structural aspects such as the flow of forces in a structure, its load bearing behaviour or its deformations, or aspects such as the effects or consequences of a certain structural design with respect to the interaction with its surroundings. The better understanding of such aspects of the design can subsequently lead to a conscious further refinement and development of the design, as illustrated by the following interview statement:

> For example, in the case of non-trivial models, for which it is perhaps not recognisable at first glance what the flow of forces actually looks like, then you look at such a static result, and then you say, yes, now we can actually design it in such a way that we make another large opening here, there is a local reinforcement for it here, and then perhaps something sculptural results again ... . These are experiences that you can really only draw in conclusion from such an initial static model. (Int-models-03)

With respect to the communication about the design, the effect of models to facilitate understanding can enable easier decisions and prevent misunderstandings among different people involved in the project. For instance, model-use can facilitate an understanding among architects or clients for the behaviour of a structure and the consequences this has for the design. This can in turn also inspire a greater confidence in the proposed design.

Third, model-use can *allow or enable experimenting.* This means that the model enables the design engineer to try out different ideas with respect to the design, and thus to gain experience and knowledge about the design through the model. According to the interviewees, this can take on several different forms. For instance, the design engineer can slowly approach a solution through altering parameters of the model und judging the effects. This way, different configurations or alternatives of one initial concept can be tried out, compared, and the best option can be chosen.

> These models allow us to really simulate all parameters and also to think them through in advance. ... So whether I have the cross-section design, or how rigid I arrange the longitudinal beams, or how I place precast elements, or anything else. I can simulate this first and then examine different variants. (Int-models-05)

One engineer strikingly named this approach "kneading of the design" (Int-models-01). Models provide for a playground, where things can be tried out and consequences can be judged without needing to deal with them in reality. This way, the engagement with models can provide with new experiences that lead to valuable new insights and knowledge on the design. In contrast to the second effect – facilitate understanding – through which a theoretical understanding of the design is developed, through this effect practical experience about the design is generated.

> I transfer an idea into a model, the model doesn't work, I supplement the model so that it works, and then I can transfer it again into a construction. So the model is actually a playground where I make up my little blocks, my construct, my simple thought construct, which can then ultimately be played back into a real building or into a construction. So it's actually my little playroom. (Int-models-07)

With respect to the objective of communication about the design, the experience, knowlegde, and insights gained through experimenting with the model enable the design engineer to present alternatives and comparisons of different designs, which potentially leads to better informed decisions in collaborative work processes. Furthermore, through reactions of collaborators to different design alternatives presented to them, the underlying interests, expectations, or goals can become clear for themselves but also for others and thus become negotiable.

The effects of the three model mechanisms and the respective positive impacts they have on the overarching objectives of design development and communication are summarised in Table 6.3.

Table 6.3. The three effects of the model mechanisms and their impacts on the overarching objectives in the structural design process, design development and communication.

Effects of the Model Mechanisms		Positive Impact on Design Development	Positive Impact on Communication
1.	Support or assume imagination	Free brain power	Common image detached from imagination
2.	Facilitate understanding	Theoretical understanding of the design	Easier decisions; less misunderstandings; higher confidence in design
3.	Allow or enable experimenting	Practical experience about the design	Backed decisions based on alternatives; interests, expectations, and goals become visible and negotiable.

How Models Work: Translation Processes and Their Effects

While the previous paragraphs explained mechanisms behind models and their effects and impacts on design development and communication, the following paragraphs focus on the how behind model-use, that is the activities and practices that constitute it. Even though the interviewees described these activities and practices in different words, the analysis revealed that how a model is generated or further developed can always be traced back to some kind of translation activity, no matter if the model is used for design development or for communication. One of the interviewees summarised this main form of engagement as follows:

> The engineer must be a translator, from a real system, from a real body into a system of equations. And the intermediate step is model building. … This transfer … that is the real engineering achievement. Once the model is there, anybody can digitise the whole thing into the programme, and get the results afterwards. That is not the service. The core service of the engineer is actually the activity of modelling. (Int-models-07)

Through the analysis of the interviews, two kinds of translations were identified (see Figure 6.2): 1) content-centred translations performed by the design engineer that transform information on the design from one state to another while also altering this information; and 2) communication-centred translations, in which information from one person to another is transferred by a model, whereby the information is not altered and only carried by the model as the medium. These two kinds of translations constitute ideal-typical forms, which means that in reality every translation activity probably contains both elements. However, it is nevertheless fruitful to conceptually distinguish between the two forms, as they highlight the different motivations behind them: for the first type mostly to progress the design, for the second type mostly to communicate about it.

Content-Centred Translations With respect to the content-centred translation, four aspects are worth mentioning.

First, the interviews illustrate the potential *effects of translations.* A translation of information from one state into another usually aims at making this information easier understandable or at preparing it for further development processes. The translation can also aim at inducing decisions, for instance, by translating information so that it becomes comparable to other information or that the relevant aspects of it are highlighted. Usually, by translating information related to the design, one gets to know the design better which can lead to new insights about the design. For instance, a translation from 2D to 3D could reveal that there is not enough space for connections and the design is not feasible in this way. In any case, a translation of a model in a state A to a model in a state B engenders a new perspective on the design or a changed

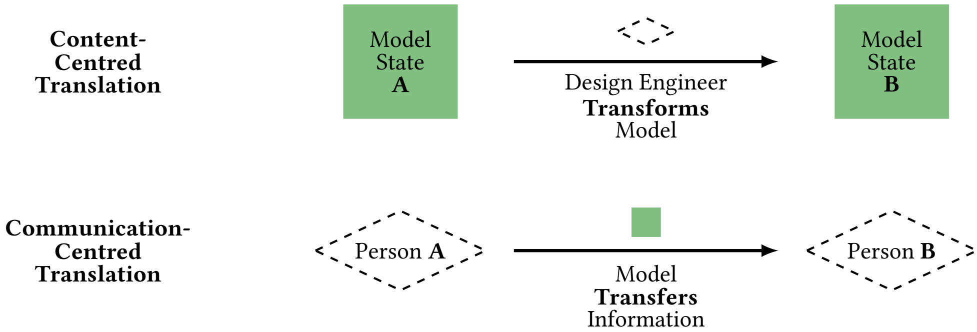


Figure 6.2. The two ideal-typical types of translations: Motivated by the desire for design development, in the content-centred translation the design engineer transforms a model from a state A to a state B. Hereby, content-related aspects of the model, which refer to the structural design, are altered. In the communication-centred translation the model transfers information from a (or more) person(s) A to a (or more) person(s) B. Hereby, information regarding the structural design are not altered but merely carried by the model as a medium.

focus, which could not have been foreseen before the translation was performed. This is explained by one of the interviewees, who said:

> It is very often the case that you build or create a model (...) and then only afterwards perhaps you recognise the positive or negative effect the model has actually had on the design. I think that's also the reason why you should build different models in order to gain these insights, because if you always work with just one model, you'll never get this variety or these perhaps further insights from other models, which you would deprive yourself of. (Int-models-03)

The interviewee stressed that the generation of new insights is the reason why multiple different models – and thus also multiple different translations of thoughts, concepts, or ideas – should be performed in parallel, in order to benefit from multiple different perspectives and experiences that can be compared to each other. Besides performing translations in parallel, another common practice in many projects according to multiple interviewees is performing a 'chain' of different translations, in which one translation motivates the next. This way, as illustrated in the following interview statement, the design is formed through the continuous engagement with models:

> That results from modelling or sketching, that you–you have some structural element, and from modelling or sketching you come to the conclusion, you should rather develop it that way, and that is a part of the design process. Then you start thinking again, because what you see either haptically in the model or on the computer, you work on that again in your head and then the next ideas are coming in the interaction, you imagine it spatially, you see it and have ideas, maybe even to discard, or to improve in a different way, or to optimise. And this model, no matter

> how it looks, is simply part of it. And not only the mental model but then really the implemented model. (Int-models-15)

Second, the interviews also provide insights into the *nature and characteristics of translation activities*. According to the interviewees, translating an idea or thought into a model should not be understood as a routine exercise, but rather as a creative process and as an achievement of the one performing the translation. It usually encompasses some kind of transformation of the information, for instance, that parts of it are abstracted, more information is added (i.e., additional dimensions or properties), or the information is presented in a different way. This implies that the translation usually provides some kind of leeway as to how it is performed and that it is influenced by the decisions of the one performing the translation process. This leeway is where new ideas can be incorporated in a design process, or where what has been developed so far can be refocused on other aspects by neglecting some of the properties that were there before. The translator thus actively shapes the design process, and each translation bears creative potential.

Third, and strongly related to the creative potential that content-centred translation processes bear, the interviews reveal that *the quality and the usefulness of the translation depends on the capabilities of the translator*. When information is translated from one logic to another, for instance, a given geometry is translated into a structural model, the translator has to be able to understand two languages: the one of the original model, and the one of the model the information should be translated to. Furthermore, the engineer needs to decide on how to perform this translation. As one engineer explains, a wrong decision hereby can lead to an incorrect structural model:

> A very important process, translation process, is the one from the sketch or from the thought in the head into the calculation model. Because today, the computer calculates virtually everything. The famous garbage in, garbage out applies. And that's why computer modelling, the right stiffnesses, the right FE-software, the right bearings, that's very important, and that's an engineering task. Of course, it's also about design and other things. But I say that it is crucial that you model your static model correctly, and when you translate what you have in your head or what you have sketched out into the calculation model, so many things are done wrong. (Int-models-17)

In this respect, it is important that the interview analysis also suggests that translation processes can be trained and practised.

Lastly, a content-centred translation process is usually a process of *iterative rapprochement*. In each step of this process, either the content of the information could be changed or the representation of it or both. Hereby, the information can be abstracted, refined, sharpened, or parts of information or properties could be added or neglected. These different elements of content-centred translation processes cannot be sharply detached from another; one translation process can also incorporate all of these different elements. For instance, one might translate an idea from an image in the head to a first rough sketch, then refine this sketch in a 2D drawing, only to then translate it further to a 3D model of the geometry which can itself be translated into a Finite Element model for calculation. Often, the outputs of the translations get more detailed and rich in information along the process.

> I've never experienced a 3D model flowing directly out of an idea. I have never experienced that in a design process. Maybe the tools are missing, I don't know, maybe they will be available in the next few years. But you always come via, via lines and surfaces, even in 3D, you tend to come via such forms to the actual model. And that starts out a bit simpler at the beginning and then becomes more and more, yes, more resolved and structured, perhaps. (Int-models-13)

The several translation steps are not predefined, but rather shaped by the outcome of the previous translation steps. Translation processes however can also follow a certain scheme and can even incorporate phases of dull execution. As one engineer explains, there are typical steps that can be followed, for instance, when translating a sketch into a 3D model. According to one of the engineers, it can be pragmatic to dissect the sketch into basic elements, translate these elements one by one from the sketch logic to the 3D logic, and recombine them in the new model:

> And so the models, the transfer, it works– from a sketch you don't automatically have a 3D model, so to speak, it must also be broken down, so to speak, into elements, and the elements must be combined with each other in such a way that you then come to what you have imagined, if possible. (Int-models-13)

Communication-Centred Translation The interviews also delivered insights on the second type of translation processes, in which information from one person to another is transferred by a model. Hereby, the motivation for the translation is not to further develop the design, but instead to communicate it. In this process, the model acts as a mediator between two or more persons, as illustrated nicely in the following interview excerpt. The information that is transferred remains unchanged, only the form is altered so that it can be understood by others. The translation's purpose is to transfer knowledge from one person to another and not to transform the knowledge itself.

> I had this picture in my head, but – no one could draw it for me with Rhino. And then I said, well, guys, I have to build a model now so that you understand what's in my head. Then I went to my team with the model and said, this is what I want. Do you get it now? I couldn't – that

> was again – I couldn't express myself properly. I had a communication problem. And the model here was purely a means of communication. And then suddenly everything was clear, then you could represent that in Rhino. (Int-models-17)

Even though this type of translation is centred on the objective of communication, the interviews revealed two ways in which it can also support the further development of the structural design. First, the *model as a mediator* can represent a common ground from which a common understanding can be established that supports collaborative work. It is a base that first and foremost enables the start of a conversation about the design, which is an essential prerequisite for any further development.

> Above all, to have a basis that can be looked at from different angles and with very different backgrounds. And everyone interprets it differently, but it needs a basic understanding and a basic proportion, a basis that can be evaluated by everyone, perhaps with very different results, but simply a common basis that can be discussed. (Int-models-19)

With respect to communication among engineers or architects, the model can accelerate the process and make misunderstandings less likely. This is due to the fact that models often represent information directly, without detours through words. This way, particularly geometric information gets transported faster and more reliable than by trying to describe it:

> The scale drawing is also a kind of model, we have a convention about what does a 1:20 drawing include, what does a 1:100 drawing include, and these are things when you get into that convention, a lot of information is conveyed without even thinking about it, or let alone talking about it, and that's, that's why models are ideal in the early versions. (Int-models-14)

With respect to collaboration among others involved in the planning process without the relevant disciplinary background knowledge, the model can get everyone on the same page and establish a common ground of information. It can also be used for explanatory purposes, and convey complex disciplinary aspects of the design to laypeople, such as the flow of forces through a building. In both cases, the better the model is understood by the people working with it and the better the knowledge on what the model can yield and what its limits are, the easier the communication about it usually is.

Yet, it is not always the case that the model establishes a common ground as described above. Instead, as models usually leave a certain scope for interpretation, it is equally as likely that everyone who interacts with a model will see something slightly different in it. This, however, must not be evaluated as something negative and can instead be described as the second way in which communication-centred translation processes can support design processes, namely in that the model acts as a *multiplier for new ideas.* Hereby, what a person sees in a model is influenced by that person's experience, background, and way of thinking. These different interpretations lead to different ideas as to how the model and thus the design could be further developed, and constitute a creative potential:

> And there is actually something that arises at the beginning through this coarseness of the model, many, let's say, variations are still possible, and actually also directions. And actually, everyone understands it a bit differently, and if we then play it a bit further, everyone for themselves, and then bring it together again, you realise that it is exactly this added value that arises, which you could not do yourself. (Int-models-01)

There are two opposite ways in which this effect can be strategically employed for a generative collaborative model-use. For one, the design development can be spurred by deliberately leaving certain elements vague and blurry or completely out of the model. The vagueness then provokes reactions from the people working with the model, which lead to specifications and thus to the further refinement and development of the model into a variety of directions. For another, by specifying certain aspects, even though the final form of these aspects has yet to be developed or decided on, the recipients of the model can be provoked to change what is then already in front of them. Through the specific formulation of these aspects, they become negotiable and a subject to alterations, which can be easier than having to come up with new formulations from scratch.

The two aspects, the model as a mediator and the model as a multiplier for ideas, show that even though the communication-centred translation is focused on transferring information from person to person, ultimately it also supports the development of the design.

Summary: The Potentials of Model-Use

As has become evident in the descriptions of the model mechanisms, of their effects and impacts as well as of the translation processes, model-use has multiple diverse potentials, both for design development and for communication. The further analysis of the interview segments suggests that what makes them so beneficial is the *profound engagement with the design through the interaction with the model.* This aspect converges with insights deducted from reviewing example cases of modelling processes described in the Literature (see Section 3.2.1). Furthermore, it converges with creativity research, in which preparation and incubation have been identified as the first two steps of creative processes (Chan, 2013; Santamarina & Akhoundi, 1991, see Section 2.2). The translations described in this section, in turn, can be regarded as ways in which creative insight, the third step of a creative process, can be triggered, similarly to the procedures of creative insight described by Rosenmann and Gero (1993).

The findings further suggests that it is not decisive how this profound engagement happens, that is through which kind of translation process. Rather, the more active the engagement is, thus the more translations are performed, for instance through employing several different models in the same process, translating the content from one model to another, or explaining the content through different models to multiple collaborators, the more different perspectives and angles can be generated on a design, and the higher the chances are to have new ideas regarding the design, that is to generate a creative potential.

> The novelty comes from dealing with [the design] again and again, then recording it again, and, and then maybe telling that to colleagues, hey, I made that up, and then another one comes up with something. (Int-models-16)

> The model is somehow also a tool that helps you to push the design further through you working with [the model], that is, if I do a lot of sketches, at some point there might be a sketch where I say, oh yes, that's right, or someone watches and says, no, that's not right. (Int-models-17)

6.2.3 Model Evaluations: Critical Perspectives on Models, Model-Use, and Tools

The previous section primarily focused on why and how models work, thus on the potentials of model-use for structural design. However, in the interview statements that have been showcased so far, it also became apparent that the interviewees have critical perspectives with respect to models, model-use, and the tools used to generate models. This is important, as the way engineers judge specific models shapes how they use and interact with them. In this line, this section will focus on the model evaluations of engineers, and specifically on their critical perspectives on specific models, model-use, and the tools they use to develop models. These perspectives become tangible, for instance, in the advantages and disadvantages of models mentioned by the engineers, or in their objective and subjective reasons to use a specific model. The analysis is divided into three parts. The first part deals with the suitability of specific models for the objectives of design development and communication as well as for specific tasks. The second part, then, comprises of more general evaluations of the risks associated with model-use. Based on these two parts, the third part summarises how specific models, the engineer using them, and the tools they are developed with impact creative model-use. Furthermore, it formulates requirements for creative model-use.

Suitability of Specific Models

In general, the interviews reveal that the design engineers evaluate specific models particularly with respect to three aspects: their suitability for 1) design development, 2) communication, and 3) specific recurring tasks in the structural design process.

Suitability for Design Development With respect to whether specific models are suitable for design development, that is, whether specific models are particularly apt to support creativity, the dichotomy between *haptic and digital models* was omnipresent in the interview data. Most of the interviewees agreed that working with pen and paper, sketching, or drawing helped them to be creative. One engineer stated that the sketch is the first and most important tool, as "creativity, at least for me, always comes out of the wrist" (Int-models-03). And another explained this as follows:

> I can't draw exactly with a pencil. With a pencil, I can basically just sketch something freehand. And then I say at this corner I go over it again and press even harder on it, and through that I recognise the shape. And then I further work on this shape. And this intuitive, immediate feedback that I have in that moment, from my mental image to what I see, what I produce with the freehand sketch, I don't think that's possible in these parameterised model building environments. (Int-models-01)

Another big topic with respect to the creative design development was the dichotomy of *simple and complex models.* Also in this case, the evaluation of the interviewed engineers was very straightforward: Most of them favoured simple over complex models, which they justified with the easier handling of and interaction with simple models. For instance, as one engineer stated, to sketch something in 2D first rather than directly in 3D is an easier and faster start into the design development (Int-models-02). Another interviewee expressed a similar opinion, but without really being able to explain this:

> I think it's important not to start immediately [with complex modelling]. Similar to my colleagues in architecture, they say: no, not immediately in the computer, but first a cardboard model. And I say: no, not immediately in the 3D model, but first a hand calculation. (Int-models-14)

And yet another engineer expressed that the development of concepts, which is important in early stages of design processes, works better with simple models in a "Sendung mit der Maus-style" (Int-models-16), which refers to a German TV-show for children, than with complex models.

Lastly, with respect to design development, the aspect of the *scale of models* was stressed by multiple engineers. Hereby, the engineers did not refer to a specific scale but rather meant that sketches or drawings should be made in scale at all as opposed to just in arbitrary sizes. One of them stated that by drawing in the right scale from the beginning, one can get a feeling whether and how a certain structure will work:

> [Important is that] such sketches or drawings are simply made in scale. That's very, very important in designing, to look at these things in relations from the beginning. ... So something small in relation to something big, if you put it in the right proportion, then you see immediately, you

> get a better feeling of how something works. Whether it works and how it works. (Int-models-03)

Suitability for Communication The interviews further provide insights into the engineers' evaluations of a specific model's aptitude for communication purposes. Hereby, two opposing opinions were identified. The first one is that a model is better suited for collaboration the more aspects (by different disciplines) it incorporates:

> I think there is a clear tendency for models to become more and more interdisciplinary, to contain more and more information, and for the dependencies to become more and more complex, beyond the planning disciplines. And that is a good thing and important. I am convinced that if this is applied and used in this way, the buildings will be better overall. (Int-models-08)

Second, other interviewees saw more value in simple models for collaboration and communication, such as sketches or even only verbal explanations in conversations. The logic behind this is that these models are easier to understand for laypeople, for instance, because they directly represent certain effects or simplify complicated phenomena. Examples that were named were strut-and-tie models that make visible the flow of forces, or 3D models that directly represent the geometry of structures in all three dimensions and thus make strong visualisation abilities redundant. One engineer even claimed that most collaborators are not interested in the disciplinary models of the structural engineer, so that the attempt to communicate them in a complex interdisciplinary model does not make sense at all:

> It's unfortunate, it always sounds nice with BIM and playing back and forth, but it doesn't really work because the other stakeholders do not care at all about my models, there is no value in it. (Int-models-07)

Suitability for Specific Tasks In addition to the suitability for design development or communication, there were also multiple statements that referred to the aptitude of specific models for specific recurring tasks in structural design. Some exemplary interview statements are summarised in Table 6.4. As with model-use in general or approaches to structural design on a more abstract level, the decision which model to use for which task depends on the engineer and their skills, experience, and preferences with respect to models. Thus, this Table is by no means a recommendation as to which kind of model should be employed for which task. However, what can be deducted from it is that the interviewed engineers have strong personal and differing opinions on what the right model for a certain task is. Taken together with the previous findings on simple vs. complex and haptic vs. digital models, it shows that in the opinions of the interviewees, the type of model has an influence on the use of the model, the interaction with it, and possibly also the results than can be generated with it.

Table 6.4. Exemplary interview statements that showcase the engineer's valuations of specific models for specific tasks.

Type of Model: ***Task***	**Example Statement**
Drawing/Sketch: *get a feeling for the design*	So for me, I need the drawing, I need my pencil, I need to make sketches. I personally can on that base develop a feeling for how something will turn out. (Int-models-04)
Physical model: *percipience of the design*	You always think, with a digital 3D model you can also capture everything when you turn it, but in fact, with such a physical model, if you get close to it, somehow, you can perceive it differently. (Int-models-13)
Physical model: *deduct load-bearing mechanisms*	It is easier to derive load-bearing effects from such physical models than from 3D models, because in 3D models I only have the shape, and with the physical model I actually also have at least the support, so I can see how the forces are distributed or how the deformation is. (Int-models-13)
Grasshopper-model: *parameter study*	This Grashopper process, I mean, you can simply simulate parameter studies wonderfully, which, if you would do it manually, of course, would imply quite a lot of individual steps. (Int-models-03)
Strut-and-tie-model: *understand flow of forces*	You have to think about how to distribute the loads, and for that we have our popular strut-and-tie models. These are very simple models with which we can immediately understand the flow of forces. And we also like to use these models because everyone understands them. (Int-models-09)
Detailed model: *solve complex nodes*	Complicated nodes, for instance, in which three or four elements come together spatially, they can have a relatively massive effect on the design, and I also have to consider whether I allow eccentricities, and I can only find that out in the detailed model. (Int-models-15)

Risks associated with Model-Use

With respect to model-use in general, the interviews revealed that besides its potentials for design development and communication as showcased in Section 6.2.2, the engineers also associate risks with it.

These risks can be summarised as follows: a) choosing the wrong degree of simplification or abstraction, b) using a model outside of its area of use, c) being affected in one's way of thinking by the model, d) being mislead by the model, e) loosing overview due to too detailed or complicated models, f) being dependent on tools to handle the model, g) letting the model become an end in itself, and h) making translation errors. As will become apparent in the following exemplary descriptions, these risks are interrelated and cannot be sharply delineated from each other.

The first risk is related to the fact that models generally work with simplification and abstraction. While this is one of the mechanisms that makes them so useful, *choosing the wrong degree of simplification or abstraction* in a model with respect to the task or the phase of the design process the model is employed for or in can have negative effects. With respect to the design development, one engineer expressed the following concerns:

> So models have the advantage that they provide what you are most interested in at the time, and they have of course the disadvantage that they hide other things, and that means ... by choosing the wrong model or supposedly the wrong model or a specific model, some things will not occur to me. (Int-models-14)

Thus, for one, as expressed by the interviewee, some solution trajectories might not be thought of because the model is oversimplified or too concrete. As one engineer explains, "the detailed model is simply too fast in the thought process, and hints at goals or suggests dependencies that perhaps should have no design relevance at this point" (Int-models-19). This is often the case for digital models. Particularly in early stages, the accuracy a computer model has is not needed but rather "the quickness and the idea that you want to formulate. And sometimes the computer doesn't help at all with that, because you're actually a bit hindered by the mechanics of this system" (Int-models-13). The detailed nature of computer models thus is not "productive" at this stage of the process, but rather "delimits the solution space" (Int-models-14). Furthermore, both too simple or too detailed models can lead to false calculations that can even possibly affect the structural safety of a design. An oversimplified model, for instance, can lead to a false perception of the structural behaviour, as certain structural effects may not be visible in the model. The other extreme is also possible. As one engineer explains, models can at times be more exact with respect to geometry or material values than what would actually be possible to achieve on the construction site.

Another risk the engineers emphasised is that the boundaries of what can be done with a certain model are not clear to the one using it and as a result, the model is *used outside of its area of use.* This, as demonstrated in the following quote, can lead to insensible results.

