# Chapter 1
# Theories and Models of Design: A Summary of Findings

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## 1.1 Introduction

The goal of this book is to bring together an anthology of some of the major theories and models of design that have emerged in the last 50 years of the relatively young discipline of design research. Another goal is to bring together the highlights of the discussions that took place during a workshop that was organised around the theories and models—The International Workshop on Models and Theories of Design (IWMT 2013) held at the Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore, India, during 3–5 January 2013.

The contributions in this book cover three related, but distinct aspects of research into theories and models of design—philosophical, theoretical, and empirical. Even though by no means complete, taken together the contributions and the workshop outcomes showcase the rich but varied tapestry of thoughts, concepts and results. At the same time, they highlight the effort still required to establish a sound theoretical and empirical basis for further research into design.

### *1.1.1 Contributions*

The chapters in this book are grouped according to their *main* area of contribution, i.e. philosophical, theoretical or empirical.

*Part I: Philosophical contributions*: This part commences with two chapters presenting a discussion about research into design theories and models (Vermaas

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and Sonalkar et al.). This is followed by two chapters emphasising the need to move the boundaries of design research and thus the coverage of theories and models (Taura and Horváth). The last two chapters focus on models and modelling (Lindemann and Maier et al.).

2. Vermaas, on the scientific status of design research with respect to design theories, models and their testing.
3. Sonalkar et al., on a two-dimensional structure for design theory allowing scientific rigour as well as practical usefulness.
4. Taura, on considering Pre-Design and Post-Design by including the motive of design.
5. Horváth, on the theoretical challenges imposed by social-cyber-physical systems.
6. Lindemann, on the systematic development and the desirable characteristics of models.
7. Maier et al., on using a cybernetic perspective to explain modelling in design.

*Part II: Theoretical contributions*: The chapters in this part have their main contribution in the theoretical development of the field. To understand design, it is necessary to address both the artefact and the process. Design theories and models tend to cover both, but with a clear difference in focus. The core can be strongly product-focused, strongly process-focused, or intentionally focused on both in equal measure. It has to be noted, however, that as theories and models evolve, the core may change.

The theoretical contributions are grouped according to this core: Chaps. 8–10 are largely product-focused (Albers and Sadowski, Andreasen et al., and Eder), Chaps. 11–15 are largely process-focused (Agogué and Kazakçi, Cavallucci, Gero and Kannengiesser, and Koskela et al.), Chaps. 16 and 17 focus equally on product and process (Ranjan et al., Weber et al.).

8. Albers and Wintergerst, on the Contact and Channel Approach to integrate functional descriptions into a product's physical structure model.
9. Andreasen et al., on the Domain Theory as a systems approach for the analysis and synthesis of products.
10. Eder, on the role of theory, models and methods in engineering design, with emphasis on the Theory of Technical Systems.
11. Agogué and Kazakçi, on the mathematical foundations of C–K theory, its development and its impacts in design research and practice as well as in other fields.
12. Cavallucci, on the Inventive Design Method (IDM) to guide inventive practices based on and enhancing the theory of inventive problem solving (TRIZ).
13. Gero and Kannengiesser, on the development of their Function-Behaviour-Structure (FBS) ontology and framework to represent regularities in design and designing.
14. Koskela et al., on the Aristotelian proto-theory of design as a possible design theory.

15. Ranjan et al., on the development of the Extended-Integrated Model of Designing (E-IMoD) to describe and explain the design process.
16. Weber, on the CPM/PDD approach to model products and processes based on characteristics and properties.

*Part III: Empirical contributions*: The final five chapters describe empirical contributions that inform theoretical developments and their verification.

17. Badke-Schaub and Eris, on the exploration of the role intuitive processes play in thinking and acting of designers, as a precursor to the development of a theory of design intuition.
18. Culley, on the reinterpretation of the engineering design process as a process of generating information objects.
19. Eckert and Stacey, on identifying the major causal drivers of design and their effects as first steps in incremental design theory development.
20. Goel and Helms, on the development and application of knowledge models using the example of biologically inspired design.
21. Goldschmidt, on a cognitive model of sketching in the early design phases.

### *1.1.2 Questions Addressed*

Three general questions were asked to all authors. For *philosophical* contributions, they constituted the main questions:

- What, according to you, is a theory or model of design, e.g. what is its purpose, i.e. what is it expected to describe, explain or predict?
- What, according to you, are criteria it must satisfy to be considered a design theory or model?
- How should a theory or model of design be evaluated or validated?

Authors of *theoretical* contributions were additionally asked to address the following questions:

- What is your design theory or model, what is its purpose and which criteria does it satisfy?
- What studies have you undertaken to develop and validate your theory or model, i.e. to what extent does your theory or model satisfy its purpose?

Authors of *empirical* contributions were additionally asked to address the following questions:

- What empirical findings in your area of research are the most significant for the development or validation of theories and models of design?
- What are the consequences of these empirical findings for the development or validation of theories and models of design?

This editorial chapter attempts to bring together the views of the authors, as expressed in their chapters and during the workshop, with our own views.

### *1.1.3 Workshop*

Nearly all contributions in this book were presented during the aforementioned workshop. The final sessions of each day were dedicated to group discussions. The participants were divided into three groups to address the following questions:

1. What should a theory or model for design be?
   a. what is its *purpose*, i.e. what is it expected to describe, explain or predict?
   b. what are the *criteria* it must satisfy to be considered a theory or model of design?
2. How should a theory or model of design be evaluated or *validated*?
3. Considering the current state of research:
   a. what are the gaps between theoretical and empirical results?
   b. what should be the directions of future research into theories and models of design?

One of the group members was assigned as rapporteur, who was supported by one or two PhD students as scribe to capture the discussions and produce a summary. The summaries were presented on the last day of the workshop and followed by a closing discussion involving all participants.

The results of the discussion sessions are brought together in Appendix A of this editorial chapter.

## 1.2 Theoretical Developments

### *1.2.1 Phases of Development*

Design research can be considered to have passed through three overlapping phases: the Experiential, Intellectual, and Experimental [83]. Notable attempts to develop theories and related comprehensive models during that time are ARIZ/TRIZ [3, 4], Theory of Technical Systems [43, 44], Domain Theory [5], General Design Theory [86] and Extended General Design Theory [79], Function-Behaviour-Structure Ontology [32], Logic of Design [63]. Some of these theories and models were regularly cited, but the majority never really became established (or widely accepted) as a fundamental basis for further research, at least not during this period, which has been referred to as pre-theoretical, pre-paradigmatic [19] or pre-hypothesis [41].

The situation changed rather quickly, shortly before the turn of the millennium. A new phase in design research seemed to have started, the Theoretical Phase [13]. Several new theories of a very different nature were proposed at almost the same point in time: Mathematical Theory of Design [17], Universal Design Theory [37, 53], $K^L D^E{}_0$—Theory [69, 70], Axiomatic Design [74, 75], and Theory of Synthesis [76, 80]. These were soon followed by C-K Theory [38], Infused Design [66, 67], Domain Independent Design Theory [50, 51], GEMS of SAPPhIRE Model now called Integrated Model of Designing [58, 71], CPM/PPD framework [84], and the systematised theory for concept generation [78]. At the same time, earlier work was subject to considerable further development, such as Gero's Function-Behaviour-Structure Framework [33], Chap. 13 in this book,[1] Andreasen's Domain Theory [6], Chap. 9, and Altschuller's ARIZ [21], Chap. 12.

Most of these theories and models have been covered by the chapters in this book. Some of the major theories and models could not be included as the authors were not able to attend the workshop. As they are well worth mentioning and for the purpose of completeness, they are briefly introduced in Appendix B. Historical overviews can also be found in Blessing [9, 11], Lossack [51], Pahl and Beitz [57], Heymann [40] and Weber [85], Chap. 16.

### 1.2.2 Differences

The developments in the Theoretical Phase clearly distinguish themselves from the theoretical developments in the earlier phases. Firstly, the new theories and models received much more attention and have become more widely known. Importantly, they have done so in a much shorter period of time. The increased number of publications (due to the pressure to publish), the increased accessibility of publications due to the internet and open access policies, as well as a larger and more established design research community are certainly factors that contributed to the speed of dissemination, but they cannot fully explain this visibility. We think that dissatisfaction with the state of design research, as expressed in various publications (such as [8, 10, 12–15, 41, 60–62]) has fuelled interest in theoretical developments as a much needed foundation for the growing research community to build upon. Such a foundation is required not only for further development of a theoretical basis, but also to allow theory-based analysis, e.g. to explain differences between methods [47, 67].

Second, the developments in the Theoretical Phase differ from earlier ones in that they increasingly build on each other, rather than being developed largely independently from each other. Furthermore, they are accompanied by more fundamental discussions about design research and design science, gradually

[1] Hereafter, any reference to "Chap." refers to a chapter in this book.

allowing comparisons of research results, the identification of research paradigms, and discussions about quality and rigour (e.g. [13, 15]).

Third, there is now an explicit focus on validating theories and models using empirical data using observational studies or historical cases. This is fuelled on one hand by the increased demand for rigour in the discipline, and on the other hand by the increasing availability of empirical studies.

Fourth, the newer theories and models are richer in nature, using more and different concepts compared to the earlier theories and models (see Appendix C). A likely reason is our increased understanding of design resulting from a growing number of empirical studies into design. In her investigation of existing empirical studies up to 1992, the second author could only find 74 publications describing a total of 47 studies [9]. In 1999, Cantamessa counted 90 studies in one conference alone (the International Conference on Engineering Design), even though this conference was not dedicated to empirical studies [20]. Since then, empirical studies have become an established part of design research. Most research groups employ such research, albeit to varying degrees, and special conferences and interest groups have emerged. Notwithstanding this progress, our understanding remains fragmented [16] and as Koskela et al. [46], Chap. 14 conclude: 'many design theories and methods seem to be based on descriptive but somewhat shallow knowledge on some aspect of the design process'.

Finally, design research has always focused on increasing understanding *and* supporting practice, but often as separate streams [8, 13]. It was only in the Theoretical Phase that research that was focused on theories and models paid *explicit* attention to applicability in practice. A possible reason is the widely expressed dissatisfaction with the lack of adequate demonstration of the impact of earlier attempts on practice.