> One engineer started to enter a rope in a framework programme. And of course that couldn't work, I knew that right away, but it wasn't so clear to [the engineer]. And that's just the way it is – you have to understand what this model can do. (Int-models-14)

In general, models and the routine employment of them can greatly *affect the way engineers think*, as they can promote thinking in predefined patterns, or to a certain extent limit free thought. In this line, the engineers particularly stressed the risk that working with too complex or detailed models can engender. For instance, when the model someone is developing has too strong and rigid structures in which the design has to be fitted into, this can greatly limit creativity. Specifically BIM models were named as examples in this respect. Some reasons given for this are, for instance, the need to define multiple parameters of a design early on when they don't have relevance yet, or the possibility to choose from predefined structural elements, which promotes the development of stereotypical structures:

> And that's where I see the danger with BIM, when there are many prefabricated elements already there, for example cross-section types. Or pier types. And then they're just stubbornly used because it's quick or whatever, or because it's easy. Or because you don't have that much experience. And then I see a bit of a danger that a lot of stereotypes will be created. (Int-models-05)

Closely connected to the previous aspect, models can at times be *misleading*. Particularly if the model appears very realistic due to a lot of details and depth, the risk is that the modeller forgets about the simplifying nature of models and wrongly assumes that what is not included in the model is also not there in reality. Several engineers stressed the importance of the awareness that one is working only with the model, not with the real physical conditions. With respect to the communication purpose of models, specifically with respect to visualisations, recipients such as clients can also be "seduced" by the model, as the engineer can easily 'cheat' by adjusting the visualisation to get the desired effects:

> Then there are great visualisations that seduce, right, visualisations seduce, and then the project wins, but there is no, no real concept there at all. And some structural parts are flying and so on. (Int-models-16)

But also unintentionally, through highlighting or ommitting the 'wrong' aspects in a model, the model can be misleading:

> [It is possible, that] my intention or my goal, which I wanted to transport, by the choice of my model perhaps does not come across at all. So maybe the effect that I had hoped for in my head is not perceived at all through the chosen sketch. (Int-models-19)

When a lot of data and information is integrated in models, another risk is that they become too complicated and that *overview is impeded.* Hereby, multiple engineers stressed that the structural concepts, which are central to the early stages of a design process, can be overshadowed and not easily be recognised in the model anymore, so that their further development and refinement gets harder. Similarly, one engineer emphasised that the model can cloud the view on one's own tasks:

> I can simply work well with my model, while in the overall system the whole thing is far too complex and far too confusing, I have to rightly [adjust] the whole thing so that I can see the big picture in the small. (Int-models-07)

Another aspect of too complicated models is that the engineer is more likely to *become dependent on tools to handle the model*, for instance, on specific computer programmes. Model developments and changes have to be carried out with a specific tool, which results in the engineer giving up control over the model to a certain extent:

> I have a complex system, which I can no longer calculate, the computer then takes over for me. But if I have a simple system with three, four rods, I could or I can calculate it by hand. And the simpler it is, the better I can still do the whole thing by hand. If I still have a grip on it, I can work on it relatively quickly, control it, that's actually the most creative thing. Having a large model doesn't really have a lot to do with creativity. That's not really the big creative process anymore. And it takes longer, because in the end you're primarily occupied with model building, you're actually constantly finding and searching for the errors of the model, and more concerned with the input than with the output. (Int-models-07)

As becomes also apparent in the statement above, the engagement with complicated computer models furthermore takes a lot of time, and changes the nature of interaction with the model, from a contentual engagement centred around the creative development of a structure to an engagement centred around the right translation of a structure into the logic of the computer model. Multiple engineers also criticised that computer models are usually very detailed and contain a lot of information, which results in them being much harder to handle than simpler ones, when changes occur or optimisation work needs to be carried out. In this respect, a risk mentioned by the interviewees is that the *model becomes an end in itself* rather than a means to an end. Then, the model would only "rob time and energy", but would "not really benefit the planning process" (Int-models-07). Another engineer explains that working with digital models demands one's attention in other ways than, for instance, drawing and developing something on paper:

> When I see something on the computer or have to draw something there, then, then I lack somehow capacity for other things. Because you [concentrate] very much on the, on the operation of the computer. (Int-models-10)

And another one stresses that particularly the translation from the logic of simple engineering models to the way these are implemented in the logic of the computer so that the phenomena are represented correctly binds capacities that are then not available for creative developments:

> As soon as I start entering things such as pretensioning in the model, I already have so many questions about the model formation that this effort is then only in this knitting of the model and no longer in the creative development of the solution. (Int-models-14)

A related risks that several engineers emphasised is that *each translation process engenders the possiblity to make an error.* This is especially relevant with respect to translation processes into the logic of digital models, as these often produce results even if the model does not make sense. When these potentially wrong results are not questioned by the engineer, it can have grave consequences. This is especially relevant, as the computer is usually used for more complex calculations the engineer cannot easily check with hand calculations, especially if they are not used to translating complex structures into simple engineering models but are routinely employing computer models to directly solve these complex questions. One engineer said:

> And I have often experienced that there is a certain, let's say, obedience to the computer, so that people say, well, but the structural analysis programme delivers this result. But the structural analysis programme only delivers the result according to the boundary conditions I have entered, and if I make a mistake, the result can soon be wrong. And then they say, but the result is here, black on white. But are the boundary conditions, which I have entered, the correct ones? Sometimes I don't even know anymore with complex systems. (Int-models-04)

Summary: How Specific Model Types, the Designing Engineer, and Specific Tools Impact Creative Model-Use

In this part, the goal is to summarise how specific model types, the designing engineer, and the tools used to develop models impact creative model-use, meaning how they impact the potentials of model-use that were identified in the summary of the previous Section 6.2.2. On that base, requirements engineers pose on their models, requirements for the designing engineers themselves, and requirements for the tools models are developed with can be deducted.

With respect to creative design development, the interviewees favoured haptic over digital models, simple over complex models, as well as models that are made in scale over one's in which the scale is not specifically defined. These aspects as well as some direct statements by the interviewees suggest that in order for a model to be suited for creative model-use, it should be easily understandable and characterised by simplicity and clarity. Further, it should be flexible to adaptations. The model should not be too structured in order to openly support idea development. And it should be suitable to the respective task, as complicated as necessary but as simple as possible.

Second, the analysis of the risks associated with model-use made evident that not only the model needs to fulfil certain requirements, also the engineer as the user must be capable to interact with the model. For instance, the engineer needs to choose the right model, employ the model in its area of use, prevent translation errors, and so forth. Thus, the multiple risks of model-use brought forward by the interviewees highlight the great responsibility of the design engineer in the context of model-use, which has already been identified with respect to the translation processes.

Third, the analysis of the evaluations presented in the previous two parts of the section suggests a further main conclusion: not only the type of the model that is used or that is developed is important for creative model-use, but rather the model in combination with the tool that is used to generate it and work with it. In Section 6.2.1, some tools that the interviewees use in the structural design process have been summarised. Furthermore, four aspects have been identified, with respect to which these tools can be categorised. The question that is dealt with in this summary is how the different tools are evaluated by the interviewed engineers with respect to creative design development.

Considering the potentials of model-use that are rooted in the processes of translation as described in Section 6.2.2, a main factor for creative model-use is whether the engineer can easily interact with the tool they use to develop the model. Thus, an important requirement for tools with respect to creative design development is that they need to be suited to the design engineer employing it. Hereby, above all, the importance of an intuitive interaction with the model through the tool is stressed by the interviewees. This means that the engineer should not encounter barriers during the use of the tool. Rather, a fluent and quick interaction is seen as positive, as well as a high flexibility, e.g., that multiple different parameters of the model can be easily altered in the tool – in short, that the engineer can handle the tool well. Hereby, the personal preferences of the engineers play a big role with respect to what characteristics tools should have.

> And that is perhaps very important, that programmes work intuitively so that there is not too much of a barrier from the creative process to the implementation in the model. (Int-models-06)

Furthermore, the interviewees' answers to the question on the nature of a future, ideal tool to develop models also allowed for conclusions with respect to requirements for the tools models are developed with. For instance, one of the engineers imagined a programme that would evaluate sensible load-bearing structures (Int-models-01). Other interviewees – some more directly than others – imagined a tool that would not facilitate translation work but rather do it for them, so that they would only have to choose from multiple model alternatives instead of developing them themselves. For instance, some engineers said that after the first idea implementation through the engineer, the model should generate and propose variants and alternatives to choose from: "I now have this idea, bring me a suggestion, show me something like that, how could that look like, put a dimension on it, and so on" (Int-models-09). Others even wished for automatic translation, for instance, from an analogue sketch to a digital one, and one engineer explicitly imagined an idea translator:

> An idea translator, you say I want to solve this and that point, and then in principle to get a solution for it, or you get several solution variants for it with the concept or the boundary points that you have put into the model. But where you can still somehow – just like it is now with generative design – if somehow something comes up that you didn't actually want at all, that it can then somehow easily be filtered out or the boundary conditions can be easily supplemented. It would be in principle a direct translation from the brain to a 3D visualisation, perhaps. … In principle, what we are doing now, but automated. (Int-models-12)

With respect to the findings presented above – that the potential of model-use lies in the deep engagement with models, thus in the very act of performing translation processes – these 'wishes' of the design engineers with respect to future, ideal tools are at least alarming. Furthermore, they contradict the statements of multiple interviwees on 'engineering thinking', which was circumscribed as "to think about a problem for yourself and generate your own solution" (Int-process-12, see p. 88) or the statement that the "model building … the activity of modelling" is "the core service of the engineer" (Int-models-07, see p. 114). This further emphasises the necessity of a deeper engagement with the topic of model-use and creativity, not only theoretically but also in the context of structural engineering practice and the tools employed for it.

6.2.4 Intermediate Reflection: A Qualitative Definition of Models and an Assessment of their Role in Structural Design

In this section, the question of what defines a model in structural design was approached through first, looking at the model terminologies and the context they were used in, second, looking at the mechanisms, effects, and impacts of model-use and its driving practice of translation, and third, looking at how engineers evaluate model-use. Through the analysis of these aspects, the essence of models in engineering became clearer. The aim of this reflection is to synthesise these findings into a qualitative definition of models in structural design and to assess the role models play for the structural design process.

The previous findings have shown that the 'model' is a term with "blurry edges". This is a notion coined by Wittgenstein, who used it with respect to the definition of the term 'game'. His aim was to "produce the same sort of effect which Galton produced when he took a number of photos of different faces on the same photographic plate in order to get the picture of the typical features they all had in common" (Wittgenstein, 1965, see also Galton (1878)). In this sense, "through the superimposition of multiple synonyms the specific characteristics of a term and their functions are upgraded against the general, the now visible specific cases constitute the blurry edges – in contrast to a universal, clear-defined term" (Leopold Museum Wien, 2022).

In this spirit, the proposed model definition consists of a core, as well as of three specifications. The core definition of each model is that it is *something that is used in the structural design process and is in relation to a source object.* This alone is a general and not yet sufficient definition of the model, however it already represents the relational aspect of the model's nature. The three specifications define the model further in the context of structural design. They concretise 1) the source object the model is in relation to, 2) the type or nature of this relation, as well as 3) the usage and the effects of the model in contrast to the source object's. Each of these specifications alone would not suffice, yet pieced together they appropriately define the model's nature. At the same time, they constitute the blurry edges, as they can be fulfilled in a variety of ways, as showcased in Table 6.5.

Table 6.5. A qualitative definition of the model for the structural design context. The core definition is specified with respect to three aspects: the source object the model relates to (What), the type of this relation (How), and the usage and effects of the model (Why). The examples for possible specifications anchor the definition in the structural design context.

Core Definition	Specification	Examples for Possible Specifications
Something that is used in the structural design process and is in relation to a source object	Source object (**What**)	Conception, design result/end product, geometry, idea, object of inquiry, physical concept, problem, reality, something not yet realised, task, thought, ...
	Type of relation to source object (**How**)	Abstracted, adaptable, clear, evolutionary, expedient, manageable, materialised, of different medium or scale, reduced, simplified, tangible, transportable, understandable, visible, ...
	Usage and effects (**Why**)	Epistemic object enabling alterations, representation, visualisation, communication.

In this context, it is necessary to mention that some of the interviewed engineers raised further requirements an object has to fulfil in order to be a model. For instance, some stated that being three-dimensional is a necessary requirement for models, a definition which would exclude not only thought models, but all kinds of sketches and drawings or basic mechanical concepts such as the single-span-girder. However, the analysis of the model-use, which revealed mechanisms, effects, and impacts of models, does not indicate that such a limitation of the term model is fruitful in the context of structural design.

With respect to the role of models in the design process, the interviewed engineers overall agree that the model is absolutely essential for every design process and that a planning process without models would not be possible at all. Another aspect they agreed upon is that even though models are essential in the design process and have diverse potentials, they cannot replace the imagination of the design engineer. Multiple engineers expressed this thought in one way or another in the interviews:

> But one's own imagination always comes first, I think. And no model can take that away, it's just an aid, so of course it does not replace the creative process that takes place in the head, it doesn't replace that but it supports it. (Int-models-06)

> What happens in the head, that will still be the decisive thing in the design, or in a good design. (Int-models-15)

These statements imply that the interviewees do not want to attribute the model with a similarly active role than the designing engineer, a finding that converges with Wendler, who has observed that models are oftentimes denied a more active role in modelling processes (Wendler, 2013, pp. 39-40).

Another aspect to be considered for the evaluation of the model's role in the process is whether and how specific types of models and tools impact creative model-use, and thus influence the structural design process and its outcome. As analysed in the previous subsection, most interviewees have highlighted the aspect of the interaction between engineers and models, which places emphasis on the type of tool or model. However, some interviewees claimed that the type of model or tool is not important. For instance, some interviewees insisted that whether digital or analogue models are used does not impact the design process in a negative or postitive manner when it comes to the creative development of designs or ideas in general:

> Of course, I don't dare to judge whether [digital models] are a significant improvement. Because I think we have a lot of designs from previous times that still have enormous significance today, such as the Colloseum, the Eiffel Tower, they didn't have these tools at their disposal, but they still modelled things, just like we did. (Int-models-03)

> I think that in the end it leads to the same result, and for this reason I don't think that the goal changes depending on whether I do it physically or on the computer. (Int-models-15)

These interview excerpts, too, suggest that some of the interviewees do not think that models or tools have a capacity to actively shape and direct the design process. This is in contrast to the multiple evaluations expressed by the interviewees with respect to which tool or model should be used for which task, as described in Section 6.2.3, or on which tools should be used in which working mode or for which strategy of the structural design process (see Sections 6.1.2 and 6.1.3). Also previous research, for instance with respect to how 'good' specific models perform as representations of structural systems or how tools impact workflows (see Sections 3.1.1 and 3.3.1) seems to be in contrast to the statement that the specific type of model or tool is not decisive. Thus, the fact that some of the interviewed engineers do not want to attribute this kind of power to models or tools is potentially some kind of wishful thinking: It has to be that way, otherwise, this would imply less control on the side of the engineer.

To conclude, this section has shown that the model is defined though it's relational character, which is the core element of the proposed model definition. The model exists always in relation to something else, and defines itself with respect to the object it represents, how it represents it, and the actions for which it was developed.

Consequently, this emphasises once more the importance of the context for the understanding of models, their use, and their potentials. This refers to the general context of the structural design process (see Section 6.1), yet equally to the small, specific situations models are employed in, as well as to the numerous translation processes that happen within a design process and that are a crucial factor when it comes to the model's creative potentials. Specifically, it became apparent that model-use has multiple positive effects and impacts, but also bears risks with respect to unconscious, unthinking use. Furthermore, it remains in the responsibility of the engineer to find the right model for a specific task. Very important is the factor of the engagement with the model. The intensity of the engagement, shaped by the number of translations, plays a huge role for the creative effects of model-use. The creative potential of translations emphasises the need to further analyse the interaction with models, thus the practices of modelling, to understand models and their active potentials in the structural design process.

In order to better understand the practice of modelling as a creative activity, the specific context of their use needs to be investigated. This will be done in the following section, which summarises the findings from a participatory observation of diverse modelling situations in an engineering office.

6.3 The Activity of Modelling and its Contribution to Creativity in Structural Design

The previous sections approached the topic of the generation of creativity in the structural design process by describing the contributions of the two main actors in this process, the structural engineer and the model. Building on the previous findings, in this section, the interaction between these two agents – in other words, the activity of modelling – is scrutinised. Hereby, the focus is set on the practices that constitute the activity of modelling in the structural design process.

In contrast to the previous two sections, which were based on qualitative interviews, this section is based on a participatory observation of modelling activities in an engineering office. Hereby, multiple different patterns of actions related to the activity of modelling were identified. The analysis of the empirical data suggested a differentiation of these recurring practices of modelling into two kinds, with respect to what *part of the model* the design engineer is interacting with: either the model as understood and defined in Section 6.2.4 – in the following referred to as the model-content –, or the model environment, meaning the medium that makes this model-content accessible and that is used to alter the model content. The tools for model development, which the previous sections referred to, can be regarded as model environments. However, the term environment goes beyond what is usually understood as a tool and also encompasses the carriers of models, such as paper, or mental tools, such as the brain. Thus, the practices of modelling can be classified as either practices of engaging with the model environment, or as practices of engaging with the model content. These two kinds of practices will be explained in the following two subsections in more detail. The intermediate reflection at the end of the section synthesises these findings by describing the two different types of interactions between engineer and model and the practical nature of the activity of modelling.

6.3.1 Engaging with the Model Environment

The practice of engaging with the model environment refers to all actions that are necessary due to the nature or structure of the model environment, meaning the medium the model is contained in and the tools the model is altered with. In general, the practice of engaging with the model environment was one of the most obvious and striking phenomena observed in the participatory observation. This is interesting, as while this topic was already raised in the qualitative interviews, it did not have the same significance there. Instead, the interviews had focused much more on what can be described as the model content, and on how the design engineer develops it. The analysis of the observation protocols, in contrast, revealed multiple practices that constituted first and foremost an engaging with the model environment. These practices were thus not related to the creative development of the design through the engineer but instead placed emphasis on the model environment's agency.

There were numerous meetings, spontaneous discussions, or consultations, that had the sole purpose to talk about the programme or tool the model was generated in. These centred on the topics of which programme or tool to use for which task, how to use a specific environment correctly, or tips and tricks on how to better handle or control a specific environment. For instance, there was a meeting that centred solely on how to input the previously designed structural frame into the programme Rhino 3D in such a way that the connection between the Rhino-model and the Karamba-Template would be working (see also Table 5.4). The importance given to this topic was underlined by the project lead explaining that "the goal for this week is to get the system running. We should not worry about geometry, or dimensions, or the exact connection of the structural elements, as long as the overall system is running this week" (observation-protocol-4). Later over the course of the project, when both the geometrical model in Rhino as well as the structural model in Karamba were finished, there was another meeting to calibrate these two models so that they could be linked together (observation-protocol-20). Engaging with the model environment also played a significant role in the project coordination meetings with the architects and all specialist planners. In one of them, for instance, it was discussed how the environment of the architectural model could be transformed to be easier accessible for all other disciplines (observation-protocol-13).

The analysis of these situations reveals that there are always at least two actors – the model environment and the design engineer – and that the observed situations can be distinguished with respect to which actor exerts their agency over the other: For one, the model environment as an actor can demand, direct, or steer the design engineer to carry out certain activities, for another, the design engineer can perform actions to handle the model environment.

How the Model Environment Exerts Agency Over the Design Engineer

With respect to the model environment as an active agent, there were multiple situations in which the model environment – directly or indirectly – imposed some kind of action on or required reaction from the design engineer. This agency manifested in several different manners, from explicit actions to more implicit ways. The different ways in which the model environment exerted agency over the design engineer can also influence each other or occur at the same time, as will become apparent in the following detailed descriptions.

Explicitly Exerted Agency First, many of the model environments, for instance, the combination between the Rhino-model with the Karamba-Template, *require a significant amount of computational power.* This became evident whenever there was not enough computational power for the environment to work as it should. In one meeting, two engineers were performing calculations with the structural model and were directly editing it accordingly, but the model was reacting very slowly. When the programme seemed to have frozen, one of the engineers suggested to simply let the programme crash and start anew. As the programme continued to react very slowly, they further suggested to deactivate the immediate calculations, to change the mesh types used in the programme, and lastly to deactivate some of the load-cases they were not needing in that moment. Thus, due to the lack of computational power, the programme was not working properly and in consequence, set in motion a chain of considerations as to what could be done to change the situation leading to several actions on behalf of the design engineer.

Another way in which the model environment exerted agency was in *demanding the input to comply with a certain structure*. For instance, the connection between the geometrical Rhino-model with the Karamba-Template required the single model elements to be named in the exact same way in both programmes so that the connections would work. This forced conventions onto the design engineer that needed to be fulfilled, requiring additional effort without having a contentual impact (observation-protocol-4). A more profound way this can manifest itself is when a model environment only allows input of structural elements, boundary conditions or load cases in predefined ways. Hereby, every piece of information on the design needs to be adapted to the logic of the model environment first, in order for the programme or tool to work properly. For instance, for one of the projects an earthquake loadcase needed to be considered. As there was no direct way to input earthquake loads into Karamba, a workaround had to be found. One of the engineers commented "it's like you are trying to do something the model doesn't want you to do" (observation-protocol-26).

The examples above already suggest that model environments *steer or direct workflows or actions* of the design engineers to a certain extent, so that they satisfy or comply with the requirements of the model environment. For instance, in the case of the Karamba-Template, each change or renaming of one of the elements in the geometrical model in Rhino had to be updated manually in the Karamba-Template as well (observation-protocol-04). Another example for the environment directing the workflow is the different steps that are necessary in different model environments for achieving the same outcome. As one engineer explained, in the programme they used before, the calculation of the drift could be done within the programme and the results merely had to be exported to Excel. In contrast, in RFEM the raw data (movements of the single structural elements) had to be exported to Excel and the calculation of the drifts had to be done there (not in the RFEM programme), which implied four extra steps to get to the drift values (observation-protocol-25).

Furthermore, not a single model environment, but *the way in which multiple model environments need to be combined* in a project context can also exert a certain agency over the design engineers using these environments. For instance, the structural model of the observed project was built in both the Rhino 3D and the Karamba-Template environment, and different engineers were responsible for either of these environments. Thus, the working approach was relying on constant communication and exchange of data or files between these engineers (observation-protocol-04/20/28).

Error messages to the user were perhaps the most explicit way in which the model environment's agency manifested itself. These error messages occurred, for instance, when the single structural elements did not have the exact same names in the Karamba-Template and in the Rhino-model as described above, or when specific settings prevented the start of calculations. The messages required immediate attendance, as no calculations could be run as long as they were not addressed. In that sense, for one, they inflicted a kind of urgency to act on the design engineer, and for another, they also specified very precisely what the next steps of action should be. The error messages, on the one hand, ensured that the input complied with what the model environment required, so the model environment could sensibly carry out the needed calculations or any other actions, respectively. On the other hand, error messages also seduced the design engineers to rely on them, that is, the design engineers let themselves be guided by the instructions of the error messages. For instance, in one situation the observed engineer did not really know what to do with the model once all error messages were dealt with, in other words, once the model environment stayed silent and did not provide further guidance (observation-protocol-17).

Implicitly exerted Agency There were also more subtle ways observed, in which the agency of the model environment expressed itself. For instance, when observing one engineer modelling the geometry of a structure, they talked about that when they were engaged in the same task the day before, they got caught up in the process and modelled more and more details. This detailed modelling was not what they had planned to do, as they actually needed to create a first overview of the whole structure (observation-protocol-29). There were also other instances in which the observed engineers explicitly stated that they had lost the overview over the model (observation-protocol-13). With respect to the 3D model of the geometry of the project, the architects also voiced that it was hard to see the hierarchy of the design in it, and that they should prepare simpler sketches to make it visible again (observation-protocol-13). Thus, the model environment can *seduce to certain actions or cloud one's own overview.*

Besides provoking certain actions or reactions, the model environment can also *evoke emotions* in the design engineer with respect to the task of modelling. In the case of the slowly reacting programme, one of the engineers got impatient and irritated during the interaction with the model environment (observation-protocol-33). Others have described a certain disconnect with respect to what is actually happening inside the model environment, as small changes in the model environment – simply clicking one box – that seem insignificant or are even overlooked can have effects that are hard to understand. For instance, starting multiple elaborated calculations requires only the ticking of a few boxes in RFEM, but the results may be hard to understand or not of any relevance to the design task: "You could easily click on this box and the programme would run an extra analysis"(observation-protocol-25). In the above mentioned situation in which the programme did not work properly due to a lack of computing power, in the end, one of the engineers saw by accident that there was one setting turned on, which is usually only used for rendering but not for calculation, and without this setting the programme worked smoothly again (observation-protocol-33). The feeling of disconnect can further be emphasised when the model environment's logic does not make sense to the modeller. For instance, when building the Karamba-Template model, one engineer stated that the way the loads are applied in the model environment was strange, as one has to define the load case for every layer of structure separately, thus one has to draw multiple load planes for the same load (observation-protocol-16).

How the Design Engineer Exerts Agency Over the Model Environment

Naturally, design engineers are not merely subjected to the agency of the model environment but also exert agency of their own. There were several ways in which the observed design engineers managed to exercise this agency.

Handling Complex or Big Models First, model environments usually provide for different ways how to make even complex or big models manageable. This was most apparent in the interaction with the model environment Rhino. Among other strategies, the engineers used different layers for the parts of the structure they were still working on and for already finalised parts, created additional geometrical elements as reference points such as lines, grids, and planes, or worked with a clipping plane to hide the elements behind it to get a better overview of the model (observation-protocol-22/28/29). Knowledge about ways to handle certain model environments can enable a fast and efficient workflow while using these models. However, it is usually only acquired through long-term or intensive experience with a certain model environment, or passed on from engineer to engineer, which also takes time and effort (observation-protocol-25/28). For instance, in a meeting in which two of the project engineers discussed the calculations done with the Karamba-Template model, the project lead guided the project engineer step by step through the process of drawing additional struts into the existing geometry:

> First, you need to go into top view. Then you can select the strut. Once you selected it, you can go into front view to move it to the right position. Now, you can just copy this strut and paste it to all of the lower floors. (Employee-04, observation-protocol-33)

Every engineer usually develops their own strategies how to cope with a certain model environment after working with it for a while. For instance, when one of the engineers involved in the observed project asked a colleague for help with a programme, the colleague explained: “I built a few tools for myself within the programme, for instance, this one enables me to display red lines, to get orientation in the geometry” (observation-protocol-27). Another engineer had implemented a small routine to be able to visualise the single structural members with different colours depending on their degree of utilisation (observation-protocol-28).

Performing Environment-Centred Translations Second, in the light of the previous findings, it is not surprising that the evaluation of certain model environments or the choice of a specific environment for a set task is a personal topic. This became apparent in multiple situations that were observed during the field stay. For instance, during a modelling session, one of the engineers explained the many advantages of Rhino 3D to the researcher, ending with “it is a good environment to solve problems in multiple ways” (observation-protocol-29). Another engineer worried after a talk about BIM procedures which had been presented at the office, that “if [the office management] want to do the Closed BIM approach, then we would all have to learn ArchiCAD” (observation-protocol-7). In a conversation about the Karamba-Template with the researcher, one engineer said that the programme was a little strange in the way the loads are applied in it (observation-protocol-16). Naturally, these valuations of certain model environments are also influenced by previous experience with other model environments. One engineer specifically stated that due “to knowing another similar software, I am now looking for the same features in RFEM” (observation-protocol-25). In this line, a way in which the modeller can exert agency over the model environment is simply by changing it to better suit personal preferences and experience. In the observation, a *change of the model environment* to quickly verify or test a thought or an idea with respect to the design happened multiple times.

This practice can be conceptualised as a translation process; however not – as described in Section 6.2.2 – from model to model through the design engineer or from person to person through the model, but instead as a third ideal-typical type of translation process: a transfer of model content from one model environment to another without altering the model content (see Figure 6.3). An example for such an environment-centred translation would be the transfer of content from a hand sketch to a 2D drawing or a 3D model without adding additional contentual information. In the observation, in numerous situations the engineers made screenshots of 3D models, which then served as input for meetings with the architects (observation-protocol-11). At another instance, the geometrical model built in one Rhino-file needed to be transferred to the Rhino-file which was connected to the Karamba-Template.

The observation provided further insights with respect to this type of translation. First, in contrast to translations that alter the content of the model, translations between environments usually happen ad hoc. An example for this are screenshots made from 3D models. Second, in contrast to translation processes that alter the content, which are usually motivated by the desire to progress the design, and in

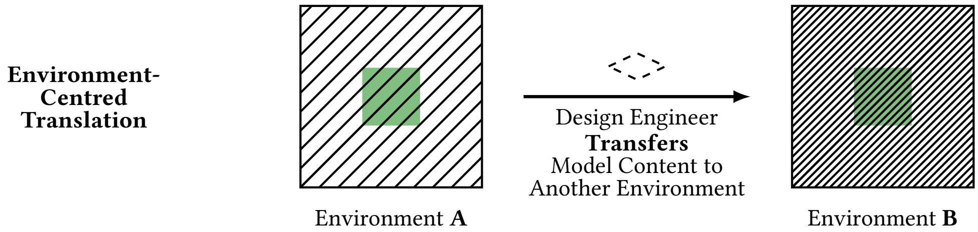


Figure 6.3. The environment-centred translation as a third ideal-typical type of translation: The model content is transferred by the design engineer from an environment A to an environment B. Hereby, the model content itself is not altered.

contrast to translation processes from person to person, which are usually motivated by the desire to communicate, translations between environments can either support design development or communication, and often impact both.

An example of how an translation of the environment can progress the design is when a specific model environment only has limited functionalities and additional ones are needed. For instance, as one engineer reported, to calculate structural shifts, the raw data from RFEM needed to be exported to process it in Excel, as the programme itself did not have this functionality (observation-protocol-25).