### *1.2.3 Theory and Practice*

Design research has largely adopted the scientific paradigm in which it is assumed that there are regularities that underlie phenomena and it is the role of research to discover and represent those regularities [33], Chap. 13. We would add that design research also assumes that many of the observed phenomena can be changed, i.e. design practice (and education) can be improved, and that design research has an additional role: to develop and evaluate ways of realizing these changes. The majority of authors in this book confirm this combination of developing understanding and support, i.e. of scientific and practical/societal goals, as the purpose of design theories and models (see Sect. 1.4).

Having this double aim strongly affects both the research process and its outcomes. Design research is 'pulled in two opposing directions—towards scientific rigour on one hand, and a greater relevance for professional practice on the other', resulting in 'formal design theories deriving from mathematical roots that rarely influence practice' and 'process models that serve as scaffolds for professional designing, but lack scientific validity' (Sonalkar et al. [72], Chap. 3). To resolve this dichotomy, Sonalkar et al. propose a two-dimensional structure for design theory that displays scientific rigour while being useful to professionals. Our own attempt to resolve the dichotomy has been to propose a research methodology, DRM, which explicitly addresses both aims [16].

### *1.2.4 Competing and Complementing Theories and Models*

Some theories and models are further developments of a particular theory, such as Gero's situated FBS, some are developments based on existing theories in other domains, such as Hatchuel and Weil's C-K Theory, others are based on critical reflections on existing theories. Usually theories and models are based on a combination of sources. The result is a multitude of theories and models. The question is, whether this constitutes a problem. Some authors, such as Buchanan [18], consider the existence of different views a strength, while others are worried that this might prevent coherent theory development [82], Chap. 2 and—cause the Problem of Disintegration [31]. In our opinion, both views can be correct, depending on the relationship between the theories or models.

Overall, the existence of multiple theories within the same domain *over time* can be interpreted positively as a sign of work in progress, indicating that an area is alive and developing. The evolution of design theories can be interpreted as an attempt to increase their generative power without endangering their robustness [39].

Theories and models that exist *at the same time* can be competing (addressing the same phenomena) or complementary. The latter can be divided into those that address different phenomena in design, and those that address the same phenomena from a different perspective. Vermaas [82], Chap. 2 seems to focus on the former (competing theories and models) when he warns that we might be creating too many theories and models, which jeopardises the coherence of the discipline. The reason of the multitude, according to Vermaas, is that 'design research does not yet have means to test and refute design theories and models'. Maier et al. [54], Chap. 7 found that in general 'researchers consider too much heterogeneity of models problematic and that design research should aim towards rationalisation, consolidation and integration of the ideas'. For Goel and Helms [34], Chap. 20, having multiple theories and models is inherent to design research: 'Research on design adopts many perspectives ranging from anthropology to neurobiology to philosophy. The various research paradigms produce not only different theories and models of different aspects of design, but also different types of theories and models'. Cavallucci [21], Chap. 12 emphasises the need for fundamentally different theories of design that will engender fundamentally different methods and tools for design activity's framing. For Eckert and Stacey [28], Chap. 19 having multiple, complementary, what they call partial, theories is a transitional phase: 'Design is far too complex and too diverse for understanding the whole of design in one step, so we need an incremental approach to accumulating understanding'. Only after validating theory fragments, should they be connected into larger, more complete, partial theories covering more of the interlocking causal processes shaping how designing is done, by matching and merging the elements of different theory fragments. Weber supports this view: 'Developing/designing products is such a complex process that not one model alone can explain every aspect; several models may exist in parallel. However, an integrating framework would be beneficial' [85], Chap. 16. The latter is also emphasised in, and is a major driver for the work in Ranjan et al. [59], Chap. 15.

Earlier we wrote that discussions about what constitutes design research and how it is distinct from or similar to other disciplines are still very much on-going [13, 16]. We worried, however, about the lack of a common view as to what design research attempts to investigate, what its aims are, and how it should be investigated: many different aspects are investigated, many different aims pursued, and many different methods are applied. We quoted Samuel and Lewis [65], who stated that 'design research is highly fragmented and focused streams of activity are lacking', and Horváth [41] who found it 'not easy to see the trends of evolution, to identify landmarks of development, to judge the scientific significance of the various approaches, and to decide on the target fields for investments'.

In the last few years, the number of discussions about design research and theoretical developments has seen a further strong increase, in particular due to special sessions at the main conferences in the field, as well as through the workshops of the Design Theory SIG (Special Interest Group) of the Design Society. Nevertheless, the main issues (see e.g. [15]) have not been resolved yet, as the list of main difficulties for research on Design Theory suggests Le Masson et al. [48]:

- no self-evident unity of the design theory field,
- multiple paradigm shifts that threaten the specificity of design,
- the fragmentation of the design professions and,
- the limits of empirical research.

Le Masson et al. conclude that the renewal of design theory should lead today to a body of sustainable collective research, will help build a powerful discipline, a unified body of knowledge, should help to understand and support contemporary forms of collective action and might help to invent new forms of design action.

## 1.3 Definitions of Design Theories and Models

The authors of the chapters in this book were asked to describe what they considered a theory or model of design to be, what its purpose is, i.e. what it is expected to describe, explain or predict. In this section, we provide a structured overview of their definitions. Details can be found in the respective chapters.

### 1.3.1 Introduction

In literature, considerable variation exists in what a theory is, what a model is, and what the overlap is between these two. One reason is certainly the general use of the terms in everyday life which covers a spectrum of meanings as dictionary entries show: the definitions of *theory* range from 'belief', 'ideal or hypothetical set of facts' and 'an unproved assumption' to 'a plausible or scientifically accepted general principle or body of principles offered to explain a phenomena' (Merriam-Webster in Ranjan et al. [59], Chap. 15). Similarly, definitions of *model* include 'an example for imitation or emulation', 'a type or design of product', 'a description or analogy used to help visualise something that cannot be directly observed', 'a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs; also: a computer simulation based on such a system' (Merriam-Webster online dictionary). Overviews are given by Ranjan et al. [59], Chap. 15, Lindemann [49], Chap. 6 and Vermaas [82], Chap. 2. In the following sections, we focus on definitions used by the authors in this book.

### 1.3.2 Theory

For Goel and Helms [34], Chap. 20 'A scientific theory is (i) based on testable hypotheses and makes falsifiable predictions, (ii) internally consistent and compatible with extant theories, (iii) supported by evidence, and (iv) modifiable as new evidence is collected'.

According to Ranjan et al. [59], Chap. 15 a theory consists of 'a set of constructs and their definitions; and a set of propositions, expressed as descriptive relationships among the constructs, as statements about designing'.

Badke-Schaub and Eris [7], Chap. 17 add a user perspective in their definition of design theory as 'a body of knowledge which *provides an understanding* of the principles, practices and procedures of design'.

The same with Vermaas [82], Chap. 2, who refers to the definition of theory given by Ruse [64]: 'A scientific theory is an attempt to bind together in a systematic fashion the knowledge that one has of some particular aspect of the world of experience. The aim is to achieve some form of understanding, where this is usually cashed out as explanatory power and predictive fertility'. Thus, in Vermaas' view, Design Theory 'is an attempt to systematically bind together the knowledge we have of experiences of design practices'.

According to Eder [29], Chap. 10, 'the theory should describe and provide a foundation for explaining and predicting 'the behaviour of the concept or (natural or artificial, process or tangible) object', as subject. The theory should answer the questions of 'why,' 'when,' 'where,' 'how' (with what means), 'who' (for whom and by whom), with sufficient precision'.

Sonalkar et al. ([72], Chap. 3) emphasise 'the importance to distinguish between bounding the phenomenon that a theory attempts to explain and the generality of that explanation'.

Gero and Kannengiesser [33], Chap. 13 are explicit about the boundary of the phenomenon, emphasising the need to include both foundational concepts of design and designing: 'a design theory should describe any instance of designing irrespectively of the specific domain of design or the specific methods used' and should 'account for the dynamics of the situation within which most instances of design occurs'. Weber [85], Chap. 16 provides a very similar description: 'the designs (as artefacts) and the designing (as a rationally captured process to create artefacts)' should be considered and they have to be 'situated, i.e. 'external influences have to be considered as they evolve'. The explicit inclusion of designs and designing can also be found in the definition of Andreasen et al. [6], Chap. 9, even though they use a far looser basis for the theory than other authors, when they refer to their own theory as 'the authors' imagination or mental model about the nature of artefacts and their design'. Ranjan et al. [59], Chap. 7 too take both designs and designing as part of a theory of designing, as they argue that 'These propositions are meant to be used to describe or explain' the 'various characteristics of the facets of designs and designing'. They, however, go beyond these as the goals of design theories, and extend these to 'relationships among the facets' and relationships among these and various characteristics of design success'.

Cavallucci [21], Chap. 12, includes the relevance of theory for practice. A theory or model of design 'should describe the world and its realities through a prism from which, when observed through, designers could envision useful insights as regarding their designing tasks. These useful insights could be provoked by an original description, a clear definition and allow designers to anticipate with artefacts design processes with some kind of robustness. The notion of robustness can only be reached if what the theory proposes matches with temporal realities'.

All above definitions refer to theory as a *description* of a phenomenon. Weber [85], Chap. 16 is one of the authors to include a prescriptive part, when he refer to 'collecting and systematising knowledge about 'what is' (descriptive part) as well as collecting and systematising knowledge about actions and skills that can change the present state into another, previously not existing state (prescriptive)'. This is very much in line with our own view [10]: 'A typical characteristic of design research is that it not only aims at understanding the phenomenon of design, but also at using this understanding in order to change the way the design process is carried out. The latter requires more than a theory of what is; it also requires a theory of what would be desirable and how the existing situation could be changed into the desired'.

### 1.3.3 Models

The phrase 'models of design' can be interpreted in two different ways: models that are used in designing, such as scale models, CAD models, sketches etc.—this is henceforth referred to as 'models *in* design'; and models that are used to describe or prescribe how design is or should be (carried out)—this is henceforth referred to as 'models *of* design'.

#### 1.3.3.1 Models in Design

Maier et al. [54], Chap. 7 and Lindemann [49], Chap. 6 focus on models in design. Both provide a number of exemplars to illustrate the variety of models for processes as well as outcomes that are used in design. Lindemann describes a number of important characteristics for models, like transformation and reduction, purpose and subject. His discussion of quality and requirements for modelling is mainly based on these characteristics.