There were also numerous examples for environment-centred translations with the motivation to communictate. For instance, in one situation, the project lead wanted one of the project engineers to code the different structural elements with colours according to their structural function for the building. As the engineer did not understand what the project lead wanted at first, the second project engineer quickly made a screenshot of the model with the Snipping Tool and highlighted the different structural elements with the colours in the screenshot, which was then posted into the Teams chat of the meeting (observation-protocol-28). Here, the irritation or lack of understanding of the first project engineer motivated the second project engineer to translate the task to another environment so that it would be easier to understand. Furthermore, in the bigger context of the whole design team (including architects and specialist planners), intermediate results generated in disciplinary models needed to be translated to a common reference point, namely the architectural model in the observed project, so that everyone could judge the impacts of the disciplinary results (observation-protocol-9).

Additionally, multiple situations were observed in which a combination of both motivations was the case. For instance, the model environment was too complex to perform quick operations and at the same time to collaboratively assess the outcome of such quick operations (observation-protocol-10/11).

Using Fundamental Engineering Knowledge A third way in which the design engineer can exert agency over the model environment is through fundamental engineering knowledge that is not dependent on a specific environment. For instance, in the situation in which several engineers tried to apply earth quake loads to the Karamba-Template model, it was vital for the solution that the engineers recollected the way this can be calculated by hand to then develop a way in which the logic of the hand calculation can be translated to the Karamba-Template environment. In a similar stance, in a conversation the researcher overheard at lunch, a project manager was complaining about people from a partner office, who according to the project manager, "always blame the programmes, when something goes wrong, not the people who use them" (observation-protocol-5). This illustrates nicely that even though a model environment can have certain agency over the user, it is the engineer's task to maintain the control. Furthermore, it highlights the fact that the capabilities of the design engineer have a huge influence on model-use, as has also been stressed by multiple interviewees (see the description of content-centred translations in Section 6.2.2)

6.3.2 Engaging with the Model Content

The practices discussed in the previous section all constituted engaging with the model environment. In contrast, the practices of engaging with the model content presented in this section go beyond the purpose of handling the environment the model is contained in or generated with, by trying to circumvent the model environment and directly target the model's content.

As shown, in the practices of engaging with the model environment the different actions could be either attributed to the model environment or the design engineer as the driving actor behing them. Conversely, the agency in the practices of engaging with the model content cannot be as easily assigned to either the design engineer or the model content. Rather, the shares of design engineer and model content in the actions that make up these practices seem to be more entangled. Thus, in the first part of this section, the four identified practices are described as interactions between design engineer and model content. In these descriptions, the contribution of the design engineer to these practices is more explicit and in the forefront. However, it is also clear that all of the identified practices relate in certain ways to the model mechanisms, and their effects and impacts on design development and communication described in Section 6.2.2. The way the model content contributes to these practices of engaging with the model content is elaborated in more detail in the second part of this section.

The Observed Practices and the Design Engineer's Contribution

In the observation, four distinct practices of interaction between design engineer and model could be identified, which can be described as an engaging with the model content. The identified practices are 1) setting of goals, 2) immediate actions, 3) modelling and speaking, and 4) collaborative modelling with different roles.

Setting Goals The first practice of engaging with the model content was the very frequent setting of intermediate goals with respect to the status of the model, meaning *goals that specified what the status of the model should be like at a given deadline.* Some of these goals were, for instance, to have a sketch of the structural system ready for the design meetings with the architects (observation-protocol-04), to finish the implementation of the structural axis of both building typologies (observation-protocol-12), to progress the model so far that it can be used to represent, explain, and communicate the ideas (observation-protocol-29), or to merge the separately generated geometrical and structural model parts from the Rhino 3D and the Karamba-Template environment (observation-protocol-24).

In the four weeks of observation, at every observed meeting, *goals were constantly set, restated, or reformulated.* This happened usually in coordination meetings, either internal ones with the project members from B+G or external ones with the architects and the specialist planners. Especially in the beginning of the observation, at which time the project was still in an early stage, there was often not much new content that could be discussed in the meetings, as project members were still occupied in other projects. Yet, the meetings served as a fixed point in the project's time frame and were used as deadlines for intermediate goals (observation-protocol-11). Towards the end of the project, time pressure increased significantly. This resulted in a need to prioritise tasks (observation-protocol-15) and to frequently check in with everybody working on the project, to make sure that every task was worked on and to deal quickly with potentially arising problems or questions (observation-diary-14, observation-protocol-31).

However, even though efforts were put into achieving some of the set goals, there were also cases in which goals were not really pursued, suggesting that the setting of goals did not necessarily imply that these needed to be met exactly at the deadline. The constant setting, restating, or reformulation of goals is thus at first glance curious, as these goals are then not strictly met. However, the thorough analysis of this practice suggests that *the setting of goals serves to fulfil two additional purposes besides their achievement.*

First, through goal setting, *the development of the structural design as the main aim in the design process is prioritised.* Through the setting of goals, the state of the model, which represents the structural design, is defined content-wise, meaning that the model content is put in the forefront. As a result, the actions necessary to reach the goal are blanked out for a moment and the concentration is on the actual content-related purpose of these actions, which is the development of the structural design. The content of the model becomes more visible, as the relevant question is: How far along is the structural design represented by the model at a given point in time?

Second, in a similar stance, those project meetings in which the structural design was the main topic (as opposed to the model environment or engaging with it) served as excellent opportunities to zoom out of detailed modelling activities that are often directed towards engaging with the model environment, and concentrate on the bigger picture. The model content becomes the prominent reference point. As a result, the whole project status is measured in the model. For instance, in one meeting with the architects, one of the project engineers explained that "they are a little bit behind with the model" (observation-protocol-23), comparing the status of the structural model with the goal that had been set. This has the effect that *the overview of the project's progress can be maintained.* In a way, goal setting serves as a counterpart to the effect of losing oneself in detailed modelling, which can be spurred by engaging with complex model environments as explained in the previous section.

Immediate Actions The next practice of engaging with the model content are immediate actions. This concept evolved from the general observation that during modelling work, ideas were usually directly followed, tried out, and realised, multiple times even directly in meetings.

As a more general observation with respect to immediate actions, *speed* almost seemed to be a *value or quality in itself* for the observed engineers. One engineer said in a conversation that "it is a speciality of B+G to keep up with the speed of the architects" (observation-protocol-29). In the context of a tight project timeline, the fastest way was usually judged as the best one, or was even the decisive factor which led to the choice of a specific approach. For instance, even though another employee was planned to take over some modelling work in the project, one of the project engineers opted for doing the task instead, as "we would have to instruct [Employee-07], but we do not have time to do that right now. It will be faster if I just do it myself" (observation-protocol-15). In this line, in another situation, another project engineer compared their modelling speed with their colleague's and wanted to have the tasks distributed accordingly, as otherwise "the internal workflow would not make sense" (observation-protocol-31).

In the observed situations, the immediate actions consisted either of the realisation of an idea or of a sudden thought, the alteration of an existing model, the quick verbal reaction to a model, or the taking or revising of decisions. A closer analysis revealed three *characteristics of the practice of immediate actions*, which are closely interrelated. First, the quick nature of the interactions also evoked the association of an easy interaction. Second, due to the immediacy of the actions, the engineers often engaged in these without further or more thorough reflections. Third, the engineers who engaged in immediate actions let themselves be guided by the actions they performed, trusting in the natural process to direct them to a fruitful result. For instance, in a meeting in which the initial set-up of the Karamba-Template model was discussed, the project engineer was directly editing the model inserting the changes that were discussed, while the lead engineer was moving around the room, highlighting aspects on the screen, taking over the computer and editing things (observation-protocol-04), thus seemingly letting thoughts run free, acting directly, naturally, and immediately on impulses.

The speed in which certain actions can be performed depends on whether the environment is suited to quick and immediate interactions but also on how well the engineer knows the model environment. Furthermore, it depends on whether the respective engineer feels comfortable with this way of working or rather stressed and rushed by it (observation-protocol-31). However, if such interactions can be achieved, this can lead to a number of positive effects for the design development, as the high density of actions *highlights the basic model mechanisms, and their effects and impacts on design development and communication.*

First, multiple quick developments, for instance through fast translation steps, allow for a fast change of perspective, which allows to create new knowledge on the design quickly. For instance, during one modelling session that was observed, the question arose whether the structural grid should contain three or four floors in vertical direction. Instead of wondering theoretically about this issue, the engineer decided to simply draw the first option, and to directly evaluate it: "The proportions feel good" (observation-protocol-11). The engineer then directly got the project lead to look at the new development, who listened shortly and then said that it should simply be "set up and tried out" to be able to decide. This quick gathering of a second opinion has been observed at several other occasions during the stay in the field. In general, through quick trial and error cycles, better decisions can be taken as there is a broader empirical base for them (observation-protocol-29), which makes use of the models' effect of *enabling experimentation.*

This relates to the second effect of immediate actions, namely that the model's potential to *support or assume certain efforts of imagination* for the modeller can be efficiently used. The faster new ideas or alterations are realised in a model, the less imagination power is needed. For instance, instead of imagining the overall structural grid in his mind, the project engineer simply drew it in the model, which enabled him to "directly see where potential structural axes could be" (observation-protocol-11). The mind-set that only what is already there can be evaluated can also spur a productive pragmatism: Fast and easy steps are performed in the beginning, the results of which do not have to be perfect but should generally tell whether an idea is feasible or not. For instance, in a coordination meeting, the project engineer suggested to determine the dimensions of the beam as soon as possible, because he suspected them to become bigger than they had originally planned: "This does not have to be the 100 % solution, but it should be principally solved" (observation-protocol-24).

Another beneficial effect of these immediate actions is that *the model's effect to facilitate understanding is enhanced.* Hereby, misunderstandings that could arise due to differing yet implicit opinions of how the design should proceed can be clarified sooner. This is illustrated by the following situation, in which three engineers analysed the structural behaviour of the design:

> Employee-05: The deflection could be due to the bracing diagonals not being on both sides of the structure.
> Employee-04: No, I think the problem is rather that we do not have a vertical structural axis in that position. We need to make a framework out of the additional piles.
> *Employee-06 inserts additional diagonals to the piles.*
> Employee-04: I would not insert them in the direction of the core, but only in cross direction. We should insert the diagonals everywhere the structure has an outrigger. (observation-protocol-33)

In this situation, the interpretation of Employee-05 was directly analysed by Employee-04, who then delivered an alternative interpretation of the behaviour. Further, the suggestion how to handle the deflection was realised on the spot by Employee-06, however, not in the way it was originally meant. Due to the direct realisation, this could be corrected immediately – otherwise, it would have probably entailed a longer process. Hence, the model's effect to facilitate understanding is further strengthened by small but quick actions that each provoke different interpretations from the involved engineers, enabling the quick establishment of a common understanding.

The immediate actions put the model content in the forefront and can significantly progress the design through the above described effects and making use of the model mechanisms and their impacts in short intervals. However, they also *bear the risk of losing overview or engaging in arbitrary steps with no added value to the design development.* By guiding the focus of the one performing the actions as well as of anybody watching them, immediate actions can have a captivating effect. For instance, performing quick and easy actions on a model can lead to getting lost in the model, as one engineer said: "During the modelling of the first part of the structure, I was getting into too much detail in the model, so I dismissed the whole thing again. Now I try to focus more on the rough grid" (observation-protocol-29). Thus, multiple quick and immediate actions can also mean multiple steps in the wrong direction, producing more work afterwards, as a cleaning of the model becomes necessary. When multiple people are involved, immediate actions can distract or steer everyone's focus. For instance, it was observed how in a meeting, the focus of the participants was directed by one of the engineers drawing on the Miro Board while explaining a new idea, "altering first the existing structural model, copying elements and placing them next to each other to illustrate the modularity [of the existing design]; then [Employee-05] uses completely abstract volumetric elements to illustrate other concepts that would be possible" (observation-protocol-21). Only through the intervention of another project engineer, the attention is brought back to what was originally the aim of the meeting (observation-protocol-21).

Modelling and Speaking The third identified practice of engaging with the model content is modelling and speaking. This concept is based on the general observation that a significant amount of the modelling work actually happened in meetings as opposed to in individual work. One possible reason for this circumstance is that the engineers working on the project did not have a lot of other time slots to engage in modelling work except for the meetings, as they were also involved in other projects that were originally supposed to be finished but still ongoing by the time the observed project started (see Section 5.3). Hence, the only way to find time for the project was to organise meetings with other project participants, to have a set time frame to jointly work on the project (diary-date-21, observation-protocol-26). In these situations, the practice of modelling and speaking manifested itself in two ways. First, in meetings, the engineers in the office talked frequently about what they saw in the model, the model results, or what the model represented. Furthermore, they discussed different model environments and approaches to modelling. Second, in these meetings but also in the individual work that was observed, the engineers would comment on what they were modelling while doing it.

With respect to the *discussion of the model in meetings*, two aims of that practice directly related to the model content were identified. For one, the discussions enabled to talk about and *interpret the results* that were generated with the model. For instance, in one of the observed meetings, the lead engineer asked to see the calculated deflections of the model. Seeing the results started a joint interpretation of them:

> Employee-04: So what we can see is that the structure bends quite a bit at the bottom. But at the same time, it is tapered horizontally, but the diagonals are not yet strong enough to counteract the deflections.
> Employee-05: Is that all due to wind loads or does the calculation already include earth quake loads?
> Employee-04: This is only the wind loads. The aim was to first see, whether we like the form of the deflection. It is ok for now, there is less twist and the buckling which has been there yesterday is gone.
> Employee-05: At worst, we can still also use the bridges as additional bracing structures. (observation-protocol-28)

For another, the discussion served to *talk through the current state of the model*, to be able to decide on goals and further steps, to detect errors, but also to mutually assure each other that the project is going into the right direction:

> Employee-04: In principle, we now have a structural system which deflects normally and does not twist too much.
> Employee-05: Now we need to bring it to a point where we can render it, then we can do fine-tuning.
> Employee-04: The goal today is to bring all model parts up to this point, otherwise we won't make the deadline.

> Employee-05: I will finish the cloud, [Employee-06] finishes the blades, [Employee-07] can do the basement and [Employee-04] can start with costs and massing (observation-protocol-28).

Thus, similar to the setting of goals, talking about the current state of the model and relating it to the envisioned design result puts the model in a perspective that focuses on its content.

With respect to the *simultaneous modelling and speaking*, two modes of this practice have been observed during the field stay. First, there were several situations in which the instructions were given and the modelling actions were performed by the same person – thus, the same engineer commented on the modelling steps while performing them. For instance, in one situation a project lead was discussing the status of the model with two project engineers. He suggested some alterations, however the project engineers were not sure if they understood them. Thus, the project lead started sketching the problem on a piece of paper, and at the same time explained each step and its implications for the resulting flow of forces. This way, each step could not only be retraced visually but was additionally explained with all the consequences, which led to a *deeper understanding of the effects of the alterations* on the structural design (observation-protocol-02).

The second form of simultaneous modelling and speaking that was observed was *guiding one's own or other people's attention or provoking reactions through posing questions, listing different options for modelling alterations, or describing what one sees.* The provoked or proposed actions can either be directly realised or dismissed. In the first case, this implies a direct possibility to see what these options would entail for the design. For instance, in one situation, the three project engineers were discussing the overall design of the structure:

> Employee-05: Maybe we could get rid of the table-structure altogether, as we have the bracing now.
> Employee-06: But we need the table structure also to ensure a quick building process. Besides, the mobility lane is also carried by this structure.
> Employee-04: I haven't thought that far. We would actually need to completely get rid of the structural elements above the table structure, if the mobility lane is located there.
> *Employee-04 hides the respective parts of the structure in the model.*
> Employee-04: So now, where can we put the bracing diagonals? (observation-protocol-08).

In the second case, through the practice of describing potential further modelling steps, these are anticipated and thus potentially become redundant.

> Employee-06: Can we simply add another column under the outrigger, so that the outrigger is not as big? What would be better, multiple small and

elegant columns or a single big column?
Employee-05: The architects won't like this idea.
Employee-04: I would instead make a framework out of this column (observation-protocol-28).

Hence, in both cases, the model becomes the common ground for creative thoughts on the further development of the structural design.

In line with what was described above, the practice of modelling and speaking has one major benefit: Through *'imagining by speaking'*, the model environment can be circumvented – as opposed to the direct realisations of modelling steps, in which case it needs to be dealt with. Hereby, further developments are enabled independently from the environment. In interaction with other modellers, this can lead to creative and fast discussions (observation-protocol-29). But also in interaction only of one engineer with the model the voiced thoughts can guide and support imagination processes and thus spur the further development of the model content.

Collaborative Modelling with Different Roles The last practice of engaging with the model content that was observed is collaborative modelling with different roles. Before this practice is described, it is pragmatic to distinguish between two overarching views with respect to collaboration in project work and modelling. First, collaboration can be seen as a necessity in every project context, and models as tools to facilitate this collaboration, be it as a base for communication or as an interface. Second, collaboration can be seen as a creative potential for the design process as the capabilities, perspectives, and interpretations of multiple people can be combined or interaction processes are enabled, which bears the potential to spark new ideas (see also 'Collaboration as a Strategy' in Section 6.1.3 and the benefits of communication-centred translations for the design development in Section 6.2.2). In the following, the practice of collaborative modelling with different roles is described against the backdrop of the second view on collaboration.

As already described in the previous subsections, meetings or conversations are a vital part of modelling in general. Hereby, the collaboration happening took on several forms: from communicating or discussing organisational aspects to discussing model environments and contents, altering and editing models, working in parallel on a topic and comparing the outcome, or watching one person performing modelling work and commenting their actions. What stood out during the observed collaborative modelling situations is that the involved people usually took on different roles in relation to the model. Specifically, three pairs of roles were identified:

1. The first identified set of roles is the *student-teacher pair*, or the *instructor-implementer*. In this set of roles, one person (the teacher/instructor) usually has more experience than the other person and teaches or instructs the student/implementer with respect to a certain modelling activity, often related to

the interaction with the model environment. For instance, the 'student' has a question regarding how to achieve a certain effect in a model environment, and the 'teacher' explains their way of solving the task, oftentimes by taking over control of the student's computer and letting the student watch while solving the task (see observation-protocol-27/31). In another instance, towards the end of the project, an additional employee helped with the geometrical modelling of the structure, who was instructed by the project engineer with the responsibility for that part of the model (observation-protocol-22).

2. The second set of roles is the *idea generator-critic pair*. Hereby, one engineer as the idea generator freely verbalises ideas and thoughts on the development of the design, and another takes on the role of a critic and judges these ideas (observation-protocol-28).

3. The third set of roles is between *people with different areas of responsibility*, for instance, with respect to the overall project or different parts of the structural design. For instance, in the observed project, one engineer was responsible for inserting the structural concept into the Karamba-Template to enable structural analysis, while another one was responsible for modelling the structural concept geometrically in Rhino 3D. This distribution of responsibilities enabled both engineers to work independently on the structural model for a long period of the project, which sped up the process significantly.

By taking on different roles during modelling, the task is divided into components and the cognitive load is shared between two people. Hereby, in the first two sets of roles, the task is divided into components of different nature: For instance, for the student-teacher pair as well as for the developer-critic pair, one person is assuming the more creative part of giving instructions or ideas how to develop the design further, and the other person is implementing these instructions or ideas. In this way, the task of designing is shared between two people, who can each focus on one part of it. In the third set of roles, the task is divided into smaller tasks of similar nature, which has the effect that not just one but instead multiple people develop in parallel similar knowledge on the structural design and can thus be sparring partners that can help each other when questions occur. Through both types of task divisions, the *mental load of designing is shared* between multiple people, which enables each person to design more freely and creatively.

More specifically, a number of *positive effects* of this practice of taking on different roles during modelling activities have been observed. First, the active adoption of different roles facilitates taking on a different angle with respect to the judgement of already existing model content. For instance, in one meeting, the different perspective of the critic led to the identification of redundant diagonals in the model the developer set up (observation-protocol-33). Second, the roles can spur the development of new ideas or developments. In the observed project, the distribution of responsibilities for different parts of the model to two engineers resulted in an efficient working process while ensuring that both engineers and the project lead were deeply familiarised with the model. Thus, in discussions of the two model parts, all engineers could contribute to the conversation equally which resulted in the meeting not only being of organisational nature but also content-related. In one meeting, even new ideas with respect to the overall structural concept arose (observation-protocol-08). Third, when both pairs of one set of roles agree on the same decision, this can also serve as an additional legitimisation of decisions.

The Model's Contribution

The previous part of this section contained the description of the observed practices of engaging with the model content as entangled interactions between design engineer and model. Hereby, as already stated above, the contribution of the design engineer to the interaction becomes more explicit, as it were the design engineer's actions that were directly observed. However, even though the model's agency does not show itself in specific actions, as was the case in the practices of engaging with the model environment, its contribution to the interaction is still perceivable and an inherent and indispensable part of these interaction processes.

The analysis of the described practices suggests that the model's contribution to the interaction with the design engineer consists in the fact that the model mechanisms and their effects (see Section 6.2.2) are emphasised and enhanced through the interaction with the design engineer. Hereby, the described practices relate in different ways to the model mechanisms and their effects. In the following, the attempt is made to disentangle the model's contribution to these four practices from the actions of the design engineer to make it more explicit.

First, in the practice of setting goals, the design engineer imagines the model in a certain future state. The goal can be conceptualised as a thought model that is a projection of the current model in a future state. Through the frequent setting, restating, or reformulating of the goals in a design process, a variety of such thought models are created. Thus, these goals as thought models externalise and captivate the ideas, thoughts, and concepts that exist with respect to the future state of the model. Further, they uncover, make explicit as well as simplify and abstract the aspects of the ideas, thoughts, and concepts related to the future state of the model through summarising them in the thought model, respectively in the goal. Additionally, the goals put the focus only on the specific future state of the model, and neglect the way to achieve it at this point. As the state represents the model content, whereas the way to achieve it usually implies additionally engaging with the environment, this has the effect that the model mechanisms can unfold their effects without interference from the model environment.

In the practice of immediate actions, the model contributes to the interaction as its mechanisms and their effects are addressed in a high frequency through the quick nature of the interaction. The description illustrates that the supporting or assuming of imagination, the facilitation of understanding, as well as the enabling of experimenting are all activated repeatedly through the speed of the interactions. One observed characteristic of this practice was that the design engineers who engage in this practice let themselves be guided by the actions. This suggests that the model's contribution is particularly strong in this practice. Furthermore, it converges with Hines (2012), who states that speed is important for the generation of creativity in design processes, as it ensures "that the expression of ideas is unhibited".

Third, in the practice of modelling and speaking, the model contributes in a similar way as in the first practice of setting goals, as the model content that is talked about provokes the generation of thought models. Thus, by means of the development and alteration of thought models, the model mechanisms and their effects are activated.

Lastly, the practice of collaborative modelling with different roles does not in itself enhance the model mechanisms or effects. However, it enables each person engaged in the modelling process to benefit better from them. By dividing the task of modelling among multiple people, the mental load of designing is shared and the engagement with the model is facilitated for each person, which in turn enables each person to benefit more from the model mechanisms and their effects.

To summarise, in the practices of engaging with the model content, the contribution of the model lies in showing in enhanced manner its inherent mechanisms, their effects, and impacts.

6.3.3 Intermediate Reflection: Forms of Interaction between Engineer and Model and the Practical Nature of Modelling

In the previous parts of this section, two different kinds of modelling practices have been identified and described. First, practices of engaging with the model environment that engender closely engaging with a medium or tool used to carry or develop a model. Second, practices of engaging with the model content that are focused on the development of the structural design or the communication about it. Based on these findings, the aim of this intermediate reflection is to develop a qualitative understanding of the nature of the activity of modelling in structural design. Hereby, first, the different forms of interactions of the two types of practices are summarised and synthesised in a diagram. Second, the practical nature of modelling is highlighted.

With respect to the nature of interactions of the two practices, a fundamental difference has been observed. Engaging with the model environment, for one, can be concepualised as consisting of discrete single actions of either the design engineer or the model environment. For another, engaging with the model content can be conceptualised as the entangled and close interaction between design engineer and model. Hereby, in all the observed practices, the entangledness between the design engineer's actions and the model's mechanisms can lead to a state of flow, in which the actions of the design engineer, and the effects and impacts of the model mechanisms coalesce.

Figure 6.4 summarises both interaction schemes. During engaging with the model environment, the actions can be clearly attributed to either the model environment or the design engineer as the actors. Hereby, the model environment usually drives the interaction, by demanding or requiring certain actions or reactions from the design engineer, seducing them to perform certain actions, or influencing their general perception of the model, for instance, by impeding the overview or engendering a feeling of disconnectedness. The design engineer, in turn, employs several strategies to cope with the model environment, changes the environment, or uses engineering knowledge to circumvent it.

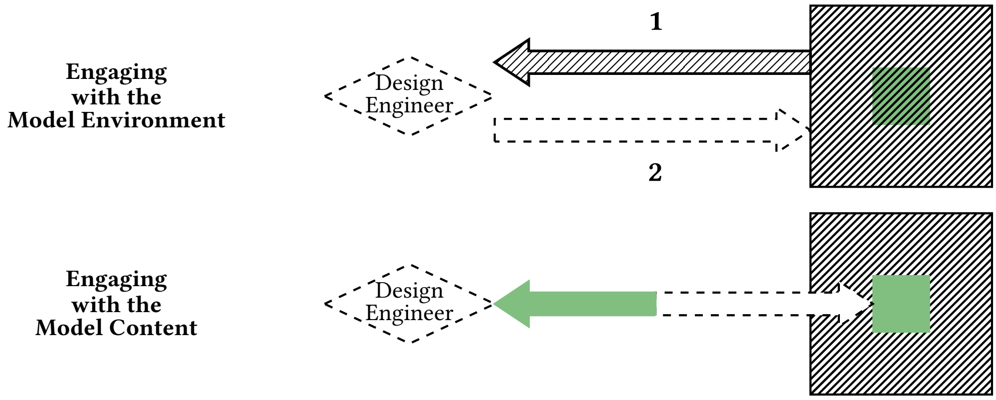


Figure 6.4. The two types of interaction between engineer and model. During engaging with the model environment, the model exerts agency over the design engineer. The design engineer reacts by employing different strategies to handle the model environment. During engaging with the model content, the actions of design engineer and model are entangled. The design engineer engages in different practices that focus on a direct access to the model content, and the model supports this through its mechanisms and their effects.

In the engaging with the model content, the design engineer engages in different practices – however, the authorship of these practices cannot be completely attributed to the design engineer, as the model also contributes to them to a certain extent. As described in the previous section, this is due to the fact that these practices make effective use of the model mechanisms (externalisation and capturing, visualisation and uncovering, simplification and abstraction, see Section 6.2.2), which are the reason why models work in the first place. Thus, through interaction between the design engineer and the model by means of the engineer's actions and the model's mechanisms, the effects of the model are heightened, which are the support and the assumption of imagination, the facilitation of understanding, and the enabling of experimentation. In consequence, engaging with the model content leads to a further development or to a better understanding of the design.

Furthermore, it can be stated that the different practices of engaging with the model content are not separate actions but rather intertwined and can occur combined or in parallel. For instance, the practice of setting goals, when done in a team, can be also seen as a form of the practice of modelling and speaking. Furthermore, the practice of taking on different roles during collaborations can happen within other practices. For instance, modelling and speaking usually implies some sort of taking on roles. Practices of engaging with the model content which are combined in such a way can also productively influence each other. For instance, acknowledging the productive capacity of collaboration between multiple actors, additionally modelling with different roles might render the other practices even more generative and creative. This further underlines the flow effect the practices of engaging with the model content can produce.

Both kinds of practices are crucial parts of the activity of modelling. For one, as the model environment is needed to structure the model content, make it visible and transportable, engaging with it is a necessary part of all modelling activities. The importance of engaging with the model environment is also acknowledged in the literature, for instance by Bucciarelli (2002), who states that "to be good at design" depends "on [the designer's] mastery of specific skills and know-how such as sketching and modelling" (see Section 2.3). However, as all actions of the design engineer are directed toward the model environment, as opposed to design development or communication, these practices do not progress significantly the design process. For another, the practices of engaging with the model content are what actually progresses the design process, as they aim at the development and the understanding of the design. In short, the practices of engaging with the model content make the activity of modelling purposeful instead of an end in itself (see also the risks associated with model-use described in Section 6.2.3). Thus, with reference to the structural design as the ultimate goal of all activities of modelling, engaging with the model environment can be described as dealing with problems of second order, while engaging with the model content can be described as dealing with problems of first order. Overall, the activity of modelling can be described as an interplay of these two practices of modelling.

With respect to the nature of modelling, it can be highlighted that the activity of modelling – as an interplay between the practices of engaging with model content and model environment – can be described as a highly practical activity from the design engineer's side. The observed practices of engaging with the model content as well as how the design engineer exerts agency when engaging with the model environment revealed that all actions of the design engineer can be brought back to either the content-centred translation described in Section 6.2.2, or the environment-centred translation described in Section 6.3.1. As these translations are defined by their practical nature, this also attributes a practical nature to the activities of modelling. In this line, the findings from the observation corroborate the findings from the interviews with respect to the *how* of modelling work, that is the way in which models are created and transformed. Furthermore, conceptualising the actions of the design engineer (both in the practices of engaging with the model environment and in the practices of engaging with the model content) as basic translation processes makes explicit how these abstract concepts manifest themselves in actual working practices in real project contexts.

The highly practical nature of these on-the-ground translations has several positive effects. These positive effects suggest that the more the design engineer actively engages in different types of translations, the more creativity can potentially be generated during modelling activities.

Action entails friction: As observed in multiple situations, every translation practice entails some kind of friction. This friction can be productive as it can reveal the weak spots of the design. Friction was mostly observed in the practices of modelling and speaking, of collaborative modelling with different roles, or of changing the model environment. For instance, in a meeting with the architects and other specialist planners, during the presentation of one of the specialist planner's results, something irritated another specialist planner. When the planner raised concerns about what was being presented, the discussion shifted from a presentation mode to a brainstorming mode. Hereby, the engineers and planners could find a solution for the irritation and produce new knowledge instead of simply communicating. In that way, during translation practices, new knowledge with respect to the design can be generated.

Action triggers further (mental) (re)action: Each translation step can trigger new thoughts, both in the ones performing and observing it. These mental actions or reactions can potentially lead to a deeper understanding of the content of the models, namely the structural design. Furthermore, not only mental but also physical reactions can be triggered, so that a chain of small translation steps evolves naturally to progress the design. This is exemplified best in the practices of immediate actions or modelling and speaking. This aspect has also been raised by the interviewees (see Section 6.2.2).

Action equips with power: Lastly, the practice of translation equips the translator with power with respect to the structural design development and its communication. As has been observed multiple times, each step of a translation activity engenders a certain scope that can be used by the translator (see the description of the content-centred translation in Section 6.2.2). For instance, one engineer explained, due to the often vague architectural models, the engineers needed to make assumptions as to what the architects meant, and to develop the structural concepts on that base (observation-protocol-29). This translation process from something vague to something concrete gives significant power to the translator, as they can decide how they want to interpret the vague model. But also translations from environment to environment can grant a certain power of interpretation to the translator, as through the translation, the translator can determine which environment is used in the further process.

6.4 Synthesis: Model-Use and Modelling as Methods for Creativity in Structural Design

In the three sections of this empirical chapter, the question how creativity can be generated in design processes has been approached from three angles, each with a different focus: first, with a focus on the design engineer's role in the design process, second, with a focus on the model as an object used to inject creativity in the design process, and third, with a focus on the interactions between design engineer and model that produce creativity. In this synthesising section, the interrelations between these three perspectives are made explicit. Based on the understanding of the design process, the model, and the activity of modelling developed in the previous Sections 6.1-6.3, a method of modelling is developed, which supports the design engineer to strategically navigate the design process employing different modelling practices.

First, the practices of modelling described in Section 6.3 are related to the structural design process as described in Section 6.1.4. In the qualitative scheme presented there, the structural design process is characterised as an open and iterative rapprochement process from a blank paper to the final design result. The scheme further includes the different working modes, focal points, and strategies employed by the design engineer, the context of the design process, and the design engineer's task, skills, and personal influence. As the practices of modelling all belong to the sphere of influence of the design engineer, the project context is neglected for the following considerations. The top part of Figure 6.5 shows the reduced qualitative scheme of the structural design process, including the elements of the design process itself (modes, focal points, strategies) as well as the design engineer, who interrelates to the process through their task, skills, and personal influence.

In Section 6.1.4, it was found that the two working modes, the focal points, and the strategies employed in the design process are all related to different models, other artefacts, or tools. The practices of modelling thus are an inherent part of all elements of the design process. To relate the elements of the design process to the practices of modelling, the working modes and the strategies are substituted with the practices of modelling identified in Section 6.3. The focal points are substituted with different models, as defined in Section 6.2.4. These models are used in the design process and are altered through the practices of modelling. Through this, the design process is detached from the project-specific working modes, focal points, and strategies, and instead related to the practices of modelling, which put the *how*, meaning the methods of structural design, in the foreground.

Resulting from these considerations, the bottom part of Figure 6.5 shows an alternative scheme of the structural design process, which equally illustrates a possible pathway from a blank paper to the design result. This pathway is defined by the parameters of time (x-axis) and of the design progress (y-axis). The pathway consists of a multitude of different modelling phases (illustrated as arrows) with intermediate

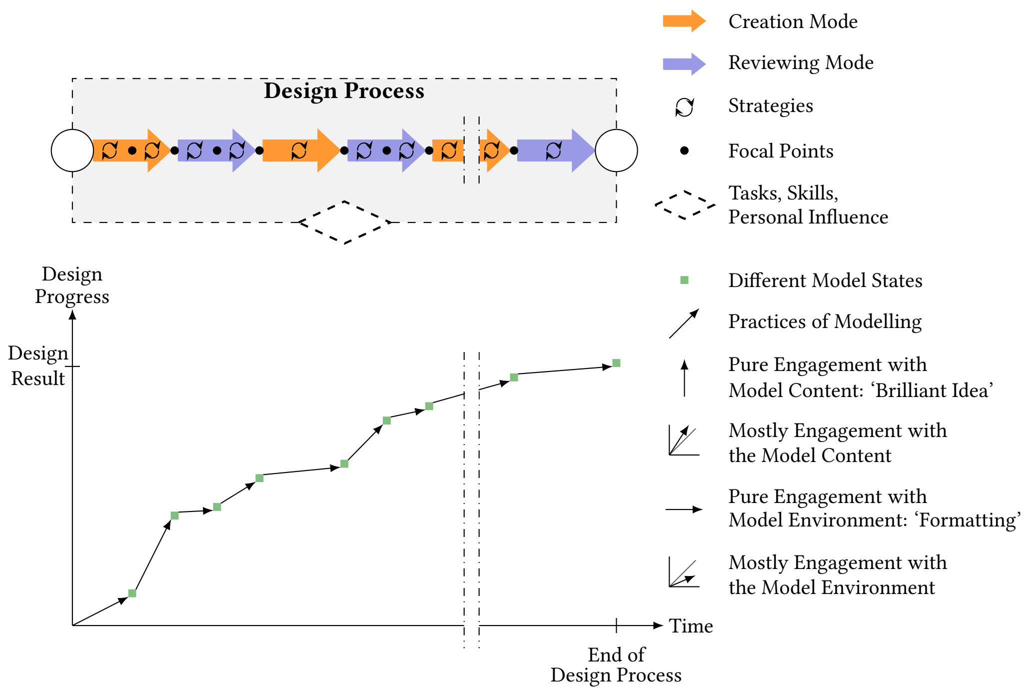


Figure 6.5. The practices of modelling in the context of the structural design process. To consider the aspects of time and design progress, the working modes and strategies from the initial scheme (see Section 6.1.4) are replaced by different phases of modelling in the bottom part, symbolised as thin arrows. Each modelling phase entails different practices of modelling and therefore also different levels of engagement with the model content or environment. The different contributions of engaging with the model content or environment to the design progress are represented by the different inclinations of the arrows. The green rectangles represent different model states (both with respect to content and environment) at the focal points in the structural design process.

results in the form of different states of models (illustrated as green rectangles in between the arrows).

In the Figure, the inclination of the arrows relates to the kind of practice that is dominant in this modelling activity. Hereby, the vertical and the horizontal arrows symbolise ideal-typical extremes. The vertical arrow symbolises a pure engagement with the model content, for instance, the sudden emergence of a 'brilliant idea' that is completely detached from the model environment. Conversely, the horizontal arrow symbolises a pure engagement with the model environment, which can be conceptualised as 'formatting' of content that is already there, taking time but not contributing to the design progress. These ideal-typical extremes do not occur in real modelling practices. Instead, each modelling phase takes a certain amount of time but also entails a certain progress in the design. As discussed in Section 6.3.3, engaging with the model content progresses the design more than engaging with the model environment. In contrast, engaging with the model environment takes often a significant amount of time but does not engender much progress content-wise. Thus, the arrows inclined 45-90 degrees symbolise phases of modelling that are more dedicated to engaging with the model content, whereas the arrows inclined 0-45 degree symbolise phases of modelling that are more dedicated to engaging with the model environment.

Figure 6.5 extends the one-dimensional scheme of the structural design process to a two-dimensional depiction that distinguishes the two aspects of time and design progress in the process. Hereby, it nicely shows the relation between the duration of the design process and the progress made content-wise, depending on the different practices of modelling that are employed.

Second, it is analysed how the practices of modelling relate to the model as defined in Section 6.2.4. Some relations have already been made explicit. For instance, the model contributes to the practices of engaging with the model content through its mechanisms and their effects. Furthermore, the actions of the modeller in the practices of modelling can be brought down to translations processes, the basic mechanisms behind model development and use (both see Section 6.2.2). These relations are now scrutinised in more detail and on a more abstract level.

To this end, it is pragmatic to differentiate between the actions of the design engineer and the actions of the model in the three types of ideal-typical translation processes, namely content-centred, communication-centred, and environment-centred translations. As described in the previous sections, content-centred translations and environment-centred translations are performed by the design engineer, while communication-centred translations happen through the model. All three translation processes have effects on the actor who is not performing the translation: Content-centred translations usually progress the model content-wise, communication-centred translations foremost generate understanding in the design engineer, and environment-centred translations transfer the model to another environment. As defined in Section 6.2.4, the model is something which is in relation to something else and further characterised by the source object, the type of relation to the source object, and its use and the effects enabled by it. Considering this definition, the changes due to the ideal-typical translations can be further specified as follows:

- Content-centred translations can change the source object or the relation to the source object. Depending on the point in the process, the source object the model is representing might change from a thought in an initial sketch to the structural design in a 3D model. Also, the relation of the model to the source object might change, for instance, from a simplification to a concretisation.

- Communication-centred translations do not change the model at all, as information is transferred from person to person through the model. The change rather occurs in the design engineer, who reacts to the communication-centred translation, usually through an increased or at least different understanding of the structural design.

- Environment-centred translations do not change the model content but the model environment, which impacts how the model can be used or the effects it might have.

The differentiation between translations performed by the design engineer or the model and reactions to these translations by the model or the design engineer, respectively, clearly attribute the actor who performs the translations with more power than the actor who reacts or shows effects (see also Section 6.3.3). This can help to identify who is the driving actor in the practices of modelling and thus what the distribution of power is. With respect to this, the results from the interviews suggest that the design engineer has (or at least should have) the power over the design process and use the model as a tool. However, the observation made apparent that most observed practices either are practices of engaging with the model environment or that they constitute ways in which engaging with the model environment can be avoided or circumvented. This implies that the model, consisting of model environment and content, is a very powerful actor in the activity of modelling next to the design engineer.

In practices of engaging with the model environment, usually the model is the driving actor, the agency of which is exerted through the model environment by demanding certain computational power, predefining input or workflows, seducing to detailed modelling, impeding overview, or engendering a disconnect from the model content. The design engineer's actions, for instance, to handle the environment, change the environment, or use engineering knowledge to trick the model environment, can be described as a reaction to the model's agency performed through the model environment, revealing how the model influences the design engineer's actions.

In practices of engaging with the model content, the design engineer acts in symbiosis with the model. Through the described practices of setting goals, immediate actions, modelling and speaking, and modelling collaboratively with different roles, the design engineer directly interacts with the model content. The model, in turn, performs its agency mainly through its main mechanisms (externalisation and capturing, visualising and uncovering, abstraction and simplification) described in Section 6.2.2, and thus supports the design engineer in the interaction with the model content.

The analysis of these relations between the different findings brought about two insights. First, the relation between the practices of modelling and the structural design process has highlighted the importance of engaging with the model content, as essentially, only this type of practice progresses the structural design. The relation between the practices of modelling and the findings regarding the model itself, however, have illustrated that the model can exert agency over the engineer as well as how this happens. The model, more specifically the model environment, is the driving actor in the practices of engaging with the model environment. A design engineer who is not aware of this active potential of the model might not have the power to change the type of modelling practice into an engaging with the model content instead. Thus, it is essential that the design engineer identifies who is the driving actor in the practices of modelling at any point in the design process, and potentially how to regain agency in the process to steer it in the right direction. The importance of this awareness has also been expressed by the interviewees, and summarised in the description of the risks associated with model-use in Section 6.2.3.

For this purpose, a strategic engagement in practices of modelling that makes use of the potentials of translation processes and model mechanisms is needed. To help with this, Table 6.6 presents a 'method of modelling' formulated on two levels. For one, an abstract level that conceptualises modelling as the three ideal-typical types of translation processes and provides with an abstract, yet also simple, understanding of how modelling works. For another, an on-the-ground level that consists of the different practices of modelling that – through the incorporation of actual modelling practices – provides with a more grounded, yet also contingent notion of modelling. For both levels, the method of modelling provides with orientation with respect to the power distribution in the activity of modelling between design engineer and model.

The method of modelling can be applied from both sides. For one, the design engineer can find orientation in the on-the-ground level, by identifying which practices of modelling are in the forefront in a current design process. When practices of engaging with the model environment are predominant, the design engineer can try to engage in practices to exert agency over the environment, as described in the Table and in Section 6.3.1 in more detail. When practices of engaging with the model content are in the forefront, the design engineer can try to enhance the creative potentials of their actions by strategically engaging in more translation processes. Vice versa, when the design engineer wants to engage in a specific type of translation process to achieve a specific goal (design development or communication), the design engineer can find orientation in the abstract level of the method. Each of the three ideal-typical types of translations is differentiated into the actions that make up the translation process performed by either engineer or model, and the reactions on the respective other part. Furthermore, the abstract and simple translations can be related to potential on-the-ground activities and consequences. Hereby, the bottom part of the Table provides with ideas of what these activities and consequences could be.

Table 6.6. The method of modelling as interactions between design engineer and model. The respective actions of design engineer and model are described on two levels: first, as abstract basic elements of the method of modelling, consisting of the three ideal-typical translations and their respective effects; second, as on-the-ground practices performed in real project contexts.

	Design Engineer	**Model**
Abstract basic elements of the method of modelling	Ideal-typical translations (•) / Reactions or effects of these translations (→)	
	• Performs content-centred translation	→ Effect: change of source object or the relation to the source object
	→ Reaction: increased/different understanding with respect to the structural design	• Communication-centred translation
	• Performs environment-centred translation	→ Effect: change of the model's use or effects
On-the-ground practices performed in real project contexts	Engages in practices of modelling	Exerts agency in the practices of modelling
	• Engagement with the model environment, i.e., through practices to handle complex or big models, environment-centred translation, application of engineering knowlegde.	• Through the model environment: explicitly, i.e., through requiring computational power, predefining the structure or type of input, predefining or directing the workflow, error messages; impicitly, i.e., through seducing to certain actions, impeding overview, evoking emotions.
	→ Design engineer reacts to specific, distinct actions of the model environment.	→ Model environment influences design engineer.
	• Engagement with the model content, exemplified i.e., in setting goals, immediate actions, modelling and speaking, collaborative modelling with different roles.	• Through the model mechanisms, i.e., externalisation + capturing, visualisation + uncovering, simplification + abstraction, and their effects, i.e., support or assume imagination, facilitate understanding, allow or enable experimenting.
	→ Design engineer interacts with the model to further develop the design or communicate about it.	→ Model supports the design engineer in the design development or communication about the design through its mechanisms.

The inertia of design practice is well known. My claim is that we can achieve a better understanding of the possible, we can get past the metaphor, through the study of design in process. (Bucciarelli, 1988, p. 167)

7 Discussion

This chapter discusses the empirical findings and the methodological approach that was employed to generate them. To this end, the first section represents a contentual discussion of the findings and centres on the question what the creative potentials of modelling practices are and how they can be strategically employed in the context of structural design. The second section, then, discusses the findings from a conceptual perspective, by assessing what the contribution and benefit of a broad model understanding and of a method of modelling are for professional practice. The last section contains an analysis of the methodological approach employed in this dissertation. By reflecting on challenges and potentials, it is discussed what such an empirical social science approach can yield for research in structural design and how as well as in which areas of research this methodology could be further applied.

7.1 Strategies for Creativity: Making Use of Modelling Potentials

In this section, the empirical findings are discussed with respect to the question of how to make use of the creative potentials of modelling. Specifically, the aim is to describe strategies for creativity – that is ways of modelling or of using and interacting with models that facilitate the generation of new ideas, insights, and in general the content-related progress in structural design processes. Hereby, the empirical findings are compared and contrasted to previous research in the areas of structural design, creativity, and modelling. It is assessed how the developed concepts relate to and exceed previous theories and contribute to the knowledge on modelling as a creative practice.

Referring back to the definition introduced in Section 2.2, a creative product or outcome of a process is usually characterised by its originality, its appropriateness, and by a third property. This third property often describes the sudden emergence or different nature of the creative product or outcome (i.e., unobvious, adaptive, leap, change, unexpected, transformation, communication, comparison, or resourceful, see Howard et al., 2008). Furthermore, a creative product or outcome is usually generated in a creative process, consisting of the four steps preparation, incubation, illumination or insight, and verification or elaboration (see Chan, 2013; Santamarina & Akhoundi, 1991). Against this backdrop, the strategies for creativity presented in the following are all based on recurring practices that were identified in the descriptions of modelling, as well as in the actions of the observed engineers while modelling. It has to be emphasised that all these strategies apply to the early conceptual design stages of projects, during which ideas are quickly generated and evaluated to decide on the general direction of the structural design.

The first strategy that was identified is to *make use of precision and blur*. The empirical evidence presented in the previous chapter has confirmed that both very precise or specific *and* very vague or blurry models can provoke the engineer, designer, or modeller to react to the model. In the case of a very precise or specific model, this is usually triggered by the fact that the model is perceived as false with respect to certain aspects, or that due to its preciseness, it makes statements that were not intended. Thus, the modeller feels a certain urge to react to this false precision and subsequently to change it. This has to be evaluated as positive and highly productive with respect to the progress of a design: Only by making statements, these can then be judged, certain aspects can be evaluated, and a further development can take place. Similarly, a vague or blurry model can provoke reactions in the engineer, designer, or modeller, as they perceive an urge to specify it, to concretise the blur, and replace it with the 'things' that they imagine in it. Thus, these two opposing properties of models lead to similar reactions in the form of content-centred translations. This has been described in a similar way by Wendler in his article on the "uncertainty relation of models" (Wendler, 2015). On a superordinate level, similar transitions from precision to blur and vice versa can be observed in the alternating modes of the structural design process, namely the vague and fuzzy creation mode and the specific reviewing mode (see Section 6.1). The strategic use of these model effects can be employed to facilitate the generation of creativity in the design process, for instance, by intentionally specifying aspects to provoke reactions even though they are known not to be the right solution, or by deliberately blurring out shapes or connections to spur the imagination of alternatives. Hereby, an understanding of the model as mainly preliminary is fruitful, which is promoted, for instance, by Currie (2017) and Peschard (2011). Another way to describe this is provided by Mahr: The model is something, which already refers to another, new thing (Mahr, 2011). This makes apparent that the strategic use of precision and blur puts the activity of modelling in the foreground instead of the model object.

The second strategy is *consciously engaging with both model content and model environment*, in order to navigate the power relation between engineer and model. The need for a conscious engagement becomes evident in the empirical findings. These suggest that despite being omnipresent, the model or the activity of modelling are sometimes hard to grasp. For instance, the descriptions of the activity of modelling, understood in the broad sense that is promoted in this dissertation, and the structural design process are almost identical. This matter leads to the question of what actually sets them apart, meaning how the activity of modelling can be distinguished from designing in general to be better understood and controlled. This entanglement and close interrelation between modelling and the design process needs to be contrasted for one, with the statements of some interviewees insisting that the process is not determined by the models used within it. For another, it needs to be contrasted with statements of some interviewees who held that the choice or (false) use of specific models can have a negative impact on the design process. The reservations against the use of certain types of models – in general, within specific phases, or by people without experience – has also been thematised in the literature (see e.g., Krafczyk, 2014). Thus, on the one hand, there is an entanglement of modelling and the design process which makes it hard to differentiate between the two. On the other hand, there are different opinions on whether solely the engineer or also the model has a certain capacity to steer the process. Thus, there is a need to evaluate the power distributions between engineer and model during the activity of modelling.

It is suggested here that it is essential for the generation of creativity to navigate this power relation in favour of the modeller, and further, that this can be achieved by consciously engaging with both model content and model environment. The analysis of the empirical material suggests that there are several ways in which this conscious engagement can be achieved and in which the engineer can gain or maintain power and thus also control over the activity of modelling. This was the main motivation for the development of the method of modelling described in Section 6.4, which attempts to summarise and systematise some of these ways. The method of modelling can be referred to on both an abstract and a practical level and thus provides with an understanding of overarching principles as well as of how these manifest in real design processes.

With respect to previous research on creativity, particularly the active engagement in the activity of modelling is worth highlighting, which should be motivated by the method of modelling. This can be easily achieved through simple and immediate actions, as explained in Section 6.3.2 and referred to in the method of modelling. As explained in the synthesising Section 6.4, creativity usually is generated when one engages in actions that are content-related and the model supports the creative development of the design. By engaging in simple, seemingly banal actions, the activity of modelling can be practiced and the modeller can learn to 'play' with the models. One explanation for this could be that through the banal actions, the often felt need for 'truthful' representation is pushed to the background and the focus is instead on the model's function as an epistemic object, which can be used, for instance, to generate a better object. This has been also observed by Reutlinger et al. (2018) with respect to the pedagogical function of toy models (see Section 3.2.2). Furthermore, frequent translations pay off due to the practice gained with each translation. In this context, the speed and simplicity of the translation activities are relevant factors. As observed by Hines (2012), creativity needs iterations – and these iterations become easier the faster one engages in them and the more courage one puts into them. Simple or even seemingly banal actions satisfy both aspects, as they can be quickly and easily performed, and are thus likely to facilitate the generation of creativity.

Even though engaging in simple actions to act instead of react might seem banal at first glance, it helps to put the model content in the forefront instead of the model environment. In processes that are more and more relying on sophisticated software that guides the engineer through the modelling process, these actions are vital to gain or maintain control over the modelling process. In essence, thus, a strategy for creativity is to always be consciously aware of the model's as well as one's own agency, and to consciously engage in modelling activities, as the one who acts instead of reacts has the power and control over the design process.

Third, another strategy for creativity is to *make use of the benefits of collaboration* when modelling. The empirical findings underline the importance of this on several levels. First, in the description of the structural design process (see Section 6.1), several interviewees emphasised the creative potential of collaboration. Second, in Section 6.2.2, the communication about the design has been identified as one of two main goals of model-use and modelling. In this section, the model has been mainly described as a communication object which enables a (common) understanding of the design. However, with respect to creativity, the model's capacity to generate divergent interpretations, meanings, or associations in its recipients is of high importance and can facilitate taking on new perspectives, generating ideas, and in general developing further the design. The practices of "modelling and speaking" or "collaborative modelling with different roles" (see Section 6.3.2) showcase how collaboration was used (whether consciously or unconsciously) in everyday modelling practices in the early stages of structural design to generate multiple divergent understandings of the design, and thus a variety of alternatives that can be explored and further developed in the design process. Hereby, the specific benefit of collective over individual modelling is that the possibilities and capacities of interpretations, associations, opinions, and ideas are multiplied. Thus, the third strategy for creativity in modelling activities can be formulated as to purposefully engage in collaborative work using the model as a multiplier for opinions, understandings, meanings, and ideas, instead of treating it as a single source of truth.

The three strategies have in common that they can all be described as practical model operations. Hereby, each of these strategies can be brought down to one guiding principle for the generation of creativity: first, to focus on modelling as an epistemic activity instead of on the model object; second to focus on the model content rather than on the model environment; and third, to focus on the multiplication of meanings, interpretations, associations, and opinions rather than to compromise on a 'single truth'. These guiding principles can be regarded as approximations to the above raised question which properties or aspects characterise models as creative agents and the activity of modelling as a method with creative potential.

With respect to the activity of modelling and the different actors involved in it, the three strategies can be situated on three levels:

- Making use of precision and blur can be described as an ideal-typical, close-up view of the activity of modelling that blanks out its context and focuses solely on the interaction between the engineer and the model.
- Consciously engaging with both model content and model environment expands this view, as it accounts for the fact that not only the model content is interacted with but also the model environment in which the model in contained.
- Making use of the benefits of collaboration portrays the activity of modelling in a more realistic fashion in a project context that encompasses also possible interaction with others in a collaborative modelling process.

Thus, the three strategies are enacted on different levels with respect to the activity of modelling, from a close-up view of an interaction between model and engineer, to a mid-level in which one person individually handles model content and environment, to a more holistic perspective on the messy and contextual practice of modelling in actual design processes.

Yet, even though operating on different levels, the three strategies are not separate from each other but instead closely related.

⟶ For instance, a vague or blurry model created by one person might be perceived and interpreted by another in a collaborative modelling situation. In this situation, the modeller would make use of both the model's blurryness and the benefits of collaboration. Furthermore, power relations are relevant in this situation, however, not between the designer and the model but between the two designers, as the interpreter of the model is attributed with power to guide the design process (see Section 6.3.2).

⟶ Another relation can be established between the topic of precision and blur and the conscious engagement with the model environment. Here, for instance, the model environment could predefine the nature of the model by only allowing for exact inputs. Conversely, the model environment could also enable an open modelling process without such restrictions. Again, in these two cases, either due to a diminished or increased scope of action of the engineer, the power distribution between model and engineer is different.

⟶ A further connection between the precision and blur and the conscious engagement is that precise models can lead the engineer to forget that they are operating in a model environment and not dealing with the real conditions, one of the risks associated with model-use (see Section 6.2.3). Thus, consciously engaging in deliberate actions is not only important when dealing with model environments, but also when dealing with the model content.

⟶ Furthermore, acting consciously and deliberately is important on the collaborative level, to not let the multiplicity of meanings, interpretations, and associations overwhelm or distract from the actual goals of creative modelling, namely the design development.