Albers and Wintergerst [2], Chap. 8, in referring to product models ('product models should refer to physical characteristics and the related functional properties of a system') seem to focus on models used by designers, rather than by researchers, although the borderline between the two is not always clear-cut.

#### 1.3.3.2 Models of Design

Ranjan et al. [59], Chap. 15 refer to Anderson [1964], who uses the term 'model' to refer to any way of visualising or conceiving of a structure or a mechanism that can account for observable phenomena. As mentioned before, they do not distinguish between models of design and theories of design.

According to Vermaas [82], Chap. 2 'scientific models represent features of a target system in the world or a scientific theory'. Note that the former includes models *in* design. He introduces five categories of scientific models: *Physical objects*, *Fictional objects*, *Set-theoretical structures*, *Descriptions* or *Equations*. 'Models of design practices may also be differentiated as models with descriptive, demarcating and prescriptive aims, but now all types of models fit much better in the characterisation of models in science, since there is such a diversity of scientific models'.

In the definition of Goel and Helms [34], Chap. 20 'a scientific model is an interpretation of a target system, process or phenomenon that proposes or elaborates on the processes and mechanisms that underlie it….. models are abstractions of reality… models are cognitive tools for generating explanations'. They specify two kinds of models in design in which they are interested: a knowledge model in design provides an ontology for representing the knowledge and a structure for organizing the knowledge in a design domain, a computational model of design provides architectures, algorithms, and knowledge models for the theory'.

Goldschmidt [35], Chap. 21 defines a model as 'a simplified and schematic representation of the essence/skeleton of a theory', which is 'highly linked to the disciplinary approach within which the theory is embedded'.

Lindemann [49], Chap. 6 provides three model definitions showing an increasing scope (italics added to emphasise the scope change): 1. 'A model is a *representation* of an object, system or idea in some other form than itself' [68]; 2. A model is the image of a system or a process *'within another conceptual or representational system*' [25]; and 3. 'A model is the *simplified* reproduction of a *planned or an existing system* including its processes within another conceptual or representational system' [81]. He concludes that all definitions leave room for interpretation, but agrees with Stachowiak [73] that each model should have three important characteristics: transformation of the attributes of the original into the attributes of the model, reduction of the number of attributes from original to model, and the pragmatic characteristics purpose, users and time frame of usage.

Maier et al. [54], Chap. 7 define a model as 'a simplified and therefore to a certain extent a fictional or idealised representation'. They distinguish three types of models depending on the claimed relationship between a model and the real world: explanatory ('the workings of a model map directly onto, or truly explain, 'real-world' mechanisms that 'cause' observable behaviour'), predictive ('a model can predict phenomena, but it is acknowledged that underlying real-world mechanisms may not exist in the form the model suggests, or the issue is viewed as unimportant'), and synthetic ('a model is explicitly recognised to not represent a real situation, but rather to represent an idea and thus to bring a situation into being'). 'Most models in design fulfil a synthetic role'. 'In the cybernetic sense, a model must be a description or conception of a situation that is used to guide or influence the response to that situation'.

An important factor to realise in this context is that 'An understanding of a model is a cognitive construct rather than an inherent property of the model, and a shared understanding is constructed through social processes of discussion and clarification' [27].

### *1.3.4 Theory or Model*

The difference and relation between theory and model is often discussed, but thus far no generally agreed upon definitions exist in our discipline.

Some authors do not make an explicit difference. For Agogué and Kazakçi [1], Chap. 11 'A design theory is a model of creative rationality'. For Albers and Wintergerst [2], Chap. 8 theories and models 'address a specific purpose and are intended to describe, explain or predict certain phenomena that pose an unsolved challenge both for the research community and for design practitioners'. Weber [85], Chap. 16 too refers in his definition to 'theories and models'. Ranjan et al. [59], Chap. 15 follow [30] in stating that 'a theory in its most basic form is a model'.

Vermaas [82], Chap. 2 does make a difference and describes three different ways in which scientific models are related to scientific theories: 1. models of theories are taken as providing rules for interpreting the terms and sentences of the theory they represent; 2. a scientific theory is seen as a set of models; 3. models are not taken as closely representing the content of theories, but seen as means to understand that content, which may imply that the models contain elements that are not part of these theories.

Goldschmidt [35], Chap. 21 explicitly states that 'a model is not a theory' and seems to refer to relations 1 and 2 as described by Vermaas when she writes: 'a model is both derived from a theory and it contributes to the development of the theory'. 'A model in design research specifies the main components of a design theory and the relationships among these components. It is often represented as a diagram or graph'.

Eckert and Stacey [28], Chap. 19 clearly refer to relation 2: 'Theory fragments comprise partial models' that 'represent the structure of real, if abstractly described, causal processes', that are 'networks of interlocking causal processes influenced by causal drivers'. And so do Andreasen et al. [6], Chap. 9 when they refer to their theory as a model based theory 'composed of concepts and models which explains certain design phenomena'.

The view of a theory as a series of models, rather than the so called received view of scientific theory, reflects changes in how philosophy of science perceives theories and models. As described in Sonalkar et al. ([72], Chap. 3) the common perspective of the design research community is the received view, which 'defines a three-part structure for scientific theory. The first part deals with logical formalism, the second part describes observable constructs and the third part describes theoretical constructs. The three parts are connected by rules of correspondence that hold the mathematical, observable and theoretical constructs together'. 'The rigidity and, hence, difficulty of developing such a theory has led to heavy criticism and rejection by most philosophers of science'. As a reaction, Craver [23] proposed the semantic or model view of scientific theory in which 'theories are abstract extra-linguistic structures quite removed from the phenomena in their domains. In this view, theories are not associated with any particular representation. Researchers have a much greater freedom than in the received view to describe their theory in terms of a series of models that explain a set of phenomenon through abstraction constructs that constitute the theory' (Sonalkar et al. [72], Chap. 3).

Sonalkar et al. follow the distinction made by Dörner [26] who succinctly describes a theory as 'a formulation that explains a phenomenon', and a model as 'an abstraction that simulates a phenomenon'. Simply put, models do things while theories explain things.

In our view, all theories are models, but not all models are theories.

Further to these views, the attendees addressed the definitions of, and the similarities and distinctions between the terms theory and model in the discussion sessions. Regarding the definitions of model and theory, the participants agreed on two main points.

First, it became clear that the term 'model' was used in two ways: models in design and models of design (see Sect. 1.1.3) and that confusion can arise if no clear distinction is made, even though several of the identified characteristics are valid for both.

Second, there is considerable overlap between the meanings of models of design and theories of design. A 'spectrum of meanings' emerged, starting from having 'no distinction in how these terms are currently used in our area', to where 'Theory defines a framework from which multiple models could be derived'. A consensus also emerged that there is a need to see 'theory as a spectrum', with terms such as taxonomies, models and theories having varying degrees of maturity in context, purpose and explanatory capacity.

It was agreed that for a discipline of research such as design, a clear understanding of these terms is crucial, since they form the basis for further research. Details of the discussions can be found in Appendix A.

### *1.3.5 Ontologies*

Although the issue of ontology was not the focus of this book, it came up in several contributions and in the discussion session. Several authors emphasised the need for an ontology to provide accurate descriptions of the concepts they used in the frameworks, theories and models they propose Agogué and Kazakçi [1], Chap. 11, Albers and Sadowsky [2], Chap. 8, Andreasen et al. [6], Chap. 9, Cavallucci [21], Chap. 12, Goel and Helms [34], Chap. 20, Gero and Kannengiesser [33], Chap. 13, and Ranjan et al. [59], Chap. 15. An ontology or—as a minimum—a clearly defined set of concepts is considered not only an important basis for theoretical development but also an important aid in analysis of empirical data and in making a theory comprehensible and transferable to design practice and education.

Appendix C lists the sets of main concepts the authors in this book used or created for their theories and models. What becomes immediately apparent is the strong diversity in concepts. Looking at the theories and models this diversity can have three reasons. First, most theories and models describe different aspects of the design phenomena or describe the same phenomena at different levels of resolution. This implies that these theories and models are partial theories and models, and potentially complementary. Second, the main concepts within a theory or model are interdependent: the definition of one concept influences the definition of others. For example, the definition of conceptual stage influences the definitions of the preceding and subsequent stages. This implies that the same term(s) may represent different underlying concepts in different theories and models. Third, where a similar aspect of design is described, different theoretical origins cause differences in the concept set, the concept definitions, or the terms used for essentially the same concept.

In our view, in order to describe the design phenomenon in a more comprehensive way, the current theories and models have to be brought together. Given the interdependency of concepts, a redefinition of existing concepts, and a coherent terminology will be necessary to achieve consistency. The need for a common ontology or agreement about the main concepts in our field has been argued for since several decades (e.g. in [15, 22]) but is still lacking. This is also reflected in the sets of keywords proposed for papers in our domain: a total of 1049 keywords were proposed for 390 papers submitted to one conference in engineering design [55]. In our view, this issue needs urgent attention, as it can hamper a coherent and more comprehensive understanding of design (ontology as basis for analysis) and our theoretical developments (ontology as basis for bringing together partial theories and models).

## 1.4 Purpose of Theories and Models

Theories, according to Koskela et al. [46], Chap. 14 can be *descriptive* or *prescriptive*. Vermaas [82], Chap. 2 includes a third category, *demarcating* theories, and points out that not all design theories 'systematically bind together the knowledge we have of experiences of design practice' and can, hence, be called scientific theories. The difference lies in the aims or purposes of the theory [82], Chap. 2:

- *Descriptive design theories*. Its aims include describing design practices that are regularly taken as design. It should bind together our knowledge of these regular design practices, and arrive at understanding, explanation and prediction of and about them.
- *Demarcating design theories*. Its aims include fixing the borders of what is to be taken as design practices.
- *Prescriptive design theories*. Its aims include singling out particular types of existing or new design practices and positing favourable properties about these practices.

According to Vermaas, only those demarcating and prescriptive theories that include a descriptive aim can be considered scientific theories. Prescriptive design theories that single out *new* types of design practices and posit favourable properties, i.e. are not descriptive, are for Vermaas at most *hypothetical* scientific theories. He emphasises that design theories that are generated in design research typically are not *pure* theories but combine aims.