These relations only represent an illustration of possible connections between these three levels and strategies. This underlines that while the strategies can be employed individually, in practice it is more likely that they are used in combination. In this line, a conscious combinations or a deliberate shift between these three strategies or the levels they operate on can be seen as a forth strategy for creativity in the design process.

This further underlines the highly practical nature of creative modelling in the early design stages: It is not an abstract, highly complex endeavour but one that simply requires action. The strategies can be strongly related to the translations that were identified in Section 6.2.2 as the basic model operations: The strategic use of precision and blur makes use of content-centred translations, the conscious engagement makes use of both content-centred and environment-centred translations, and the strategic use of collaborations makes use of all three types of translations. The forth strategy of combining and changing strategies can be conceptualised as a translation between different levels of modelling work. The four strategies, their interaction levels, and their use of translations are summarised in Table 7.1.

Table 7.1. The four strategies for creativity, the levels of interaction they are enacted on, and the translation types that they make use of.

Strategy		Interaction Level	Translation Types
1.	Use of precision and blur	Engineer and model content	Content-centred translation
2.	Consciously engaging with model content and environment	Engineer and complete model (including model environment)	Content-centred and environment-centred translation
3.	Use of collaboration	Multiple engineers and complete model (including environment)	All three types
4.	Deliberately changing between strategies, interaction levels, or translation types		

To conclude, translations can be regarded as the drivers of creativity in design processes, which further highlights the method of modelling as a distinctively practical activity. More specifically, only through actively changing the content, the environment, the recipients of the model, or the level of work, the effects and impacts already contained in the model are made visible and something new can be created on that base, which is essential for creativity. Thus, in the context of structural design, the activity of modelling as a method consisting of the above described strategies can facilitate the "creative leap" or "insight" necessary for the generation of creativity. Furthermore, employing these strategies in a deliberate, methodological way and thus translating the model content or environment, the people who perceive it, or the level one is working on can also diminish the risks associated with models and modelling. These risks include, for instance, the model affecting or directing the way engineers think, the model being confused with reality or used in a wrong way, or the engineer becoming dependent on a specific model environment, as described in more detail in Section 6.2.3.

In general, by focusing on the activity of modelling as a practical method with creative potential, the findings discussed in this section move beyond the aspects of materiality, representation, or validity of models that previous literature mostly dealt with, and instead focus on how to make strategic use of what Wendler has described as the "active potential" of models (Wendler, 2013).

7.2 The Practical within the Conceptual

In this section, the aim is to discuss the conceptual contribution of this dissertation and to assess its implications for research and practice. Considering the notion of modelling as a primarily practical activity that was established in the previous section, the guiding question hereby is what a theoretical description of modelling – as developed in this dissertation – can yield and which different perspectives and insights it enables. With respect to the goals that were formulated and contained in the research questions (see Section 4.2), specifically three questions can be asked:

1. What is the added value of a broad model understanding, as presented in Section 6.2.4?
2. What is the added value of describing embodied practices of modelling and analysing seemingly trivial processes, as carried out in Section 6.3?
3. What is the added value of conceptualising the activity of modelling as a method (see Section 6.4)?

Furthermore, with respect to the interdisciplinary literature review that was conducted, a forth question can be formulated as follows:

4. What is the added value of reviewing literature from the field of philosophy of science and technology for research in the context of structural design and how does it inform engineering practice?

With respect to the first question, the analysis of the model terms (Section 6.2.1) and of the model valuations (Section 6.2.3) has shown that multiple different objects or artefacts are referred to as models by the interviewees and further, that they evaluate these with respect to different properties and effects. The broad model definition presented in Section 6.2.4, then, assumes that all those model understandings and evaluations are valid. This broad understanding is similar to the model of model-being proposed by Mahr (2011), but adjusted and adapted to the context of structural design, particularly through the three specifications of the definition. But what does such an understanding imply for the interaction with models in the structural design process?

The broad model understanding is productive as it allows to make use of the positive mechanisms of models more extensively by allowing to see a model in a variety of objects that are used in the design process. This judging a specific artefact to be a model based on just the willingness to see it as a model of and for something needs to be distinguished from judging a specific artefact as a model due to the fact that it has certain properties. In the latter case, it is assumed that an object needs to possess specific attributes, for instance, abstraction or simplification, in order to serve as a model. In the former case, however, simply due to the fact that one is willing to see a model in a specific object, one can then ask what this object is a model of and for, and in which properties, conditions, and characteristics this specific model-being constitutes itself. Thus, the ascription has the effect that the object inherently possesses the mechanisms and their effects and impacts that are usually associated with models. In other words, the model mechanisms do not have to be worked into the objects, as they are inherent to them due to this ascription. This change of perspective can facilitate creative and productive developments of designs. This matter has been analysed in a similar way by Wendler in his account of model terms as active parts of modelling (Wendler, 2016). In essence, a broad model understanding leads to the benefit that the positive model mechanisms, effects, and impacts can be profited from in a broader range of objects than would be the case in a more narrow definition (for instance, of models as three-dimensional representations).

Second, the analysis of embodied modelling practices and interaction processes between the model and the engineer had a clear focus on “on-the-ground” processes and actions. The precise and direct descriptions of actual steps that were performed by the observed engineers allowed to identify modes of working within the activity of modelling. This focus on the *how* of modelling, rather than on typical procedures, fills a gap that has been identified by previous researchers. For instance, Gericke and Blessing (2011) have stated that the focus on procedures rather than on how these are enacted is perceived by designers as too abstract to guide actual design processes. In this respect, conceptualising modelling with a focus on the activity as a creative practice instead of on the outcome or the aspect of representation leads to a shift of perspective and allows for a better and more grounded understanding of actual working processes in engineering offices. This could, for instance, inform further research on the development of tools or interfaces that support modelling or design processes in general. With respect to design practice, the description of relatable everyday actions and their connection to creativity can spur an understanding of how these can be transferred to the own working context. The dissertation’s findings can thus particularly provide guidance to students or inexperienced structural designers on how actual design processes happen on-the-ground. For instance, the on-the-ground descriptions of the structural design process and its modes and strategies illustrate some of the multiple ways in which design processes can take place. Additionally, they spur trust in the process by providing with examples that inspire the reader to find their own way of designing (see also Hines, 2012).

Third, the dissertation provides with a conceptualisation of the practices of modelling as a method. The method of modelling, as described in Section 6.4, summarises the specific depictions of the identified modelling practices on two levels: first, on a conceptual level of translations; second, on a practical level of on-the-ground practices. This yields the benefit that the method can be related to on two different levels of abstraction. In other words, it can be understood from both a practice-oriented perspective and a research-oriented perspective, and further facilitates the translation into the respective other perspective. With respect to the contribution to structural design practice, understanding modelling as a method depicts the activity as something which can and needs to be consciously performed and thus also as something which can be steered rather than just carried out. In this line, the understanding of modelling as a method consisting of diverse strategies (see Section 7.1) promotes the use of these strategies and can put the modeller in a position of power and control over the modelling process. A more active engagement in the modelling process is thus facilitated, which yields the opportunity to make better use of the creative potentials of modelling.

Forth, the bridging of two disciplinary fields, structural engineering and philosophy of science and technology, in the interdisciplinary literature review can be understood as a further conceptual contribution of this dissertation. By connecting two before mostly separate bodies of knowledge, a balanced account of model-use and modelling was created, which is informed by these two disciplines, yet at the same time also to some extent independent from each of them. Hereby, the more conceptually and theoretically shaped perspective of the philosophy of science and technology and the more empirically influenced perspective from engineering allowed to develop both conceptual and theoretical as well as empirically grounded concepts on models and the activity of modelling within the design process. With respect to engineering practice, the added value can be described as a deeper, critical, and more general understanding of the subject. Additionally, this balanced account ensures that the findings can be understood by as well as inform both disciplines, and thus be critically received by a broader audience.

The research results on a conceptual level and their potential implications for engineering practice are summarised in Table 7.2.

Table 7.2. The conceptual research results and their potential implications for engineering practice.

Conceptual Research Results	Potential Implications for Engineering Practice
Broad model-understanding	The positive model mechanisms, effects, and impacts can be profited from in a broader range of objects.
Description of everyday embodied practices of modelling	Improved and grounded understanding of actual working processes in engineering offices; understanding of how these can be transferred to the own working context.
Method of modelling	Promotes modelling as an activity that can and needs to be steered; puts engineer in a position of power and control over the modelling process; facilitates a more active engagement in the modelling process and the use of creative modelling potentials.
Literature review including philosophical perspectives	Deeper, critical, more abstract and general understanding of models and the potentials of modelling.

To conclude, in comparison with previous research on design processes, model-use or modelling, the conceptual contribution of this dissertation clearly lies in the type of perspective that it provides. This perspective combines rich, detailed, and in-depth descriptions that serve as examples with abstract conceptualisations that introduce a generalising lens. This balanced account of the researched processes of structural design and modelling thus facilitates an understanding on multiple levels.

7.3 Qualitative Methods for Research in Structural Design – Challenges and Potentials

In this section, the process as well as the results of this dissertation are discussed from a methodological perspective. This is motivated by the fact that the chosen research approach – to use qualitative methods from the empirical social sciences – is rather unusual for research in the field of structural design, or more generally in the field of civil and structural engineering. In this area, research often deals with questions of a quantitative nature by applying methods that are established in the disciplinary field, such as analytical, experimental, numerical, or statistical methods.

In contrast, this dissertation makes systematic use of empirical social science methods to assess the working methods of structural design engineers. In the following, the employment of these empirical social science methods in the field of structural design research is analysed with respect to five aspects: first, the use of a method new to the field; second, the appropriation of the method from another disciplinary context by the researcher; third, the data conduction; forth, the data analysis; and fifth, the status of the results acquired with these methods. The aims hereby are to discuss the nature, validity, and implications of the findings, to provide with suggestions for which types of questions this research methodology could be beneficially employed in the context of structural design or engineering more generally, and to guide and inform such future investigations. The section is largely based on an essay that was written in collaboration with two other researchers from the field of structural engineering, who also employed qualitative empirical methods in their dissertations (Ruge, Ewert, & Frommelt, 2023).

First, systematically employing empirical social science methods was new to the research field of structural design. Thus, there were little to none documented examples of the employment of such methods in this field. One of the encountered difficulties was that other researchers but also the interviewed or observed practitioners in the field did not know about the background, aim, or potential of these methods. Thus, the researcher often encountered reservations or scepticism with respect to the methodology but also the findings generated with them. This included, for instance, beliefs that the methods were not structured, or that the obtained findings would be subjective or of little scientific relevance. The frequent and recurring explaining of the methods, their background, aims, and potentials required significant efforts from the researcher.

However, the fact that these methods had not been systematically employed in the field yielded the potential to gain insights that were not only new content-wise but also of significantly different nature compared to previous research on the structural design process. This has been elaborated in more detail in the previous two sections of the discussion. Furthermore, not least due to the often criticised fact that qualitative methods are usually loosely structured with respect to generation and analysis of data, the qualitative methods had the capacity to adapt to the research objects – the structural design process and the model-use and modelling within – and to properly reflect their qualitative and subjective properties (Holden & Lynch, 2004).

Second, the necessity to appropriate the methods from another disciplinary field into the context of structural design represented a challenge in itself, as the familiarisation with the methods required high efforts. For one, each method is based on a multitude of assumptions and paradigms (Holden & Lynch, 2004; Reichertz, 2016), which impact the nature, scope, and meaning of the results that can be generated with them. Therefore, the researcher needed to acquire an in-depth understanding of qualitative methods by dealing intensely with multiple publications on the subject. Additionally, applying a method is not a theoretical endeavour but a highly practical one and thus requires practice and experience. This was acquired in the context of an interdisciplinary research project, in which the author – together with other researchers who had more experience with these methods – conducted and analysed more than four dozen qualitative interviews before applying this methodology to her own research endeavour (see the description of the research process in Section 5.2.1).

However, the appropriation of the methods from another disciplinary context not only required efforts but was also highly inspiring and broadened the researcher's horizon with respect to methods in general. First, learning a new method changed the perspective also on the methods from engineering contexts the researcher had acquired during her studies. For instance, the way subjectivity is described and dealt with in qualitative methods made apparent that research using methods from the engineering context that is often referred to as objective also has distinct subjective elements. These subjective elements include the interpretation of the obtained data or more generally the question what is researched at all. Second, the combination of knowlegde on empirical social science methods with contentual knowledge from the engineering studies proved invaluable for the research endeavour. For one, it facilitated the access to interviewees and the observation. For another, there is a distinct benefit when engineers themselves employ methods such as interviews or observation for research about their own field, as it is easier for them to understand the interview statements or observed actions. What is more, interviewees or observed people will often only communicate aspects that in their opinion will be understood by the researcher (Polanyi, 1958).

Third, another challenge of employing interviews or observation as research methods was that the data generation process could not be planned in its entirety. In general, data generation with qualitative methods takes place in a social situation in which researcher and interviewed or observed people interact. The process of data generation as well as the data themselves are thus influenced by two sides: for one, by the interviewed or observed people, their reactions to the researcher, the research question, and the interview or observation situation, and for another, by the researcher, as they become the instrument for data generation themselves. To navigate the data generation process requires thus an awareness of the influences on this social situation. For instance, an interviewee's evaluation of the researcher's capabilities to understand the content of what they are talking about may be influenced by factors such as age, gender, educational background, appearance, use of language, among others (Bogner et al., 2014). Furthermore, the navigation of such a situation requires knowledge on how to steer it in a direction that would be beneficial to the research aim. Last but not least, practice and experience on the side of the researcher are invaluable in these situations, in order to remain in control, to identify if and in which direction a situation needs steering, and to implement respective activities whenever needed.

Beyond these challenges, there are also some potentials that this specific mode of data generation offers. First of all, as opposed to during quantitative surveys, the researcher can make sure that the interviewed or observed people understand the aim of the research and of the interview or observation. In this line, also the attitude as well as the valuations of the interviewed or observed people with respect to the research can be assessed and later incorporated into the interpretation of the obtained data. In the situation itself, the exact questions of the interview or the behaviour of the researcher can be adjusted accordingly. Furthermore, another benefit is that previous, preliminary results can be presented to the interviewees and their valuations and perspectives can be used to further inform the findings. As such, the data generation process can establish a link between research and practice. For instance, the interaction with the interviewed or observed people can spur critical reflection of the results, which can subsequently lead to results that are more appropriate and grounded. Furthermore, such interaction processes potentially lead to valuable hints towards new and practice-related areas of research. Vice versa, this type of research methodology has the potential to start a process of reflection in the interviewed or observed people, for instance, on the implications of the research for practice. Additionally, it could encourage interviewees or observed people to reflect on their everyday practices.

Forth, also with respect to the data analysis, several challenges and potentials were encountered during the research process. For instance, when researching with qualitative interviews and participatory observation, the actual raw data is usually generated through transcribing audio-recordings or writing field notes and diary entries right after the interview or field stay. Afterwards, the data is available in the form of large and heterogeneous amount of text. Due to the heterogeneity of the data and the qualitative nature of the research questions, an automated or partly automated analysis usually is not possible. Instead, the process of data analysis requires multiple readings and re-readings of the whole data, with different foci and perspectives in order to assess the content of it, which is immensely time-consuming. Another challenge is that these texts as such cannot be directly taken as 'true statements' about the researched objects, but have to be continously interpreted and questioned during the analysis, with respect to the situation in which they were generated, with respect to who was interviewed or observed, and with respect to the research question.

While being time-consuming and challenging, the intensive process of data analysis also leads to a deep familiarisation with the data. This deep familiarisation enables a specific understanding of the described or observed phenomena, processes, or actions. Furthermore, it constitutes the base for assessing single instances of data as 'cases' as well as for the generation of new hypotheses, concepts, or theories. Through this necessarily intensive and in-depth engagement, the researcher is able to judge the data holistically and thus to preserve the control over it. Based on such a holistic understanding of the data, statements or results influenced by special situations during the data generation process, which might lead to unreliable results, can be interpreted accordingly or excluded from data analysis.

The last aspect that is discussed with respect to the employed methods is the status of the results generated with them. As already described above, qualitative methods are often met with the reservation to produce subjective results or at best descriptions of single cases from which cannot be generalised (for a summary of frequent reservations against qualitative research, see Flyvbjerg, 2006). The question of whether or to what extent the results yield a scientific value accompanied the whole research process and was expressed by fellow researchers, journal editors, conference organisers, and interviewees alike.

However, as already explained in the methodological preface (Chapter 5), qualitative methods such as interviews and participatory observation indeed can be of significant scientific value. If the data generated with them is analysed and interpreted appropriately, qualitative methods can yield an in-depth, differentiated, and holistic understanding of the researched objects. Even though the generated findings usually represent single cases, these can in fact have meaning beyond their own scope. For instance, in an interview one engineer described how they try to solve problems during design processes by reflecting on them in the bathtub. While this does not mean that everyone should take a bath when trying to solve problems, it contains elements that are indeed transferable to other cases, such as that the combination of pressure and freedom is a fruitful environment for creativity. In this line, through assessing the researched objects holistically, recognising distinct aspects but also interrelations between them and in their context, qualitative methods can deliver good examples through which abstract theories and concepts of the researched phenomena can become tangible and relatable. Furthermore, through such methods, different implicit types of knowledge such as process knowledge, context knowledge, or interpretative knowledge (Bogner et al., 2014; Meuser & Nagel, 2009) can be made explicit and thus available for further scientific reflection. For instance, through qualitative methods it is possible to capture practical knowledge, which is important especially in a discipline such as structural design, as well as subjective qualities of the researched objects such as individual approaches to structural design. As a result, qualitative methods are highly suitable to explore previously under-researched areas and formulate hypotheses.

To conclude, the methods from the empirical social sciences employed in this dissertation were regarded as fit to appropriately represent the qualitative nature of the researched objects, namely the structural design process and the model-use and modelling within. What is more, by applying a methdodological approach new to the field, this research approach delivered new findings, both in content and nature. Hereby, the combination of qualitative interviews and participatory observation as data generation methods provided distinct advantages. First, qualitative interviews made it possible to incorporate the perspective and the judgements of the design engineer on how this process is enacted by them. The interviews further enabled not only to gather rich descriptions, but also to abstract and generalise different approaches to structural design and modelling. As both the structural design process and modelling are highly subjective endeavours that can be approached from very different angles, this was of high importance. Second, the field notes and diary entries from the observation provided insights into how modelling processes happen on-the-ground. They further enabled to analyse the underlying mechanisms of modelling practices, leading to a more detailed knowledge about the methods of structural design as it is enacted. Additonally, the data generated with the qualitative methods enabled to confirm several aspects from previous research on structural design, modelling, and creativity, which further testifies to the scientific benefits of this methodology. All in all, the qualitative interviews and participatory observation delivered scientifically reliable data, which provided insights into tacit knowledge and practices characterising the interaction between engineer and model. This enabled a more detailed critical understanding of how models are used by structural engineers and how the activity of modelling can spur creativity.

Against this backdrop, the author holds that beyond the application in this dissertation, qualitative methods such as interviews or participatory observation could benefit a variety of research endeavours in the field of structural engineering. First, similar to the use in this dissertation, this type of methodology could be applied for research questions *about* structural design, meaning for questions that aim at a meta discussion of practices, processes, methods, tools, among others. One example for this would be a grounded elaboration of the status quo concerning the application of BIM in engineering offices that could point to challenges and potentials, and thus inform further research on BIM. However, also a use directly *in* the field of structural engineering could be fruitful, for instance, to assess general relations between multiple areas in the field or for the systematic elaboration of fundamental knowledge or methods. Furthermore, as described above, the methods can be used to explore new fields of research or to specify areas in which further research is required. Another field of use could be the generation of new educational material for structural engineers, as implicit and practical knowledge, which plays a huge role in both research and practice, could be made explicit through these methods and thus processed to be taught.

The good thing [about this research] is that practical or planning engineers, who are perhaps also very pragmatic in terms of their education, also devote themselves to this topic at least once, and then give a different perspective on this problem, an impulse. (Int-models-19)

8 Concluding Remarks

This research was motivated by the hypothesis that to assume their responsibility towards society, structural engineers need to understand their own work as a creative task that engenders possibilities to design and shape *and* they need to understand how creativity can be generated in design processes. The first aspect is important as this represents a prerequisite for structural engineers to become aware of their own scope of action. The second aspect is important, as current challenges as well as the adaptation to future conditions force structural engineers to be more creative and change their work processes. In this line, this dissertation aimed to generate a better understanding of structural design as a creative process, by scrutinising model-use and the activity of modelling as methods for creativity within this process.

Building on an interdisciplinary literature review (see Chapters 2 and 3), the main research gaps were identified as a general lack of knowledge on methods of structural design, and a specific lack of knowledge on model-use and modelling in the structural design process. The main research question was formulated as *What are the creative potentials of model-use and modelling in structural design, and how can they be comprehended conceptually in a method of modelling?* (see Chapter 4).

To answer this research question, qualitative methods from the empirical social sciences, specifically qualitative interviews, participatory observation, and qualitative data analysis methods, were employed (see Chapter 5). Through this research design, a number of insights with respect to the structural design process, the effects and impacts of model-use and modelling within it, and the interaction between design engineer and model could be generated.

Specifically, main findings include a qualitative scheme of the structural design process, which highlights the alternating working modes of creation and reviewing in the structural design process, as well as a description of different strategies employed in both of these working modes to progress the development of the structural design. Furthermore, central mechanisms inherent to models have been identified, as well as the effects and impacts they have on design development and communication, the main goals in the structural design process. These mechanisms help to explain why models are such powerful agents in the structural design process. With respect to the how of modelling, three ideal-typical translation processes have been described: content-centred, communication-centred, and environment-centred translations. The empirical data has showcased how these translations are employed in everyday project contexts as the basic elements of the activity of modelling. Furthermore, the diverse evaluations of specific models and of model-use in general made explicit the risks associated with model-use and the activity of modelling, as well as how these impact creative model-use. With respect to the interaction between design engineer and model, two different practices of modelling could be identified, which exert a different quality of interaction. Furthermore, the highly practical nature of the activity of modelling has been described. As a synthesising result of the above-mentioned findings, a method of modelling has been developed, which aims to provide orientation for structural design engineers engaged in modelling processes.

The contributions of these results have been discussed in the previous chapter, from a contentual, conceptual, and methodological stance. The main contentual contribution of this dissertation is the identification of different strategies for creativity in the structural design process that manifest on different levels of interaction with the model. The main conceptual contribution is that implicit knowledge on the structural design process as well as on model-use and modelling as methods for creativity within this process was made explicit and thus available for further reflection or application. Methodologically, the dissertation contributes by providing with an in-depth and detailed example case of how qualitative methods from the empirical social sciences can be applied in the structural engineering context to generate new findings.

Beyond the presented scientific contributions, the dissertation also has practical relevance. For instance, the findings can be related to the topic of structural engineering education. The empirical findings emphasised the diverse model evaluations that greatly influence the model understanding of structural engineers and the way they interact with models. The findings also suggested that these evaluations are mostly acquired during education and early professional practice. This implies that university education can lay the foundation for creative model-use or modelling. Currently, however, creative thinking is rarely encouraged in the education of engineers, a gap both identified in the literature (Addis, 1997; Langer & Böhrnsen, 2014; Ochsendorf, 2016) and by the practising engineers who were interviewed for this dissertation. One way to change this would be to include design in the curriculum of structural engineers (see also Eibl et al., 2006; Hines, 2012), and teaching model-use and modelling as basic methods of design processes. To be able to transmit the practical nature of model-use and modelling, this should be done in the form of projects that allow enough space for individual experimenting. Hereby, a previously established basic understanding of the model mechanisms, their effects and impacts, as well as of the different types of translations could facilitate students to perceive and experience the creative potentials of modelling and to make strategic use of them.

In addition to informing engineering education, a conceptual understanding of models, model-use, and the activity of modelling that goes beyond the view of models as tools can have further effects and impacts on structural design practice. First, it can help to use and interact with models in a way that profits from their creative potentials as opposed to employing them unconsciously. Second, it can lead to the development of tools that respond appropriately to the working practices of engineers in structural design (cf. Ammon & Froschauer, 2013). Third, the findings also have practical relevance with respect to the collaboration with architects or other specialist planners in design processes. In this context, a reflection of one's own methods could promote that personal needs with respect to creative processes can be communicated better. This could result in an increased intersubjective creativity, overall leading to better results in interdisciplinary collaborations.

However, the presented research also yields some limitations. First, with respect to the scope of the empirical data, a longer observation period and an observation focusing on more than one project or taking place in different engineering offices would have increased both robustness and validity of the findings. Furthermore, comparison with similar research conducted in the field of architectural design, or an analysis of the empirical findings through the lens of Actor-Network Theory (e.g., Latour, 2005) could have benefitted the contextualisation as well as the theoretical grounding of the findings.

At the same time, these limitations point to future research trajectories. For instance, further participatory observations focusing on the activity of modelling in structural design yet with a longer duration, a broader base of projects, and in different engineering offices could help to further validate the findings. The analysis of the empirical data of this observation with the lens of Actor-Network Theory could induce additional interpretations of the data and lead to further insights. Another research trajectory could be to 'test' and validate the developed method of modelling or the strategies for creativity using an action-research approach, for instance, in design competitions or projects for university students.

To conclude, the overall aim of this dissertation was to shed light on the creative nature of structural design and provide an understanding of how creativity can be generated in the structural design process through the methods of model-use and modelling. In this respect, the author holds that making explicit and transparent the approaches and strategies used in structural design processes, that is the *how* of these processes, can lead to reflections on the multiple reasons for and the effects and impacts of their employment. This reflection is necessary to revise and change established working practices. To this end, this dissertation has provided with examples and ideas as to how such a change could manifest in more conscious and creative modelling practices. The current challenges the structural engineering profession is dealing with combined with the high responsibility of structural engineers towards society, as outlined in the introduction, render this reflection and revision of established procedures, practices, and modes of action today more relevant than ever. In this line, it is hoped that this dissertation can contribute to place a spotlight on the creative nature of the structural engineer's work, as well as to a change in the self-perception of structural engineers, which is necessary to assume their responsibility towards society: a change in self-perception from mere technicians to creative designers.

References

Addis, B. (1988). Models in engineering science and structural engineering design. *IABSE Congress Report*, *13*, 769–774.

Addis, B. (1990). *Structural engineering: The nature of theory and design.* Ellis Horwood.

Addis, B. (1994). *The art of the structural engineer.* Artemis.

Addis, B. (1997). Free will and determinism in the conception of structures – a discussion of the art of the structural engineer. *Journal of the International Association for Shell and Spatial Structures*, *38*(2), 83–89.

Addis, B. (2013). 'Toys that save millions' – a history of using physical models in structural design. *Structural Engineer*, *91*(4), 12–27.

Addis, B. (Ed.). (2021). *Physical models. Their historical and current use in civil and building engineering design.* Ernst & Sohn.

Akin, Ö. (1994). Creativity in design. *Performance Improvement Quarterly*, *7*(3), 9–21.

Aksamija, A. (2016). *Integrating innovation in architecture.* Wiley.

Ammon, S. (2019). Drawing inferences: Thinking with 6B (and sketching paper). *Philosophy & Technology*, *32*, 591–612. https://doi.org/10.1007/s13347-018-0323-5

Ammon, S., & Froschauer, E. M. (2013). Zur Einleitung: Wissenschaft Entwerfen. Perspektiven einer reflexiven Entwurfsforschung. In S. Ammon & E. M. Froschauer (Eds.), *Wissenschaft Entwerfen. Vom forschenden Entwerfen zur Entwurfsforschung der Architektur.* Wilhelm Fink.

Ammon, S., & Hinterwaldner, I. (Eds.). (2017). *Bildlichkeit im Zeitalter der Modellierung. Operative Artefakte in Entwurfsprozessen der Architektur und des Ingenieurwesens.* Wilhelm Fink.

Andia, A., & Spiegelhalter, T. (Eds.). (2015). *Post-parametric automation in design and construction.* Artech House.

Baker-Brown, D. (2017). *The re-use atlas. A designer's guide towards a circular economy.* RIBA Publishing.

Barthel, R. (2005). Naturform – Architekturform. In W. Nerdinger (Ed.), *Frei Otto. Das Gesamtwerk. Leicht bauen – natürlich gestalten.* Birkhäuser.

Bergis, L., De Rycke, K., Orlinski, A., Paschke, M., Regnault, L., Tam, M., & Vierlinger, R. (2018). *Informed geometry: Development of informatically driven design processes for tensile structures.* [Conference contribution]. Proceedings of the Innochain

Conference – Expanding Information Modelling for a new Material Age, Copenhagen, Denmark.

Billington, D. P. (2014). *Der Turm und die Brücke – Die neue Kunst des Ingenieurbaus.* Ernst & Sohn.

Bischof, A., & Wohlrab-Sahr, M. (2018). Theoriegeleitetes Kodieren, kein Containern von Inhalten! In C. Pentzold, A. Bischof, & N. Heise (Eds.), *Praxis Grounded Theory. Theoriegenerierendes empirisches Forschen in medienbezogenen Lebenswelten. Ein Lehr- und Arbeitsbuch.* Springer VS. https://doi.org/10.1007/978-3-658-15999-3

Bögle, A., Cachola Schmal, P., & Flagge, I. (Eds.). (2005). *Leicht Weit - light structures: Jörg Schlaich & Rudolf Bergermann.* Prestel.

Bogner, A., Littig, B., & Menz, W. (2014). *Interviews mit Experten.* Springer VS. https://doi.org/10.1007/978-3-531-19416-5

Boulanger, S., Gelle, E., & Smith, I. (1995). Taking advantage of design process models. *IABSE Congress Report*, *72*, 87–96.

Bredekamp, H. (2005). Modelle der Kunst und der Evolution. In S. Ginnow (Ed.), *Modelle des Denkens. Streitgespräch in der Wissenschaftlichen Sitzung der Versammlung der Berlin-Brandenburgischen Akademie der Wissenschaften am 12. Dezember 2003* (pp. 13–20).

Brensing, C. (2005). Frei Otto und Ove Arup. Szenen einer gegenseitigen Inspiration. In W. Nerdinger (Ed.), *Frei Otto. Das Gesamtwerk. Leicht bauen – natürlich gestalten.* Birkhäuser.

Bucciarelli, L. L. (1988). An ethnographic perspective on engineering design. *Design Studies*, *9*(3), 159–168.

Bucciarelli, L. L. (2002). Between thought and object in engineering design. *Design Studies*, *23*, 219–231.

Bulleit, W., Schmidt, J., Alvi, I., Nelson, E., & Rodriguez-Nikl, T. (2015). Philosophy of engineering: What it is and why it matters. *Journal of Professional Issues in Engineering Education and Practice*, *141*(3), Corpus ID: 55353046. https://doi.org/10.1061/(ASCE)EI.1943-5541.0000205

Burkhardt, B. (1995). Architekten und Ingenieure. *Bauwelt*, *31.*

Cachola Schmal, P. (Ed.). (2001). *Digital | real: Blobmeister. Erste gebaute Projekte.* Birkhäuser.

Cachola Schmal, P. (Ed.). (2004). *Workflow: Struktur – Architektur, Architecture – Engineering: Klaus Bollinger + Manfred Grohmann.* Birkhäuser.

Chan, J. (2013). Researching creativity and creativity research. In K. Thomas & J. Chan (Eds.), *Handbook of research on creativity* (pp. 21–32). Edward Elgar. https://doi.org/10.4337/9780857939814.00011

Christiaans, H. (1992). *Creativity in design: The role of domain knowledge in designing.* [Dissertation, Delft University of Technology].

Colli, G., & Montinari, M. (Eds.). (1986). *Friedrich Nietzsche, sämtliche Briefe. Kritische Studienausgabe in 8 Bänden, Band 6.* dtv; De Gruyter.

Coyne, R. (2004). Wicked problems revisited. *Design Studies*, *26*(1), 5–17. https://doi.org/10.1016/j.destud.2004.06.005

Cross, N. (1997). Descriptive models of creative design: Application to an example. *Design Studies*, *18*(4), 427–440. https://doi.org/10.1016/S0142-694X(97)00010-0

Cross, N. (2006). *Designerly ways of knowing.* Springer.

Cuff, D. (1991). *Architecture: The story of practice.* MIT Press.

Currie, A. (2017). From models-as-fictions to models-as-tools. *Ergo*, *4*(27), 759–781. https://doi.org/10.3998/ergo.12405314.0004.027

da Costa, N., & French, S. (1998). Models, theories, and structures: Thirty years on. *Philosophy of Science*, *67*(3), 116–127. https://doi.org/10.1086/392813

Del Re, G. (2000). Models and analogies in science. *International Journal for Philosophy of Chemistry*, *6*(1), 5–15.

Deutsch, R. (2017). *Convergence: The redesign of design.* Wiley.

Dickson, M. (2005). Frei Otto und Ted Happold. 1967-1996 und darüber hinaus. In W. Nerdinger (Ed.), *Frei Otto. Das Gesamtwerk. Leicht bauen – natürlich gestalten.* Birkhäuser.

Dimitrova, V., Grubbauer, M., Ruge, J., & Bögle, A. (2021). Large-scale projects as arenas for interaction: Negotiating professional cultures of architects and engineers. In J. Thiel, V. Dimitrova, & J. Ruge (Eds.), *Construction innovation: How large-scale projects drive novelty in the construction industry* (pp. 176–193). jovis.

Dorst, K., & Cross, N. (2001). Creativity in the design process: Co-evolution of problem-solution. *Design Studies*, *22*(5), 425–437. https://doi.org/10.1016/S0142-694X(01)00009-6

Duddeck, H. (2001). Modelle der Technik – Wie Ingenieure die Realwelt in Entwurfsmodelle umsetzen. *Akademie-Journal*, *1*, 2–6.

Duddeck, H. (2002). *Jenseits und diesseits von Technik: Texte und Reden aus 40 Jahren; 1962–2002.* Institut für Statik Technische Universität Braunschweig.

Eibl, J., Pauser, A., Schambeck, H., Schlaich, J., Stiglat, K., Walther, R., … Zellner, W. (2006). Zwischenruf: Verantwortung und Ansehen der Bauingenieure – ein Aufruf. *Bautechnik*, *10*, 737–738.

Ferguson, E. S. (1993). *Das innere Auge – Von der Kunst des Ingenieurs.* Birkhäuser.

Flick, U. (2009). Design und Prozess qualitativer Forschung. In U. Flick, E. von Kardoff, & I. Steinke (Eds.), *Qualitative Forschung – Ein Handbuch.* Rowohlt Taschenbuch Verlag.

Flick, U. (2011). *Triangulation. Eine Einführung.* Springer VS. https://doi.org/10.1007/978-3-531-92864-7

Flury, A. (Ed.). (2012). *Kooperation. Zur Zusammenarbeit von Architekt und Ingenieur.* Birkhäuser. https://doi.org/10.1515/9783034610568

Flyvbjerg, B. (2006). Five misunderstandings about case study research. *Qualitative Inquiry*, *12*(2), 219–245. https://doi.org/10.1177/1077800405284363

Frigg, R., & Hartmann, S. (2018). *Models in science.* https://plato.stanford.edu/entries/models-science/. (Retrieved January 8, 2019)

Galton, F. (1878). Composite portraits. *Journal of the Anthropological Institute of Great Britain and Ireland*, *8*, 132–144.

Gänshirt, C. (2020). *Werkzeuge für Ideen. Einführung ins Architektonische Entwerfen.* Basel: Birkhäuser.

Garber, R. (2014). *BIM Design: Realising the creative potential of Building Information Modelling.* Wiley.

Gavreau, P. (2019). Computing power, human insight, and the future of bridge design. In H. Corres, L. Todisco, & C. Fivet (Eds.), *Proc. of the International fib Symposium on Conceptual Design of Structures, 2019, Madrid, Spain* (pp. 167–174).

Gebbeken, N. (2020). Der Ingenieur und seine Verantwortung. Dienstleister für die Gesellschaft? *Deutsches Ingenieurblatt*, *10*, 48–55.

Gericke, K., & Blessing, L. (2011). Comparisons of design methodologies and process models across disciplines: A literature review. In S. Culley, B. Hicks, T. McAloone, T. Howard, & P. Clarkson (Eds.), *Proceedings of the 18th International Conference on Engineering Design (ICED 11): Impacting Society through Engineering Design* (pp. 393–404).

Girtler, R. (2001). *Methoden der Feldforschung.* Böhlau Verlag.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research.* Aldine Publishing.

Gramazio, F., & Kohler, M. (2007). *Digital materiality in architecture.* Lars Müller Publishers.

Hahn, V. (1996). Der Beruf des Bauingenieurs – Aufgabe der Stiftung Bauwesen. In *Der Bauingenieur und seine gesellschaftspolitische Aufgabe* (pp. 7–15). Stiftung Bauwesen.

Häußling, R. (2016). Zur Rolle von Entwürfen, Zeichnungen und Modellen im Konstruktionsprozess von Ingenieuren. Eine theoretische Skizze. In T. H. Schmitz, R. Häußling, C. Mareis, & H. Groninger (Eds.), *Manifestationen im Entwurf. Design – Architektur – Ingenieurwesen* (pp. 27–64). transcript. https://doi.org/10.1515/9783839431603

Helfferich, C. (2019). Leitfaden-und Experteninterviews. In N. Baur & J. Blasius (Eds.), *Handbuch Methoden der empirischen Sozialforschung* (pp. 669–686). Springer Fachmedien. https://doi.org/10.1007/978-3-658-21308-4_44

Henderson, K. (1999). *On line and on paper – visual representations, visual culture, and computer graphics in design engineering.* MIT Press.

Hesse, M. B. (1966). *Models and analogies in science.* University of Notre Dame Press.

Hillnhütter, S. (Ed.). (2015). *Planbilder: Medien der Architekturgestaltung.* De Gruyter.

Hines, E. (2012). Understanding creativity. In E. M. Hines, S. G. Buonopane, & M. E. M. Garlock (Eds.), *Festschrift Billington, 2012: Essays in honor of David P. Billington.* International Network for Structural Art.

Holden, M., & Lynch, P. (2004). Choosing the appropriate methodology: Understanding research philosophy. *The Marketing Review*, *4*(4), 397–409. https://doi.org/10.1362/1469347042772428

Hossdorf, H. (1963). Modellversuchstechnik des entwerfenden Bauingenieurs. *Schweizerische Bauzeitung*, *81*(17), 277–283.

Hossdorf, H. (1965). Eine programmgesteuerte, vollautomatische Modellmess- und Datenauswertungsanlage. *Schweizerische Bauzeitung*, *83*(39), 563–565.

Hossdorf, H. (1970). Architekt und Ingenieur. *Schweizerische Bauzeitung*, *88*(2), 25–28.

Hossdorf, H. (1971). *Modellstatik.* Bauverlag.

Hossdorf, H. (1972). Modellversuche im Hinblick auf die Bemessung. *IABSE Congress Report*, *9*.

Hossdorf, H. (1979). CAD – Umwälzung im Konstruktionsbüro der 80er Jahre. *Schweizer Ingenieur und Architekt*, *97*(50), 1032–1036.

Hossdorf, H. (2003). *Das Erlebnis Ingenieur zu sein.* Birkhäuser.

Howard, T., Culley, S., & Deckoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies*, *29*(2), 160–180. https://doi.org/10.1016/j.destud.2008.01.001

Howells, J. (1996). Tacit knowledge, innovation and technology transfer. *Technology Analysis & Strategic Management*, *8*(2), 91–106.

Jones, M., Mautner, A., Luenco, S., Bismarck, A., & John, S. (2020). Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Materials & Design*, *187*, 108397. https://doi.org/10.1016/j.matdes.2019.108397

Kaiser, R. (2014). *Qualitative Experteninterviews.* Springer VS. https://doi.org/10.1007/978-3-658-02479-6

Kanstinger, C. (2018). Thinking with models for natural human architecture – cooperation with my father. *Journal of the International Association of Shell and Spatial Structures*, *59*(1), 11–27. https://doi.org/10.20898/j.iass.2018.195.904

Kant, V., & Kerr, E. (2019). Taking stock of engineering epistemology: Multidisciplinary perspectives. *Philosophy & Technology*, *32*, 685–726. https://doi.org/10.1007/s13347-018-0331-5

Kara, H., & Bosia, D. (Eds.). (2016). *Design engineering refocused.* Wiley.

Katz, N., Krietemeyer, B., & Schwinn, T. (2013). Interacting with the model. In B. Peters & T. Peters (Eds.), *Inside smart geometry* (pp. 80–91). Wiley.

Kloft, H. (2014). Rückblick und Ausschau auf das Berufsbild des Bauingenieurs: Ein Interview mit Jörg Schlaich aus dem Jahr 1999. *Beton- und Stahlbetonbau*, *109*(11), 838–849. https://doi.org/10.1002/best.201400092

Kloft, H., & Hoyer, S. (2014). Zum Entwerfen von Tragwerken. *Stahlbau*, *83*(11), 806–814. https://doi.org/10.1002/stab.201410216

Knoblauch, H., & Vollmer, T. (2019). Ethnografie. In N. Baur & J. Blasius (Eds.), *Handbuch Methoden empirischer Sozialforschung* (pp. 599–617). Springer Fachmedien. https://doi.org/10.1007/978-3-658-21308-4_40

Knuuttila, T. (2005). Models, representation, and mediation. *Philosophy of Science*, *72*, 1260–1271.

Knuuttila, T., & Boon, M. (2011). How do models give us knowledge? The case of carnot's ideal heat engine. *European Journal for Philosophy of Science*, *1*, 309–334. https://doi.org/10.1007/s13194-011-0029-3

Koen, B. V. (1988). Toward a definition of engineering method. *European Journal of Engineering Education*, *13*(3), 307–315.

Koen, B. V. (2009). The engineering method and its implications for scientific, philosophical and universal methods. *The Monist*, *92*(3), 357–386.

Kolarevic, B., & Klinger, K. R. (Eds.). (2008). *Manufacturing material effects: Rethinking design and making in architecture.* Routledge. https://doi.org/10.4324/9781315881171

Kornwachs, K. (2012). *Strukturen technologischen Wissens – Analytische Studien zu einer Wissenschaftstheorie der Technik.* Nomos. https//doi.org/10.5771/9783845269146

Krafczyk, M. (2014). Risiko und Verantwortung im Kontext modellbasierter Analyse und Prognose von Ingenieursystemen. In L. Hieber & H.-U. Kammeyer (Eds.), *Verantwortung von Ingenieurinnen und Ingenieuren.* Springer VS. https://doi.org/10.1007/978-3-658-05530-1_14

Krinitzki, C., Kaczorowski, M., & Hartz, C. (2023). *Zu konstruktionsbedingten Treibhausgasemissionen (GWP) in der Tragwerksplanung am Beispiel ausgewählter Decken- und Wandkonstruktionen im Hochbau.* Technische Universität Dortmund. Retrieved from https://www.bayika.de/de/aktuelles/meldungen/2023-03-21_Neue-Studie-Treibhausgasemissionen-in-der-Tragwerksplanung.php (Retrieved March 20, 2023)

Krotz, F. (2018). Grounded Theory als integrierte Folge von Einzelfallstudien. In C. Pentzold, A. Bischof, & N. Heise (Eds.), *Praxis Grounded Theory. Theoriegenerierendes empirisches Forschen in medienbezogenen Lebenswelten. Ein Lehr- und Arbeitsbuch.* Springer VS. https://doi.org/10.1007/978-3-658-15999-3

Lang, W., & Hellstern, C. (Eds.). (2017). *Visionäre und Alltagshelden: Ingenieure – Bauen – Zukunft.* Detail.

Langer, S. C., & Böhrnsen, J.-U. (2014). Innovationsschübe und die Verantwortung der Lehrenden in den Ingenieurwissenschaften. In L. Hieber & H.-U. Kammeyer (Eds.), *Verantwortung von Ingenieurinnen und Ingenieuren* (pp. 147–159). Springer VS. https://doi.org/10.1007/978-3-658-05530-1_15

Larsen, O. P. (2019). *Physical modelling in architecture and bulding design. A design practice tool.* ICE Publishing.

Latour, B. (2005). *Reassembling the social. An introduction to Actor-Network-Theory.* New York: Oxford University Press.

Leonhardt, F. (1965). Die verminderte Schubdeckung bei Stahlbetontragwerken. *Der Bauingenieur*, *40*(1), 1–15.

Leopold Museum Wien. (2022). *Ludwig Wittgenstein. Fotografie als analytische Praxis.* [Ausstellung vom 12.11.2021–27.03.2022].

Liptau, R. (2018). *Architekturen bilden.* transcript.

Llach, D. C. (2015). *Builders of the vision – software and the imagination of design.* Routledge.

Maffin, D. (1998). Engineering design models: Context, theory and practice. *Journal of Engineering Design*, *9*(4), 315–327. 10.1080/095448298261462

Maher, M., Poon, J., & Boulanger, S. (1996). Formalising design exploration as co-evolution: a combined gene approach. In J. S. Gero, F. J. S. Gero, & F. Sudweeks (Eds.), *Advances in formal design methods for CAD.* Chapman and Hall.

Mahr, B. (2008). Cargo. Zum Verhältnis von Bild und Modell. In S. Siegel, I. Reichle, & A. Spelten (Eds.), *Visuelle Modelle* (pp. 15–40). Wilhelm Fink.

Mahr, B. (2011). On the epistemology of models. In G. Abel & J. Conant (Eds.), *Rethinking epistemology volume 1.* De Gruyter.

Marble, S. (Ed.). (2012). *Digital workflows in architecture. Design – Assembly – Industry.* Birkhäuser.

McMullin, E. (1968). What do physical models tell us? In B. van Rotselaar & J. Staal (Eds.), *Logic, methodology and philosophy of science III* (pp. 385–400). North-Holland.

Meisner, I. (2005). Im Gleichklang mit Natur und Technik. Zur Architektur und Arbeitsweise von Frei Otto. In W. Nerdinger (Ed.), *Frei Otto. Das Gesamtwerk. Leicht bauen – natürlich gestalten.* Birkhäuser.

Meisner, I., & Möller, E. (2015). *Frei Otto. Forschen, bauen, inspirieren.* Detail.

Meuser, M., & Nagel, U. (2009). Das Experteninterview – konzeptionelle Grundlagen und methodische Anlage. In S. Pickel, G. Pickel, H. Lauth, & D. Jahn (Eds.), *Methoden der vergleichenden Politik- und Sozialwissenschaft.* VS Verlag für Sozialwissenschaften. https://doi.org/10.1007/978-3-531-91826-6_23

Misoch, S. (2019). *Qualitative Interviews.* De Gruyter. https://doi.org/10.1515/9783110354614

Monk, J. (1998). Ceremonies and models. In R. Gullstrom-Hughes & J. Monk (Eds.), *The book of models – Ceremonies, metaphor, performance* (pp. 33–47). The Open University.

Morgan, M. S., & Morrison, M. (1999). Models as mediating instruments. In M. S. Morgan & M. Morrison (Eds.), *Models as mediators* (pp. 10–37). Cambridge Unisversity Press.

Morris, D. (1999). Inspiring engineers to design aesthetically. *Proceedings of the Institution of Civil Engineers*, *132*(2/3), 118–124.

Morrison, M. (1999). Models as autonomous agents. In M. Morgan & M. Morrison (Eds.), *Models as mediators* (pp. 38–65). Cambridge University Press.

Mörsch, E. (1912). *Der Eisenbeton, seine Theorie und Anwendung.* K. Wittwer.

Nerdinger, W. (Ed.). (2005). *Frei Otto. Das Gesamtwerk. Leicht bauen – natürlich gestalten.* Birkhäuser.

Ochsendorf, J. (2016). Engineering as exploration. In H. Kara & D. Bosia (Eds.), *Design engineering refocused.* Wiley.

Parker, W. S. (2009). Does matter really matter? Computer simulations, experiments, and materiality. *Synthese*, *169*, 483–496. https://doi.org/10.1007/s11229-008-9434-3

Parthenios, P. (2005). Critical points for change. In J. S. Gero & N. Bonnardel (Eds.), *Studying designers '05* (pp. 355–360).

Pentzold, C., Bischof, A., & Heise, N. (2018). Einleitung: Theoriegenerierendes Forschen in medienbezogenen Lebenswelten. In C. Pentzold, A. Bischof, & N. Heise (Eds.), *Praxis Grounded Theory. Theoriegenerierendes empirisches Forschen in medienbezogenen Lebenswelten. Ein Lehr- und Arbeitsbuch.* Springer VS. https://doi.org/10.1007/978-3-658-15999-3_1

Peschard, I. (2011). Making sense of modeling: Beyond representation. *European Journal for Philosophy of Science*, *1*(3), 335–352. https://doi.org/10.1007/s13194-011-0032-8

Peters, B., & Peters, T. (2013). *Inside smart geometry.* Wiley.

Petroski, H. (2011). *An engineer's alphabet: Gleanings from the softer side of a profession.* Cambridge University Press.

Polanyi, M. (1958). *Personal knowledge. Towards a post-critical philosophy.* University of Chicago Press.

Polanyi, M. (1966). *The tacit dimension.* Doubleday.

Polónyi, S. (1987). *... mit zaghafter Konsequenz. Aufsätze und Vorträge zum Tragwerksentwurf, 1961–1987.* Friedr. Viehweg & Sohn.

Rappaport, N. (2017). Ästhetik der Ingenieurkonstruktion. In W. Lang & C. Hellstern (Eds.), *Visionäre und Alltagshelden: Ingenieure – Bauen – Zukunft.* Detail.

Reichertz, J. (2016). *Qualitative und interpretative Sozialforschung. Eine Einladung.* Springer VS. https://doi.org/10.1007/978-3-658-13462-4

Reutlinger, A., Hangleiter, D., & Hartmann, S. (2018). Understanding (with) toy models. *The British Journal for the Philosophy of Science*, *69*(4), 1069–1099. 10.1093/bjps/axx005

Rios, F. C., Chong, W. K., & Grau, D. (2015). Design for disassembly and deconstruction – challenges and opportunities. *Procedia Engineering*, *118*, 1296–1304. 10.1016/j.proeng.2015.08.485

Rittel, H. W., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*, 155–169. https://doi.org/10.1007/BF01405730

Ritter, W. (1899). Die Bauweise Hennebique. *Schweizerische Bauzeitung*, *33*, 41–43.

Rosenmann, M., & Gero, J. S. (1993). Creativity in design using a prototype approach. In J. S. Gero & M. L. Maher (Eds.), *Modelling creativity and knowledge-based creative design.* Psychology Press.

Rowley, J. (2012). Conducting research interviews. *Management Research Review*, *35*(3/4), 260–271. https://doi.org/10.1108/01409171211210154

Ruge, J., & Bögle, A. (2019a). Models as agents of creativity? A qualitative description of the structural design process. In H. Corres, L. Todisco, & C. Fivet (Eds.), *Proc. of the International fib Symposium on Conceptual Design of Structures, Madrid, Spain* (pp. 73–80).

Ruge, J., & Bögle, A. (2019b). Models as design tools – physical models and their epistemic value. In *The evolving metropolis. IABSE Congress New York City, USA* (Vol. 114, pp. 1444–1449).

Ruge, J., & Bögle, A. (2021a). Dealing with materiality: The role of engineering thinking and material knowledge for innovation in construction. In J. Thiel, V. Dimitrova, & J. Ruge (Eds.), *Construction innovation: How large-scale projects drive novelty in the construction industry* (pp. 153–168). jovis.

Ruge, J., & Bögle, A. (2021b). Designing for innovation: From model-use to thinking in models. In C. Fivet, P. D'Acunto, M. F. Ruiz, & P. O. Ohlbrock (Eds.), *Proceedings of the International fib Symposium on Conceptual Design of Structures, Attisholz, Switzerland* (pp. 41–48). 10.35789/fib.PROC.0055.2021.CDSymp.P003

Ruge, J., Dimitrova, V., Grubbauer, M., & Bögle, A. (2022). Models, mock-ups and materials: Artefacts of collaboration in the planning of large-scale construction projects. *Building Research & Information*, *50*(8), 881–893. https://doi.org/10.1080/09613218.2022.2070451

Ruge, J., Ewert, E., & Frommelt, K. (2023). Potenziale und Grenzen qualitativer Forschung im Bauwesen – ein Erfahrungsbericht zum Einsatz sozialwissenschaftlicher Erhebungs- und Analysemethoden. *Manuscript submitted for publication.*

Santamarina, J. C., & Akhoundi, K. (1991). Findings in creativity and relevance in civil engineering. *Journal of Professional Issues in Engineering Education and Practice*, *117*(2), 155–167.

Sawyer, R. K. (2012). *Explaining creativity. The science of human innovation.* Oxford University Press.

Schittich, C., & Cachola Schmal, P. (Eds.). (2013). *DETAIL engineering 3: Bollinger + Grohmann.* De Gruyter.

Schlaich, J. (1984). Zum einheitlichen Bemessen von Stahlbetontragwerken. *Beton- und Stahlbetonbau*, *4*, 89–96. https://doi.org/10.1002/best.198400160

Schlaich, J. (1991). The need for consistent and translucent models. *IABSE Congress Reports*, *62*, 169–184.

Schlaich, J. (1994). Some thoughts on the design of concrete structures. In *Japan Concrete Institute Annual Convention.*

Schlaich, J. (1996). Finite element analysis versus strut-and-tie models? In K. Schäfer (Ed.), *Workshop: Strut-and-tie models for the design of structural concrete.*

Schlaich, J. (1997). On the quality of concrete structures. In *Proceedings of the Concrete Conference in Adelaide.*

Schlaich, J. (2000). Conceptual design of bridges – more variety! In *Proceedings Bridge Engineering Conference.*

Schlaich, J., & Schäfer, K. (1984). Towards a consistent design of reinforced concrete structures. In *IABSE Report.*

Schlaich, J., & Schäfer, K. (1996). Design and detailing using strut-and-tie models. In *Workshop: Strut-and-tie models for the design of structural concrete.*

Schlaich, J., & Weischede, D. (1981). Detailing reinforced concrete structures. In *Proceedings of the Canadian Structural Concrete Conference in Toronto.*

Schubert, C. (2019). Gebrauchsgegenstände und technische Artefakte. In N. Baur & J. Blasius (Eds.), *Handbuch Methoden der empirischen Sozialforschung.* Sringer Fachmedien. https://doi.org/10.1007/978-3-658-21308-4_88

Schwartz, M., & Schwartz, C. (1955). Problems in participant observation. *American Journal of Sociology*, *60*(4), 343–353.

Schön, D. A. (1993). Learning to design and designing to learn. *Nordisk Arkitekturforskning*, *1*, 55–70.

Stachowiak, H. (1973). *Allgemeine Modelltheorie.* Springer.