### *1.4.1 Demarcating Purpose*

The work of Eckert and Stacey [28], Chap. 19, Koskela et al. [46], Chap. 14, Taura [77], Chap. 4, Horváth [42], Chap. 5, Gero and Kannengiesser [33], Chap. 13 and Badke-Schaub and Eris [7], Chap. 17 can be seen as contributing to the demarcation by questioning the current boundary of what is to be taken as design, and hence of what is to be covered by design theory.

Eckert and Stacey [28], Chap. 19, e.g., criticise existing theories of design that 'have aimed at understanding design as a unified phenomenon', but fail to 'explain or predict the differences and similarities that we observe when studying design processes across a range of products and domains'. Design theories are 'typically presented with insufficient consideration of how much of designing they actually cover'. Eckert and Stacey propose to use *constraints* and *drivers* as major elements in demarcating various design processes, and to use this to specify the scope of models and theories of design.

Koskela et al. [46], Chap. 14 emphasise that their proto-theory (as other theories) cannot cover the whole area of design: 'it has to be contented that there are aspects and stages in design that are best approached through rhetoric. The task of agreeing on the boundaries of the phenomenon of design seems still seem to be in front of us'.

Taura [77], Chap. 4 proposes a typology of designing consisting of pre-design, design, and post-design stages in order to include the 'motive of design', thereby proposing a demarcating theory of possible design practices. He argues that discussions on particular aspects of design that have not been considered yet have 'the potential to extend existing methods and to develop products that will be more readily acceptable to society'. The motive of design is discussed in terms of the fundamental issues faced in designing highly advanced products. Specifically, Taura proposes the conception of a social motive that is created and contained in society in contrast to the so-called motive of the individual, which can be referred to as personal motive.

The argumentation of Horváth [42], Chap. 5 is quite similar. He describes how the shift to developing socio-cyber-physical systems raises major design challenges, since such systems cover the broadest possible range of phenomena as the focus of design, and hence would lead to development of design theories that are robust enough to address any subset of such systems, e.g. physical, social, cognitive, socio-physical, socio-cyber, or cyber-physical systems. He argues that multi-disciplinary research is needed to successfully address these challenges: 'new design theories and principles and system design methodologies are needed to be developed'. Although implicit, he considers the borders of what is taken as design practice in current theories no longer valid. 'A unified design theory and methodology that facilitates addressing of the issues of both worlds (cyber and physical)' is required. This considerably expands the scope of theories and models of design.

Gero and Kannengiesser [33], Chap. 13 also extend what is to be taken as design: 'a design theory should describe any instance of designing irrespectively of the specific domain of design or the specific methods use' and should 'account for the dynamics of the situation within which most instances of design occurs'.

Badke-Schaub and Eris [7], Chap. 17 point out that 'rational decision making and its influence on design performance has been (and should be) a major source of empirical studies for the purposes of developing theories and models of design', but that the design phenomena is broader: 'design theories need to be able to also explain the need of and the processes for the unconscious such as intuition in design', as there is 'rich empirical evidence highlighting unconscious and mainly inaccessible processes that support the designer in making pragmatic and useful decisions that do not offer explicit rationale'. They note that although 'researchers seem to acknowledge that designers 'use' intuition on a daily basis, there is hardly any targeted empirical work which tries to understand whether intuition works in designing and if so, how'. Their research on intuition aims to fill this gap.

In our view, demarcating theories are still very relevant for design research as an area with ill-defined boundaries. Defining the boundaries, which may be very wide, will also contribute to the earlier mentioned need for a common ontology or agreed set of main concepts.

## *1.4.2 Descriptive and Prescriptive Purposes*

### 1.4.2.1 Theories

As any other theory, the purpose of a design theory is to describe, explain and predict. In addition, the majority of authors emphasises that the ultimate purpose is to create support to improve practice, based on the understanding obtained. Note that this does not automatically imply the development of a prescriptive theory: descriptive theories and models are used to obtain understanding that can be used to develop improvement measures. As the following paragraphs show, the characteristics of design to be described, explained and predicted can vary, but tend to be fairly wide.

A typical example is Ranjan et al. [59], Chap. 15, following Blessing and Chakrabarti [16]: 'a model or a theory of designing should be able to describe or explain characteristics of one or more facets of design and designing, including relationships among the facets involved (at one or more stages of designing, including the transitions from one stage to another, of a design process) and the relationships among these and various characteristics of design success. Furthermore, a model or theory of designing should be used as a basis to identify the positive and negative characteristics influencing design. Further, design models or theories can be used as a basis to improve the design process'.

Similarly, Badke-Schaub and Eris [7], Chap. 17 view design theory as 'a body of knowledge which provides an understanding of the principles, practices and procedures of design. That knowledge leads to hypotheses on how designers should work, and such hypotheses provide the basis for the prescriptive part of design methodology'.