Star, S. L. (1999). The ethnography of infrastructure. *American Behavioral Scientist*, *43*(3), 377–391. https://doi.org/10.1177/00027649921955326

Stiglat, K. (2004). *Bauingenieure und ihr Werk.* Ernst & Sohn. https://doi.org/10.1002/stab.200490210

Strauss, A., & Corbin, J. (1996). *Grounded Theory: Grundlagen qualitativer Sozialforschung.* Psychologie Verlags Union.

Strübing, J. (2013). *Qualitative Sozialforschung. Eine komprimierte Einführung für Studierende.* Oldenbourg Wissenschaftsverlag. https://doi.org/10.1524/9783486717594

Strübing, J. (2018). Grounded Theory: Methodische und Methodologische Grundlagen. In C. Pentzold, A. Bischof, & N. Heise (Eds.), *Praxis Grounded Theory. Theoriegenerierendes empirisches Forschen in medienbezogenen Lebenswelten. Ein Lehr- und Arbeitsbuch.* Springer VS. https://doi.org/10.1007/978-3-658-15999-3_2

Swoyer, C. (1991). Structural representation and surrogative reasoning. *Synthese*, *87*, 449–508. https://doi.org/10.1007/BF00499820

Thierbach, C., & Petschick, G. (2019). Beobachtung. In N. Baur & J. Blasius (Eds.), *Handbuch Methoden der empirischen Sozialforschung.* Springer Fachmedien. https://doi.org/10.1007/978-3-531-18939-0_66

Thomas, S. (2019). *Ethnografie. Eine Einführung.* Springer VS. https://doi.org/10.1007/978-3-531-94218-6

United Nations Environment Programme. (2022). *Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector.* https://wedocs.unep.org/handle/20.500.11822/41133.

Vollstedt, M., & Rezat, S. (2019). An introduction to grounded theory with a special focus on axial coding and the coding paradigm. In G. Kaiser & N. Presmeg (Eds.), *Compendium for early career researchers in mathematics education* (pp. 81–100). Springer International Publishing. 10.1007/978-3-030-15636-7_4

Vossenkuhl, W. (2017). Leben gestalten. In W. Lang & C. Hellstern (Eds.), *Visionäre und Alltagshelden: Ingenieure – Bauen – Zukunft.* Detail.

Vrachliotis, G. (Ed.). (2017). *Frei Otto. Denken in Modellen.* Spector Books.

Wartofsky, M. W. (1979). Telos and technique. Models as modes of action. In M. W. Wartofsky (Ed.), *Models. Representation and the scientific understanding* (pp. 140–153). Dordrecht.

Wendler, R. (2013). *Das Modell zwischen Kunst und Wissenschaft.* Wilhelm Fink.

Wendler, R. (2015). Zu einer Unschärferelation der Modelle. In H. Bredekamp & W. Schäffner (Eds.), *Haare hören – Strukturen wissen – Räume agieren.* transcript. https://doi.org/10.1515/9783839432723-010

Wendler, R. (2016). Modellbegriffe als Elemente der Modellierung. In T. H. Schmitz, R. Häußling, C. Mareis, & H. Groninger (Eds.), *Manifestationen im Entwurf. Design – Architektur – Ingenieurwesen* (pp. 271–286). trancript.

Wetzk, V. (2010). *Brückenlager. 1850–1950.* [Dissertation. Brandenburgische Technische Universität Cottbus].

Wittgenstein, L. (1965). Lecture on ethics. *The Philosophical Review*, *74*(1), 3–12.

Woolgar, S. (1991). The turn to technology in social studies of science. *Science, Technology & Human Values*, *1*(16), 20–50.

Yaneva, A. (2009). *Made by the office for metropolitan architecture.* 010 Publishers.

Appendix

A Qualitative Interviews ‘Process’

A.1 Interview Guideline ‘Process’

Interview guideline that was used for the qualitative interviews conducted in the context of the research project ‘Large-Scale Projects as Drivers for Innovation in the Construction Industry’ the author was part of from 2018 to 2020. The interviews were conducted in 2018 and 2019. They centred around innovation and their generation in large-scale construction projects. The interviews were conducted in German, the original German guideline is provided on the next page.

Guideline in English

1. Can you describe your role in the project and how it evolved over the course of the project?
    - How did you get involved in the project?
    - Which phases did you accompany?
    - What positions and tasks did you take on at each phase?
2. What was special about the project from your perspective? What sets the project apart from others?
3. In which of these special features were you personally involved? From your perspective, can you trace the origin and development of these special features?
    - Origin: what can the emergence of the special features be traced back to?
    - From your perspective, which were the relevant factors that led to the emergence of these special features? When were these factors decisive?
    - How could these special features be implemented (work processes, cooperation)?

Guideline in German

1. Können Sie uns beschreiben, welche Rolle Sie in dem Projekt gespielt haben und wie sich diese über den Projektverlauf entwickelt hat?
   - Wie sind Sie dazu gekommen?
   - Welche Phasen haben Sie begleitet?
   - Welche Positionen und Aufgaben haben Sie jeweils übernommen?
2. Was war aus Ihrer Perspektive an dem Projekt besonders? Was zeichnet(e) das Projekt gegenüber anderen aus?
3. In welche dieser Besonderheiten waren Sie persönlich involviert? Können Sie aus Ihrer Perspektive die Entstehung und Entwicklung dieser Besonderheiten nachzeichnen?
   - Ursprung: Worauf ist die Entstehung der Besonderheiten zurückzuführen?
   - Was waren aus Ihrer Sicht die relevanten Faktoren, die zur Entstehung dieser Besonderheiten geführt haben? Wann waren diese Faktoren entscheidend?
   - Wie konnten diese Besonderheiten umgesetzt werden (Arbeitsprozesse, Zusammenarbeit)?

A.2 Overview of the Interviews Selected for Analysis

Overview of the interviews 'Process' from the research project 'Large-Scale Projects as Drivers for Innovation in the Construction Industry' that were selected for a systematic analysis in the exploratory stage of the dissertation.

Large-Scale Project	Interviewee Background	Interviewee Reference
Elbe philharmonic hall	Structural engineering design	Int-process-01, Int-process-02, Int-process-04, Int-process-05
Elbe philharmonic hall	Structural engineering design / architectural design	Int-process-03
European Central Bank	Structural engineering design	Int-process-06, Int-process-08, Int-process-09
European Central Bank	Energy design	Int-process-07
Gänsebachtal Bridge	Structural engineering design	Int-process-10, Int-process-11, Int-process-12, Int-process-13, Int-process-14
Berlin Central Station	Steel design	Int-process-15, Int-process-16
Berlin Central Station	Structural engineering design	Int-process-17, Int-process-18
Kochertal Bridge	Structural engineering design	Int-process-19, Int-process-20
Wehrhahn Metro Line	Structural engineering design	Int-process-21, Int-process-22, Int-process-23, Int-process-24

A.3 Code-Set for the Analysis of the Interviews ‘Process’ with Respect to the Structural Design Process

Code-set that was developed for the analysis of the selected interviews with respect to the structural design process.

Code	**Description**
Requirements for the design engineer	Knowledge, skills, or mind-set the design engineer should have according to the interviewees.
Influence of the design engineer	Ways in which the design engineer influences the design process or the design result.
Requirements for the design (result)	Requirements that the design outcome should meet.
Task	Description of the task of the design engineer in the design process or parts of it.
Character of the design (result)	Characteristics and properties of the design result.
Influences and boundary conditions for the design (result)	Aspects that influence the design result.
Working modes, strategy, approach	Working modes, strategies, approaches, or methods that design engineers use in the design process.
Character of the design process	Characteristics and properties of the design process.
Influences and boundary conditions for the design process	Aspects that influence the design process.
Steps or components of the design process	Individual steps or components of the design process.
Collaboration	Collaboration with other design engineers or partners during the design process.

A.4 Code-Set for the Analysis of the Interviews 'Process' with Respect to the Model Understanding

Code-set that was developed for the analysis of the selected interviews with respect to the model understanding of the interviewed design engineers.

Code	**Description**
Ontology: Dimension, Scale, Material	The model term or the context in which it is named contain a reference to the dimension (e.g., 3D model), the scale (e.g., 1:50 model) or the materiality (e.g., digital model) of the model.
Model Situation: Activity	The model term or the context in which it is named contain a reference to the activity that is carried out with this model, e.g., calculation model.
Model Situation: Source Object	The model term or the context in which it is named contain a reference to the object that the model represents, e.g., inventory model.
Model Situation: Purpose	The model term or the context in which it is named contain a reference to the purpose for which the model is used, e.g., communication model.

B Qualitative Interviews 'Models'

B.1 Interview Guideline 'Models'

Interview guideline for the qualitative interviews 'models'. The interviews were structured into two blocks, one focusing on the background of the interviewees, the structural design process and creativity, and the tools used for structural design, and one about the model. From this second block, not all questions were asked in each interview; instead, the questions were selected depending on the previous responses of the interviewees in the interview situation. The interviews were conducted from May to August 2021. The original german guideline is included after the English one.

Guideline in English

Block 1: Background, structural design and creativity, tools

1. Background
   a) Can you tell me something about your professional education/studies/ career?
   b) What is your current position and what are your tasks in the engineering office?
2. Structural design and creativity
   a) How do you approach the task of structural design, e.g., in competitions or concept developments?
   b) How does the structural design process develop? Can you describe this with an example from your practice?
   c) What kind of margins arise for the structural design within the design process?
   d) What is particularly important to you during structural design?
   e) Can you give examples of situations in which you were particularly creative? What was the process like? How did you work?
3. Tools
   a) Which aids or tools do you use in the development of structural designs or concepts? What are the underlying methods, workflows, or processes?

   b) Do certain tools or aids play a special role for creative processes?
   c) How do you select tools for specific tasks? According to which criteria?

Block 2 Models in structural design

1. Model understanding
   a) What do you define as a model? What classifies something as a model?
   b) What would be typical examples of models in structural design?
   c) Do you distinguish between the framework in which model-use or model development takes place (e.g., given by a certain programme, situation, or materiality) and the model itself?
2. Context of model-use
   a) In which situations do you use models?
   b) What do you make models *of*? What do you use models *for*?
   c) Why do you use models/do you model?
   d) How do you choose the appropriate working method, tool, or model?
   e) In the structural design process, do you rather use models or develop them?
   f) What is the difference between model-use and model development? What are the different impacts of these activities?
3. Interaction with models
   a) What do you do when you work with models? What actions does it engender?
   b) Can you describe your interaction with models in more detail?
   c) How would you characterise your interaction with models (deliberate, routinised, automated, reflexive, creative, curious, ...)?
   d) What do you do when you develop or use models? What activities characterise these two modes, both mental and physical?
   e) Are there any constraints when working with models, i.e., activities that are required by the model or necessary to use or develop a model?
   f) To what extent does this depend on the framework of modelling (e.g., given by a particular programme, situation, materiality)?
   g) Do you work with models alone or in a team?
4. The role of models
   a) Which role do models play in the structural design process?

   b) Which effects does working with models have on workflows in structural design processes?
   c) To what extent do models promote or support certain thought processes, developments, or creativity? Can you give examples?
   d) What would be criticism or concerns you have with respect to working with models? Can you give specific examples?

5. Potentials of model-use and model development/modelling
   a) What are the effects or impacts of working with models?
   b) Did you have any special experiences (negative, positive, surprising, eye-opening, sudden insights) with models?
   c) Is there a surplus or extra, i.e., do models produce more than they contain?
   d) What kind of benefits or added value can models ideally have?
   e) What would an ideal model be like?

6. Is there anything else you would like to add on the topic of models or working with models in structural design processes?

Guideline in German

Block 1: Hintergrund, Entwerfen und Kreativität, Hilfsmittel

1. Hintergrund
   a) Können Sie mir etwas über Ihre professionelle Ausbildung/Ihr Studium/ Ihren Werdegang erzählen?
   b) Können Sie mir etwas über Ihre Position und Ihre Aufgaben im Ingenieurbüro erzählen?
2. Entwerfen und Kreativität
   a) Wenn Sie an die Aufgabe Entwerfen denken, z.B. in Wettbewerben oder Konzeptentwicklungen, wie gehen Sie an diese Aufgabe heran?
   b) Wie entwickelt sich der Prozess? Können Sie dies anhand eines Beispiels aus Ihrer Praxis beschreiben?
   c) Was für Spielräume ergeben sich dort?
   d) Was ist für Sie beim Entwerfen besonders wichtig?
   e) Können Sie Beispiele nennen, wo Sie besonders kreativ waren? Wie war der Prozess? Wie haben Sie gearbeitet?

3. Hilfsmittel
   a) Welche Werkzeuge, Hilfsmittel oder Tools setzen Sie bei der Entwicklung von Entwürfen oder Konzepten ein, welche Methoden, Arbeitsabläufe oder Prozesse stehen dahinter?
   b) Spielen bestimmte Werkzeuge, Hilfsmittel oder Tools eine besondere Rolle bei kreativen Prozessen?
   c) Wie wählen Sie bestimmte Werkzeuge, Hilfsmittel oder Tools für bestimmte Aufgaben aus? Nach welchen Kriterien?

Block 2 Modelle im Tragwerksentwurf

1. Modellverständnis
   a) Was verstehen Sie unter einem Modell? Was klassifiziert etwas als Modell?
   b) Was wären für Sie typische Beispiele für Modelle in der Tragwerksplanung oder in Entwurfsprozessen?
   c) Was ist für Sie der Unterschied zwischen dem Rahmen, in dem Modellnutzung/-entwicklung stattfindet (z.B. gegeben durch ein bestimmtes Programm, eine bestimmte Situation, eine bestimmte Materialität), und dem Modell selbst?
2. Kontext der Modellnutzung
   a) In welchen Situationen benutzen Sie Modelle?
   b) *Von was* machen Sie Modelle? *Für was* machen Sie Modelle?
   c) Warum benutzen Sie Modelle/modellieren Sie?
   d) Wie wählen Sie die passende Arbeitsmethode, das passende Werkzeug oder das passende Modell aus?
   e) Findet in Entwurfsprozessen eher Modellnutzung oder Modellentwicklung statt?
   f) Was ist der Unterschied zwischen Modellnutzung und Modellentwicklung? Welche unterschiedlichen Auswirkungen haben diese Tätigkeiten?
3. Interaktion mit Modellen
   a) Was machen Sie, wenn Sie mit Modellen arbeiten? Welche Tätigkeiten führen Sie aus?
   b) Können Sie Ihre Interaktion mit Modellen genauer beschreiben?
   c) Wie würden Sie ihre Interaktion mit Modellen charakterisieren? (überlegt, routiniert, automatisiert, reflexhaft, kreativ, neugierig, immer gleich, …)

   d) Was machen Sie, wenn Sie Modelle entwickeln oder anwenden? Was charakterisiert diese beiden Tätigkeiten, sowohl mental als auch tatsächlich?
   e) Gibt es irgendwelche Handlungszwänge, wenn Sie mit Modellen arbeiten, d.h. Tätigkeiten, die vom Modell erfordert werden oder die nötig sind, um ein Modell zu benutzen oder zu entwickeln?
   f) Inwiefern ist dies abhängig von dem Rahmen des Modellierens (z.B. gegeben durch ein bestimmtes Programm, eine bestimmte Situation, eine bestimmte Materialität)?
   g) Wie arbeiten Sie mit Modellen: alleine, im Team?

4. Rolle von Modellen
   a) Welche Rolle spielen Modelle im Entwurfsprozess?
   b) Welche Auswirkungen hat Arbeiten mit Modellen auf Abläufe in Entwurfsprozessen?
   c) Inwiefern fördern oder unterstützen Modelle bestimmte Gedankenprozesse, Entwicklungen oder Kreativität? Können Sie hierfür Beispiele nennen?
   d) Was wären Kritik oder Bedenken die Sie in Bezug auf Arbeiten mit Modellen haben? Können Sie hierfür konkrete Beispiele nennen?

5. Welche Potentiale liegen in der Modellnutzung und Modellentwicklung/dem Modellieren?
   a) Welche Auswirkungen oder Effekte hat das Arbeiten mit Modellen?
   b) Haben Sie besondere Erfahrungen (negativ, positiv, überraschend, Aha-Momente oder plötzliche Erkenntnisse) mit Modellen gemacht?
   c) Gibt es ein Surplus oder ein Extra, d.h. produzieren Modelle mehr als sie enthalten?
   d) Was für einen Nutzen/Mehrwert können Modelle idealerweise haben?
   e) Was würden Sie sich von idealen Modellen wünschen?

6. Haben Sie noch etwas, was Sie zum Thema Modelle oder Arbeiten mit Modellen in Entwurfsprozessen ergänzen wollen?

B.2 Overview of Potential Engineering Offices for the Interviews

Overview of the potential engineering offices for the qualitative interviews 'Models'. All of these offices had been nominated or won an engineering award between 2011–2021. In the Table, BBP refers to Deutscher Brückenbaupreis (German Bridge Engineering Award), IBP to Deutscher Ingenieurbaupreis (German Engineering Award), UF to Ulrich Finsterwalder Ingenieurbaupreis (Ulrich Finsterwalder Engineerig Award) and BN to Nalthasar Neumann Preis (Balthasar Neumann Award).

	Office	**Project**	**Engineering Award**
1	Bergmeister Ingenieure GmbH	Isarsteg Nord, Freising	BBP Nominiation 2018
2	Dr. Gollwitzer – Dr. Linse Ingenieure	Wooden shell of the synagogue in Regensburg	IBP Distinction 2020
3	DR. SCHÜTZ INGENIEURE	Campus Bridge, Würzburg	BBP Nomination 2016
4	EHS Beratende Ingenieure für Bauwesen	Henneberg Bridge, Braunschweig	BBP Nomination 2018
5	EiSat	Roof for Göbekli Tepe	UF Award 2019
6	Engelsmann Peters Beratende Ingenieure	ZOB Pforzheim	BN Distinction 2016 and IBP Distinction 2016
7	Furche Geiger Zimmermann	Salzlagerhalle (Salt storage hall)	BN Distinction 2018 and IBP Distinction 2018
8	ifb frohloff staffa kühl ecker	Leibniz Bridge, Eberswalde	BBP Nomination 2016
9	Ingenieurbüro Grassl GmbH	Rethe Bascule Bridge, Hamburg	BBP Award 2020
		Steel viaduct Binnenhafen Bridge	UF Distinction 2013
10	Knippers Helbig	Wooden bridge at the Birkelspitze	BBP Distinction 2020
11	Konstruktionsgruppe Bauen	Lahntal Bridge near Limburg	BBP Nomination 2018
12	KREBS+KIEFER Ingenieure	Kienlesberg Bridge, Ulm	UF Distinction 2019 and IBP Award 2020
13	Leonhardt, Andrä und Partner	Bridge at Schwaig (A3) near Nürnberg	BBP Distinction 2020
14	Mayr | Ludescher | Partner	Donau Bridge near Deggendorf	BBP Award 2016

	Office	Project	Engineering Award
15	Merz Kley Partner ZT GmbH	Lifecycle Tower LCT ONE	BN Distinction 2014
16	MKP (Marx Krontal Partner) GmbH	De-construction Lahntal Bridge near Ulm	IBP Distinction 2020
17	osd – office for structural design	ETA-Plant, Darmstadt	IBP Distinction 2016
		National Archive NRW	BN Award 2014
18	Penzel Valier AG	Hydropower plant Hagneck	UF Distinction 2017
19	schlaich bergermann partner	Bleichinsel Bridge, Heilbronn	BBP Award 2018
		National Stadium, Warsaw	UF Award 2013
		Streetcar Stop Berlin Central Station	UF Distinction 2017
		Weinberg Bridge Bundesgartenschau	IBP Distinction 2016
		Metro-station Elbbrücken	IBP Distinction 2020
		Bridge Rotes Steigle (Kreuz Stuttgart A8)	IBP Distinction 2018
		Trumpf Bridge Ditzingen	UF Distinction 2019 and BBP 2020
20	schlaich bergermann partner Sonne	Ultimate Through Test Loop California	UF Distinction
21	SL-Rasch GmbH	53m umbrella construction Ehingen	IBP Distinction 2016
22	SSF Ingenieure AG	Pilot structure Greißelbach	BPP Nomination 2018
23	Walt + Galmarini AG	Elephants Park Zoo Zürich	UF Award 2015
25	Werner Sobek	Adidas World of Sports	BN Distinction 2021
		ThyssenKrupp Testing Tower Rottweil	BN Award 2018 and IBP 2018
26	WTM Engineers	Steel viaduct Binnenhafen Bridge	UF Distinction 2013

B.3 E-Mail Request and Information for the Interviewees

The following E-Mail was sent to the potential interviewees, together with a handout that included more detailed information on the dissertation, to inform about the context and aim of the dissertation and the interviews. The original German E-Mail and information is included after the English translations.

E-Mail in English

Subject: Dissertation project ‘Model-use in conceptual structural design’ | Interview request

Dear Mr.... ,/ Dear Ms ..... Dear Sir or Madam,

for my dissertation on the topic of model-use and modelling in conceptual structural design I am looking for participants for qualitative research interviews. Through the award [name], I became aware of the engineering office [name], and would like to inquire whether you or one of your structural design engineers would be available for an interview.

About the dissertation:
Due to their everyday and routine use in structural design, models are often regarded as purely pragmatic tools. As a counter-thesis to this, in my dissertation I aim to identify the potentials of model-use and modelling, for example with respect to creativity or the understanding of complex phenomena. For this, I conduct and analyse qualitative interviews with structural design engineers and a participatory observation on modelling processes. The dissertation is funded by the Studienstiftung des Deutschen Volkes and supervised by Prof. Dr.-Ing. Annette Bögle at the HafenCity University Hamburg (HCU). I have included a more detailed description of the project in the attachments.

About the interviews:
For my dissertation, insights into personal experiences in structural design as well as in dealing with a wide variety of models are of crucial importance. I would therefore be very pleased if one of your design engineers would be willing to be interviewed and thus support my research work. The research interview, which will last about 60 minutes, will be divided into two thematic blocks: firstly, it will be about design and creativity, whereby I am also interested in individual training, experience and design philosophy; in the second block, I will ask specifically about the use of various models as tools or aids in design processes. The interview will take place via video call (e.g., zoom). All statements made in the interview will be treated confidentially,

anonymised, and evaluated exclusively for research purposes. I am flexible with regard to scheduling and will be happy to accommodate to your availability.

If you have any questions about the research project or the interview, please do not hesitate to contact me.

Additional Information in English (E-Mail Attachment)

PhD Project

The potentials of modelling in structural design –
towards a conceptual model understanding

M. Sc. Johanna Ruge | johanna.ruge@hcu-hamburg.de | 040 42827 5231 |
Supervision: Prof. Dr.-Ing. Annette Bögle

Research question and goals:

Current challenges, such as climate change or increasing urbanisation, lead to an increased demand for innovative and sustainable structures. To meet this demand, engineers must possess of a high level of design competence; an understanding of the creative design process and its underlying methods is thereby essential. In this context, working with of models – whether digital or physical, mental or material, concrete or abstract – as a method applied in all design phases is of particular importance.

Due to their everyday and routine use, however, models are often regarded as purely pragmatic tools, and many engineers are not aware of the potential that lies in the use of models, for instance with respect to creativity or the understanding of complex phenomena. The aim of this PhD project is to develop a conceptual understanding of models that describes the role and potential of modelling in the design process. The focus is thus less on the model as an object than on modelling as a method and the understanding of the interaction between engineer and model. Due to the advancing digitalisation of the building industry, digital modelling in particular is the focus of the work: how does digital materiality influence the interaction between engineer and model and what effects does it have on the design process?

A conceptual understanding of modelling and its potentials can lead to a better understanding of the design process itself, allowing for easier adaptation to changing circumstances and more creative and innovative outcomes. An understanding of the interaction between engineer and model further enables the development of models that respond appropriately to the working practices of engineers.

Data conduction methodology:

The PhD project uses two qualitative methods for data conduction: qualitative interviews and participatory observation.

Phase one – qualitative interviews 'structural design process': As a first explorative empirical data basis, qualitative interviews with practising engineers were conducted and analysed. The interviews shed light on the design process in various projects and provide initial insights into the development and application of different models as well as into the engineers' understanding of models.

Currently: Phase two – qualitative interviews 'models' In the second round of qualitative interviews, the explorative findings on models will now be reviewed and expanded. The interviews focus specifically on the context, effects and backgrounds of various model uses and developments and aim to uncover and question the desired and undesired potentials of modelling.

Phase three – participatory observation: In order to study models in the process of their development and application, as well as to directly capture actual practices of modelling and the interaction between model and engineer, a participant observation will be conducted after the interviews, during which the researcher will participate in and observe the daily work in an engineering office.

Support and Funding:

The PhD project is supervised by Prof. Dr.-Ing. Annette Bögle – Design and Analysis of Structures – at the HafenCity University Hamburg and is supported by a scholarship from the Studienstiftung des Deutschen Volkes.

E-Mail in German

Betreff: *Dissertationsprojekt Modellnutzung in konzeptionellen Entwurfsprozessen | Interviewanfrage*

Sehr geehrter Herr . . . ,/Sehr geehrte Frau . . . ,/Sehr geehrte Damen und Herren,

für meine Dissertation im Bereich Tragwerksentwurf zum Thema Modellentwicklung und -nutzung in konzeptionellen Entwurfsprozessen bin ich auf der Suche nach TeilnehmerInnen für qualitative Forschungsinterviews. Durch den Preis [Name] bin ich auf das Ingenieurbüro [Name] aufmerksam geworden, und möchte nun ganz konkret anfragen, ob Sie oder einer Ihrer EntwurfsingenieurInnen für ein Interview zur Verfügung stehen würden.

Zur Dissertation:
Modelle werden durch ihre alltägliche und routinierte Anwendung im Tragwerksentwurf oftmals als rein pragmatische Werkzeuge betrachtet. Als Gegenthese dazu möchte ich anhand von qualitativen Interviews sowie teilnehmender Beobachtung Potentiale der Modellnutzung, beispielsweise in Bezug auf Kreativität oder dem Verständnis komplexer Phänomene, herausarbeiten. Die Dissertation wird durch die Studienstiftung des Deutschen Volkes gefördert und von Prof. Dr.-Ing. Annette Bögle an der HafenCity Universität Hamburg (HCU) betreut. Im Anhang finden Sie eine detailliertere Beschreibung des Vorhabens.

Zu den Interviews:
Für meine Dissertation sind Einblicke in persönliche Erfahrungen in der Entwurfserarbeitung sowie im Umgang mit verschiedensten Modellen von entscheidender Bedeutung. Ich würde mich daher sehr freuen, wenn einer Ihrer EntwurfsingenieurInnen zu einem Interview bereit wäre und damit meine Forschungsarbeit unterstützen würde. Das etwa 60-minütige Forschungsinterview ist thematisch in zwei Blöcke geteilt: zunächst wird es um Entwerfen und Kreativität gehen, wobei mich hierbei auch die individuelle Ausbildung, Erfahrung und Entwurfsphilosophie interessiert; im zweiten Block werde ich spezifisch zur Nutzung verschiedenster Modelle als Werkzeuge bzw. Hilfsmittel in Entwurfsprozessen fragen. Das Interview wird per Videocall (z.B. zoom) stattfinden. Alle im Interview getätigten Aussagen werden selbstverständlich vertraulich behandelt, anonymisiert und ausschließlich für Forschungszwecke ausgewertet. Terminlich bin ich weitgehend flexibel und richte mich gern nach Ihrer Verfügbarkeit.

Sollten Sie Fragen zu dem Forschungsprojekt oder dem Interview haben kontaktieren Sie mich gern.

Additional Information in German (E-Mail Attachment)

Dissertationsprojekt

Potentiale des Modellierens im Tragwerksentwurf –
eine Annäherung an ein konzeptionelles Modellverständnis

M. Sc. Johanna Ruge | johanna.ruge@hcu-hamburg.de | 040 42827 5231 |
Betreuung: Prof. Dr.-Ing. Annette Bögle

Fragestellung und Ziele:

Aktuelle Herausforderungen, beispielsweise der Klimawandel oder die zunehmende Urbanisierung, führen zu einer vermehrten Nachfrage innovativer und nachhaltiger Bauwerke. Um dieser zu begegnen ist eine hohe Entwurfskompetenz der Ingenieur:innen erforderlich; ein Verständnis des kreativen Entwurfsprozesses und der ihm zugrundeliegenden Methoden ist dafür essentiell. Hierbei kommt dem Arbeiten mit verschiedensten Modellen – ob digital oder physisch, gedanklich oder materiell, konkret oder abstrakt – als eine in allen Entwurfsphasen angewandte Methode ein besonderer Stellenwert zu.

Durch ihre alltägliche und routinierte Anwendung werden Modelle allerdings oftmals als rein pragmatische Werkzeuge betrachtet, vielen Ingenieur:innen ist nicht bewusst, welche Potentiale in der Modellnutzung liegen, beispielsweise in Bezug auf Kreativität oder dem Verständnis komplexer Phänomene. Ziel des Dissertationsvorhabens ist die Entwicklung eines konzeptionellen Modellverständnisses, welches die Rolle und Potentiale des Modellierens im Entwurfsprozess beschreibt. Der Fokus liegt hierbei weniger auf dem Modell als Objekt als auf dem Modellieren als Methode und dem Verständnis der Interaktion zwischen Ingenieur:in und Modell. Anlässlich der fortschreitenden Digitalisierung des Bauwesens steht insbesondere das digitale Modellieren im Fokus der Arbeit: wie beeinflusst die digitale Materialität die Interaktion zwischen Ingenieur:in und Modell und welche Auswirkungen hat sie auf den Entwurfsprozess?

Ein konzeptionelles Verständnis des Modellierens und seiner Potentiale kann zunächst zu einem besseren Verständnis des Entwurfsprozesses selbst führen, womit eine leichtere Anpassung an sich verändernde Umstände sowie kreativere und innovativere Ergebnisse ermöglicht werden. Ein Verständnis der Interaktion zwischen Ingenieur:in und Modell ermöglicht außerdem die Entwicklung von Modellen, die in angemessener Weise auf die Arbeitspraktiken der Ingenieur:innen antworten.

Methodik der Datenerhebung:

In dem Dissertationsvorhaben kommen zwei qualitative Methoden zum Einsatz: qualitative Interviews und teilnehmende Beobachtung.

Erste Phase – Qualitative Interviews 'Entwurfsprozess': Als erste explorative empirische Datengrundlage wurden qualitative Interviews mit praktizierenden Ingenieur:innen durchgeführt und ausgewertet. Die Interviews beleuchten den Prozess des Entwerfens in verschiedenen Projekten und ermöglichen erste Einblicke bzgl. der Entwicklung und Anwendung unterschiedlicher Modelle sowie der Modellverständnisse der Ingenieur:innen.

Aktuell: Zweite Phase – Qualitative Interviews 'Modelle': In der zweiten Runde qualitativer Interviews sollen nun die explorativen Erkenntnisse zu Modellen überprüft und erweitert werden. Die Interviews fokussieren speziell Kontext, Auswirkungen und Hintergründe verschiedener Modellnutzungen bzw. Modellentwicklungen und zielen darauf ab, erwünschte wie unerwünschte Potentiale des Modellierens aufzudecken und zu hinterfragen.

Dritte Phase – Teilnehmende Beobachtung: Um die Modelle im Prozess ihrer Entwicklung und Anwendung untersuchen zu können sowie tatsächliche Praktiken des Modellierens und die Interaktion zwischen Modell und Ingenieur:in direkt zu erfassen, ist eine teilnehmenden Beobachtung im Anschluss an die Interviews geplant, bei der die Forschende am Büroalltag eines Ingenieurbüros teilnimmt und diesen beobachtet.

Förderung:

Das Dissertationsprojekt wird von Prof. Dr.-Ing. Annette Bögle – Design und Analyse von Tragwerken – an der HafenCity Universität Hamburg betreut und durch ein Promotionsstipendium der Studienstiftung des Deutschen Volkes gefördert.

B.4 Overview of Conducted Interviews ‘Models’

Anonymised overview of the 19 conducted interviews.

Interviewee reference	Date	Duration (h)
Int-models-01	27.05.2021	01:12
Int-models-02	28.05.2021	01:03
Int-models-03	01.06.2021	01:03
Int-models-04	22.06.2021	00:57
Int-models-05	31.05.2021	01:18
Int-models-06	04.06.2021	01:33
Int-models-07	08.06.2021	01:10
Int-models-08	09.06.2021	01:10
Int-models-09	09.06.2021	01:08
Int-models-10	23.06.2021	01:07
Int-models-11	15.06.2021	00:32
Int-models-12	14.06.2021	01:14
Int-models-13	16.06.2021	01:26
Int-models-14	18.06.2021	00:52
Int-models-15	14.07.2021	01:09
Int-models-16	28.07.2021	01:19
Int-models-17	09.08.2021	01:27
Int-models-18	05.08.2021	01:00
Int-models-19	16.08.2021	01:34

B.5 Code-Set for the Analysis of the Interviews 'Models'

Code-set that was developed and used for the analysis of the interviews 'Models'.

Code / Subcode	**Description**
Modeller / Design engineer	
Influence of the modeller	Examples of the modeller's influence on the choice, use, or development of models.
Education	Description of the interviewee's education or professional background in relation to model-use and development.
Experience	Description of the interviewee's experience in relation to model-use and development.
Self-perception	Self-perception of the interviewee in relation to the task of the engineer and the design (process).
Model understanding and definition	
Model utopia, future or ideal model	Description of models that may be available in the future, utopian concepts of ideal models.
Model requirements	Properties a model should fulfil or activities that should be possible with models.
Qualitative properties	Qualitative properties of models, e.g., simplification.
Types of models	References to different types of models.
Tools	References to different tools used in the design process other than models.
Applications and functions of and reasons for model-use or models	Description of reasons for using models or the functions of models.
Model context or situation	Descriptions of the context or situations in which models are used.
Mode of modelling	
Model Development/Modelling	Creating a model specifically for the task.
Model-use or application and model choice	Choosing and using an existing model or modelling framework.
Teamwork with model	Description of collaboration with other participants in the design process or third parties in relation to the model.
Interaction with model	Description of interactions with a model.

Code / Subcode	**Description**
Modelling steps / process chains	Description of certain consecutive steps with respect to model-use or model development or description of specific types of models used consecutively in the design process.
Translations	Description of translation processes, for example from one model to another, from a conception to a model, from design engineer to design engineer, etc.
Effects and potentials of modelling	Description of positive and negative effects of modelling or model-use, including creative potentials but also risks in relation to modelling or model-use.
Valuation (of specific models or tools)	Evaluations and judgements of the use of specific models in the structural design process.

C Participatory Observation

C.1 Guideline Participatory Observation

Guideline to support the participatory observation. The guideline was informed by the research questions and the planned focus for the observation, but also by the four analytical approaches to artefacts described by Latour: 1) which heterogeneous entities are involved in the use of a certain artefact (e.g., parts of a model, the modeller); 2) how are the relations between these entities? 3) what would happen, if one of the entities does not work? and 4) which translations result from the use of the artefact as well as from the relations between artefact and persons? (Latour 2000, as cited in Schubert, 2019).

General aspects:

- Focus on processes and statements that are important for the research question.
- Distinguish between language of the observed and language of the observer (said vs. observed)
- Report as verbatim as possible, as many specific details as possible.
- Categorisation: Observation notes; theoretical notes; methodological notes.

Observation guideline

1. Who is modelling?
    - When several people are involved: Why?
    - How is the collaboration working? How is the interaction between the modellers?
    - Do the collaborators understand each other, does communication happen, do problems occur, is there friction?
2. Who else participates in the design process?
    - How is the interaction between the modellers and other participants of the design process?
    - When is the activity of modelling talked about and with whom?
3. What is the goal of the modelling activities? What is the model a model of? What is the model a model for (point of reference)?

4. Temporal aspects:
    - When in relation to the design process do the observed modelling activities take place?
    - What is the duration of the activity of modelling in relation to the overall design process?
    - In which steps is it divided?
5. What kind of modelling activity takes place?
    - Digital (2D, 3D), on paper (sketches), physical?
    - Why was a particular model chosen?
    - Was the choice of model made consciously?
6. Interaction:
    - Which activities, actions, or steps constitute the activity of modelling?
    - Is the interaction fast and easy or slow and difficult?
    - Which objects or (digital) tools are used in the modelling process?
    - How does the framework of the model influence the interaction?
    - What effects does the seeing of the model cause?
7. Translations: Is there a change between different types of modelling?
    - What kind of translation takes place (model – model, modeller – modeller)?
    - Does the quality of the information, medium, model, collaboration, … change?
    - What is the direction of the translation? (simple → complex, parallel translations)
    - How does it take place? (Simple, fast, deliberate, intuitive, fixed rules)
    - Why?
    - What effect does the translation have?
8. Potential of modelling:
    - When and how does something unexpected, creative, or a surplus arise in the activity of modelling?
    - In which situations?
    - With which models?
    - When and how show the models a logic of their own in the interaction?
9. Location: Where does the modelling activity take place?
    - Specification of the rooms, the equipment, who else is there, what is the working atmosphere like?

- How does the environment influence the activity of modelling?

10. How are 'finished' models treated?
11. Are there deviations from the usual procedure? (Is there a usual procedure?) How do the observed people react, what are the effects of this? Are there contradictions between what is said and what is done?

C.2 Template for Field Diary Entries

Template to structure the daily field diary entries during the participatory observation.

Daily Report No.:
Date:
Activities / situations:
Written protocols:

1. Chronological description of the observation process: events, context of the observed situations, etc.:
2. Procedure and behaviour of the observer:
3. Development of the observation role:
4. Development of the observation phases:
5. Questions that arise during observation:
6. Own reactions, self-reflection, ideas, hypotheses:

C.3 Information for the Employees of the Engineering Office

This information on the PhD project was distributed to the people working at the engineering office B+G Vienna to inform them about context and aim of the dissertation and the participatory observation. The original German version is provided after the English translation.

Information in English

PhD Project

The potentials of modelling in structural design –
towards a conceptual model understanding

M. Sc. Johanna Ruge | johanna.ruge@hcu-hamburg.de | 040 42827 5231 |
Supervision: Prof. Dr.-Ing. Annette Bögle

Research question and goals:

Current challenges, such as climate change or increasing urbanisation, lead to an increased demand for innovative and sustainable structures. To meet this demand, engineers require a high level of design competence, which in turn presupposes an understanding of creative design processes and the methods on which they are based.

The dissertation deals with modelling as a fundamental method in engineering. Through everyday and routine use, however, models are often regarded as purely pragmatic tools, and many engineers are not aware of the potentials that lie in the activity of modelling, for example with respect to creativity or the understanding of complex phenomena. The aim of the dissertation project is therefore to develop a conceptual understanding of models that describes the role and potential of modelling in the design process. The focus is less on the model as an object than on modelling as a method and the interaction between engineer and model. Due to the advancing digitalisation of the building industry, digital modelling in particular is in the focus of the thesis.

It is expected that a conceptual understanding of modelling and its potentials will lead to a better understanding of the design process itself, enabling easier adaptation to changing circumstances and more creative and innovative outcomes. An understanding of the interactions between engineer and model also enables the development of tools that respond appropriately to the working practices of engineers.

Data conduction methodology:

The conduction of empirical data to answer the research question is carried out in three successive phases. In the process, two qualitative methods are used: qualitative interviews and participatory observation.

As a first data basis, in **phase 1 explorative interviews** with engineers were conducted. These shed light on the design process in various projects and provide initial insights into the development and use of different models as well as the engineers' understanding of models.

Focused interviews in phase 2 verified and extended the explorative findings. These addressed the context, effects, and backgrounds of various model-uses and developments and aimed to uncover and question the desired and undesired potentials of modelling.

Due to the often routine and little-reflected use of models in everyday engineering, models escape analysis through interviews to a certain extent. In order to examine the models in the process of their development and application, as well as to capture directly the actual practices of modelling and the interaction between model and engineer, a **participatory observation** is carried out **in phase 3**. The researcher takes part in the everyday life of an engineering office, observes it, and is involved in different situations. For instance, this can be looking over the shoulder, participating in model development and use, or attending meetings. Data collection is mainly done by taking notes of actions and situations and is intended to influence everyday office life as little as possible. Supplementary interviews will be conducted as needed and as opportunities arise to explore reasons for the observed actions as well as reflections of the engineers on their working practices. A four-week observation period is aimed for. The specific time and duration will be based on the schedules of the observed engineers and their projects.

Support and Funding:

The PhD project is supervised by Prof. Dr.-Ing. Annette Bögle – Design and Analysis of Structures – at the HafenCity University Hamburg and is supported by a scholarship from the Studienstiftung des Deutschen Volkes.

Information in German

Dissertationsprojekt

Potentiale des Modellierens im Tragwerksentwurf –
eine Annäherung an ein konzeptionelles Modellverständnis

M. Sc. Johanna Ruge | johanna.ruge@hcu-hamburg.de | 040 42827 5231 |
Betreuung: Prof. Dr.-Ing. Annette Bögle

Fragestellung und Ziele:

Aktuelle Herausforderungen, beispielsweise der Klimawandel oder die zunehmende Urbanisierung, führen zu einer vermehrten Nachfrage innovativer und nachhaltiger Bauwerke. Um dieser zu begegnen ist eine hohe Entwurfskompetenz der Ingenieur:innen erforderlich, welche wiederum ein Verständnis für kreative Entwurfsprozesse und die diesen zugrundeliegenden Methoden voraussetzt.

Die Dissertation beschäftigt sich mit dem Modellieren als eine grundlegende Methode im Ingenieurwesen. Durch alltägliche und routinierte Anwendung werden Modelle allerdings oftmals als rein pragmatische Werkzeuge betrachtet. Vielen Ingenieur:innen ist nicht bewusst, welche Potentiale, beispielsweise in Bezug auf Kreativität oder das Verständnis komplexer Phänomene, in der Tätigkeit des Modellierens liegen. Ziel des Dissertationsvorhabens ist daher die Entwicklung eines konzeptionellen Modellverständnisses, welches die Rolle und Potentiale des Modellierens im Entwurfsprozess beschreibt. Der Fokus liegt hierbei weniger auf dem Modell als Objekt als auf dem Modellieren als Methode und auf dem Verständnis der Interaktion zwischen Ingenieur:in und Modell. Anlässlich der fortschreitenden Digitalisierung des Bauwesens steht insbesondere das digitale Modellieren im Fokus der Arbeit.

Es wird erwartet, dass ein konzeptionelles Verständnis des Modellierens und seiner Potentiale zu einem besseren Verständnis des Entwurfsprozesses selbst führt, womit eine leichtere Anpassung an sich verändernde Umstände sowie kreativere und innovativere Ergebnisse ermöglicht werden. Ein Verständnis der Interaktionen zwischen Ingenieur:in und Modell ermöglicht außerdem die Entwicklung von Tools, die in angemessener Weise auf die Arbeitspraktiken der Ingenieur:innen antworten.

Methodik der Datenerhebung:

Die Erhebung der empirischen Daten zur Beantwortung der Fragestellung erfolgt in drei aufeinander aufbauenden Phasen. Dabei kommen zwei qualitative Methoden zum Einsatz: qualitative Interviews und teilnehmende Beobachtung.

Als erste Datengrundlage wurden in **Phase 1 explorative Interviews** mit Ingenieur:innen durchgeführt. Diese beleuchten den Prozess des Entwerfens in verschiedenen Projekten und liefern erste Einblicke bezüglich der Entwicklung und Nutzung unterschiedlicher Modelle sowie der Modellverständnisse der Ingenieur:innen.

Die explorativen Erkenntnisse wurden in **Phase 2** durch **fokussierte Interviews** überprüft und erweitert. Diese thematisierten Kontext, Auswirkungen und Hintergründe verschiedener Modellnutzungen bzw. Modellentwicklungen und zielten darauf ab, erwünschte wie unerwünschte Potentiale des Modellierens aufzudecken und zu hinterfragen.

Durch den oft routinierten und wenig reflektierten Gebrauch von Modellen im Ingenieuralltag entziehen sich Modelle zu einem gewissen Grad der Analyse durch Interviews. Um die Modelle im Prozess ihrer Entwicklung und Anwendung zu untersuchen sowie tatsächliche Praktiken des Modellierens und die Interaktion zwischen Modell und Ingenieur:in direkt zu erfassen, wird in **Phase 3** eine **teilnehmende Beobachtung** durchgeführt. Dabei nimmt die Forschende am Büroalltag eines Ingenieurbüros teil, beobachtet diesen und ist in verschiedene Situationen eingebunden. Dies kann beispielsweise ein Über-die-Schulter-Gucken oder Mitwirken bei Modellentwicklung und -nutzung oder die Teilnahme an Besprechungen sein. Die Datenerhebung erfolgt hauptsächlich durch Protokollieren von Handlungen und Situationen und soll den Büroalltag so wenig wie möglich beeinflussen. Bei Bedarf und Gelegenheit werden ergänzende Interviews durchgeführt, die Gründe für die beobachteten Handlungen sowie Reflektionen der Ingenieur:innen zu ihrer Arbeitsweise thematisieren. Es wird eine vierwöchige Beobachtungsphase angestrebt. Der konkrete Zeitpunkt und die Dauer orientieren sich an den Zeitplänen der beobachteten Ingenieur:innen und ihrer Projekte.

Förderung:

Das Dissertationsprojekt wird von Prof. Dr.-Ing. Annette Bögle am Arbeitsgebiet Design und Analyse von Tragwerken an der HafenCity Universität Hamburg betreut und durch ein Promotionsstipendium der Studienstiftung des Deutschen Volkes gefördert.

C.4 Overview of the Observation Days: Exploratory Phase

Day-by-day overview of the exploratory phase of the participatory observation.

Aim: Get to know daily routines, identify valuable situations for observation, introduce researcher to the field, explain her presence, get approval from all observed people.		
Reference	**Date**	**Activities**
Observation-diary-01	01.03.22	Arrival in the office and setting up the working space, presentation of the researcher to the present employees by the secretary and the office manager, observing situations from the working space, taking part in a first internal meeting of the observed project centred around the layout of the structural model used for the project.
Observation-diary-02	02.03.22	Meeting with a selected group of employees to present in more detail the aim, scope, and process of the observation to them, personal conversations with employees, two project meetings with externals and the client, taking part in an office workshop, reviewing documentations of past projects.
Observation-diary-03	03.03.22	Personal conversations, internal project meeting about the next steps of the observed project.
Observation-diary-04	04.03.22	Project meeting with externals, monthly office meeting with presentation of the aim, scope, and process of the participatory observation, meeting outside of the project context, getting acquainted with the tool Karamba and the Karamba-Template developed in the office, which were both used in the observed project, meeting with supervisor on past and planned activities of the observation.
Observation-diary-05	07.03.22	Personal conversations, observation of daily office activities.
Observation-diary-06	08.03.22	Interview with one employee, internal project meeting, observing one employee working on the Rhino-model of the project.

C.5 Overview of the Observation Days: Focused Observation Remote

Day-by-day overview of the part of the focused observation that was conducted remote due to a Covid-19 infection.

Aim: Observe relevant situations remote, generate additional data.		
Reference	**Date**	**Activities**
Observation-diary-07	09.03.22	Project meeting with externals, office internal Karamba-Workshop.
Observation-diary-08	14.03.22	Catching up on field protocols and diaries, project meeting with externals, planning of possible activities during the remote observation, actively asking employees to be integrated in modelling-related meetings or activites, arranging interviews.
Observation-diary-09	15.03.22	Observation of an employee modelling with Rhino 3D and the Karamba-Template, organisation of more situations for the observation.
Observation-diary-10	16.03.22	Observation of several meetings: project meeting with externals and the client, internal project meeting about handing over the structural model from one employee to another, internal meeting as follow-up to the external design meeting.
Observation-diary-11	17.03.22	Adding reflections to the already written field protocols, extending of the descriptions, observation of internal project meeting about the Rhino-model of the project.
Observation-diary-12	18.03.22	Project meeting with externals and internal follow-up, conversation and observation of one employee outside of the project context, interview with employee.

C.6 Overview of the Observation Days: Focused Observation Presence

Day-by-day overview of the focused observation in presence.

Aim: Observe relevant situations at the office.		
Reference	**Date**	**Activities**
Observation-diary-13	21.03.22	Observation of several situations outside the project context from the working space, meeting with supervisor.
Observation-diary-14	22.03.22	Observation of several situations from the working space within and outside of the project context, description of the Rhino-model used in the project, observation of one employee doing modelling work in Rhino 3D.
Observation-diary-15	23.03.22	External project meeting, client project meeting, parametric sessions (office-internal workshop), description of the Karamba-Template used in the project.
Observation-diary-16	24.03.22	Observation of project lead and employee analysing the structural model of the project, description Teams channel.
Observation-diary-17	25.03.22	Observation of project meeting with externals, observation of several situations from the working space, completion of the descriptions and protocols.

C.7 Overview of the Field Protocols

Overview of the field protocols that were written during the observation. The term 'Project-related' refers to whether the observed situation was related to the project the observation focused on described in Section 5.3.

Reference	Date	Project-related	Content/Topics
Observation-protocol-01	01.03.22	no	Handling of large, digital 3D models.
Observation-protocol-02	01.03.22	no	Translation digital model to sketch for understanding.
Observation-protocol-03	01.03.22	no	Impact of BIM on work process.
Observation-protocol-04	01.03.22	yes: Meeting B+G	Karamba-Template, Rhino 3D, Miro: switching between models, explaining how the model works; building the model together; interacting with the model environment (more than modelling).
Observation-protocol-05	02.03.22	yes: Internal Design Meeting	Report on project progress, the model is referred to for this purpose.
Observation-protocol-06	02.03.22	yes: Client Meeting	Physical model as agent.
Observation-protocol-07	02.03.22	no	BIM project presentation; collaboration (rules) with BIM; question of which programmes to work with is taken very seriously, is individual, emotional.
Observation-protocol-08	03.03.22	yes: Meeting B+G	Working on the model; discussion of content and further development.
Observation-protocol-09	04.03.22	yes: Internal Design Meeting	Model as reference point for coordination.
Observation-protocol-10	04.03.22	no	Model as the relevant end result; difficulties of large models.
Observation-protocol-11	08.03.22	yes: Meeting B+G	Getting ideas through modelling; unspectacular/banal approach, but which can lead to new things.
Observation-protocol-12	08.03.22	yes: Meeting B+G	Team organisation; context.
Observation-protocol-13	09.03.22	yes: Internal Design Meeting	Talk about the model with the architects; model as active agent; simple, smaller architectural model needed as reference.

Reference	Date	Project-related	Content/Topics
Observation-protocol-14	09.03.22	no	Lunch talk about interfaces between programmes; a lot of thought is given to which model should be used when (which frameworks/environments).
Observation-protocol-15	14.03.22	yes: Meeting B+G	Work highly person-bound (only certain people can handle the programmes); meeting on work organisation; further procedure is discussed on the basis of the template.
Observation-protocol-16	15.03.22	yes: Meeting B+G	Interaction with model framework; ideas through modelling.
Observation-protocol-17	15.03.22	yes: Meeting B+G	Perplexity with a finished model: what is actually done with it?
Observation-protocol-18	16.03.22	yes: Internal Design Meeting	Model as an exchange object.
Observation-protocol-19	16.03.22	yes: Client Meeting	Physical model as a representation of the results or essence of the project.
Observation-protocol-20	16.03.22	yes: Meeting B+G	Discussion of the model in pairs directly on the model; settings of the programme that influence or define the model.
Observation-protocol-21	16.03.22	yes: Internal Design Meeting	Direct and free translation of thoughts into sketches during meetings.
Observation-protocol-22	17.03.22	yes: Meeting B+G	Division between conception and implementation of the model; handling of large models.
Observation-protocol-23	18.03.22	yes: Internal Design Meeting	Switch from organisational to substantive/contentual discussion in case of irritation.
Observation-protocol-24	18.03.22	yes: Meeting B+G	Discussion on the organisation of further work.
Observation-protocol-25	18.03.22	no	What is done in which framework? How does the modelling framework impact the outcome/process? Handling of large models; ideas through modelling; handling of modelling environments; model as an end in itself; detachment from the actual task/goal.
Observation-protocol-26	21.03.22	yes: Meeting B+G	Person-bound knowledge about tools; programme-independent knowledge particularly relevant, finding workarounds, familiarising oneself with new programmes; many changes of environments during a task.

Reference	Date	Project-related	Content/Topics
Observation-protocol-27	22.03.22	yes: Meeting B+G	Person-bound knowledge about tools.
Observation-protocol-28	22.03.22	yes: Meeting B+G	Work organisation in the project; discussion of the structure based on the model.
Observation-protocol-29	22.03.22	yes: Meeting B+G	Step-by-step observation of modelling process; interpretation required when translating architectural model into structural model; losing overview while modelling (power of model environment); unspectacular/banal approach, but this can lead to something new; model as essential result; tricks in dealing with certain modelling frameworks; speed as a paradigm.
Observation-protocol-30	23.03.22	yes: Internal Design Meeting	Oganisational aspects of the project.
Observation-protocol-31	23.03.22	yes: Meeting B+G	Fast discussion of any remaining issues.
Observation-protocol-32	23.03.22	yes: Client Meeting	Physical model: modelling process is not willingly given out of hand.
Observation-protocol-33	24.03.22	yes: Meeting B+G	Modelling: Changes according to calculation results; iterative changing of the structure; handling of the large model; handling of the tool; irritation with respect to the result as a reason for discussion, trying to understand the structure; engaging with the model; changing the medium/environment.
Observation-protocol-34	25.03.22	yes: Internal Design Meeting	Organisational meeting.

C.8 Overview of the Descriptions

Overview of the descriptions that were written during the observation regarding the office, the observed project, and the people involved in it as well as the employed tools.

Reference	Comment
Description-office	Description of the office as the setting of the observation.
Description-project	Description of the observed project and it's progress.
Description-people	Description of the people involved in the observed project.
Description-Teams	Description of the Tool MS Teams and how it was used in the office and the observed project.
Description-Miro	Description of the online whiteboard Miro and how it was used in the observed project.
Description-Rhino	Description of the programme Rhino 3D and how it was used in the observed project.
Description-Karamba	Description of the programme Karamba and the Karamba-Template that was developed in the office, and how both were used in the observed project.

C.9 Overview of the Observed Employees and the Conducted Interviews

Anonymised overview of all observed employees and the interviews that were conducted during and after the observation.

Reference	Role	Interview
Employee-01	Engineer involved in the development of the Karamba-Template	Int-observation-01 (08.03.2022)
Employee-02	Engineer involved in the development of Karamba	Int-observation-02 (18.03.2022)
Employee-03	Engineer who just started at the office at the beginning of the observation and was thus new to the tools, approaches, and processes in the office	Int-observation-03 (19.04.2022)
Employee-04	Architect leading the observed project	Int-observation-04 (26.04.2022)
Employee-05	Architect involved in the observed project	Int-observation-05 (04.05.2022)
Employee-06	Engineer involved in the observed project	Int-observation-06 (13.05.2022)
Employee-07	Architect involved in the observed project	-
Employee-08	Engineer	-
Employee-09	Engineer	-