Eckert and Stacey [28], Chap. 19 argue that a theory of design should explain and predict the behaviour of real processes and should be useful for understanding and improving design processes in industry. 'We are primarily interested in why design processes are as they are, and how they could be made to work better, to produce better products, to increase the profitability of companies or produce products faster and with less effort, or involve happier, less stressed, more fulfilled participants'. Taura [77], Chap. 4, Koskela et al. [46], Chap. 14 and Weber [85], Chap. 16 make similar statements. Taura expects a theory or model of design 'to extract the essences of phenomena within the real design process' but also 'to predict and lead future new design methods'. According to Koskela et al. a theory should provide better 'explanation, prediction, direction (for further progress) and testing' and 'provide tools for decision and control, communication, learning and transfer (to other settings)'. For Weber a model or theory should 'explain and predict observations in its field.' The framework he proposes should 'integrate many existing approaches and to deliver some explanations of phenomena in product development/design that have been insufficiently understood so far'.

Eder [29], Chap. 10 follows the above, but does extend the purpose to include the various life-cycle phases. The theory should describe and provide a foundation for explaining and predicting 'the behaviour of the concept or (natural or artificial, process or tangible) object', as subject. […] The theory should support the utilised methods, i.e. 'how' (procedure), 'to what' (object), for the operating subject (the process or tangible object) or the subject being operated, and for planning, designing, manufacturing, marketing, distributing, operating, liquidating (etc.) the subject'.

Albers and Wintergerst [2], Chap. 8 include the designers as a target audience. A design theory should be 'explaining, or predicting certain phenomena', but also 'facilitating designers to analyse design problems and to create appropriate solutions'. Referring to the latter, they specify that 'theories and product models provide a framework for making information accessible (analysis) as well as for expressing design concepts and decisions (synthesis). They serve designers to capture, to focus, to structure, to make explicit and to simplify the complex relationships of a system's properties and characteristics. Thus, they serve as a means to overview, explore, understand and communicate such relationships at a systems level'.

For Cavallucci [21], Chap. 12 the main purpose is practical use: 'a theory or model of design is supposed to provide designers with answers to their everyday professional difficulties. Along each tasks assumed by designers, a relevant Theory of Design should provide first theoretical roots, scientifically proven, then a methodological declination of it for appropriate use and practice'.

Andreasen et al. [6], Chap. 9 look in particular at the concepts used in a theory or model by specifying the purpose of a design theory as 'the creation of a collection of concepts related to design phenomena, which can support design work and to form elements of designers' mindsets and thereby their practice'.

Some of the authors mention additional purposes that extend the role of design theory for the design research community and beyond.

Goel and Helms [34], Chap. 20 add that 'An important cognitive feature of a scientific theory is that it suggests a process or method for building, evaluating, revising, and accepting (or abandoning) a theory'. They, e.g., used their knowledge model, which specifies the ontology and the schema for representing and organizing knowledge of design problems (the aspect of design they considered) as a coding scheme for their research into design processes, as a pedagogical technique to help students in formulating design problems, as support for designers, and to structure a knowledge base to help facilitate search. Gero and Kannengiesser [33], Chap. 13 refer to a similar aim: the use of their model (or ontology) as a project-independent scheme to code data from the protocols.

Eckert and Stacey [28], Chap. 19 see the possibility to use the set of drivers they identified (i.e. the elements of their model) to categorise a design, and to be better able to inform practice what kind of design processes are and should be followed for such design.

Agogué and Kazakçi [1], Chap. 11 contribute with a description and purpose of each step involved in developing a theory. First, it aims at *revitalizing the knowledge* accumulated in engineering design. Then, deepening the formal aspects of a design theory helps to both *unveil and explain* the surprises, the paradoxes, the oddness of design reasoning that goes beyond classic rationality and logics. Moreover, a design theory being a model of creative rationality, it can circulate and *become a framework for disciplines outside of design*, where there is a need for innovation and for building understanding on creative reasoning. 'A design theory enables a dialogue that either benefits from or contributes to other disciplines'.

#### 1.4.2.2 Models

As mentioned earlier, several authors do not distinguish between theory and model and, hence, consider a model to have the same descriptive, explanatory and predictive purposes as a theory (see Sect. 1.4.2). In this section we focus on those authors that explicitly discussed the purpose of models.

Lindemann [49], Chap. 6 points out that models are developed for a multitude of purposes. Some examples he mentions are specification and demonstration models, experimental models, geometry models, theoretical models, i.e., these are models in design. The purpose determines which attributes of the original are selected and how they are transformed, but also puts 'limits to the validity of a model'. He accepts 'the reality of having a large and ever increasing number of models', but emphatically expresses the need for providing the pragmatic characteristics of a model (purpose, users and time frame of usage): He particularly stresses the importance of *usefulness* of the model in satisfying a purpose (its purpose) as the main criterion for its use'.

The purposes mentioned by Maier et al. [54], Chap. 7 are: 'explaining or predicting behaviour, or articulating and realizing something new'. The former overlap with earlier definition of descriptive theories, the latter is of a more predictive nature.

Goel and Helms [34], Chap. 20 are more specific: the purpose of a model is to 'productively constrain reasoning by simplifying complex problems and thus suggest a course of analysis' and 'serve as tools both for specifying and organizing the current understanding of a system and for using that understanding for explanation and communication'. Vermaas [82], Chap. 2 adds that 'Scientific models also have epistemic value: their creation, analysis and development allow scientist to understand the target systems and the theories represented'.

This is in line with the purpose mentioned by Goldschmidt [35], Chap. 21: 'to facilitate the disjunction of a theory into constituent parts and to lay down relationships among components, for further investigation and/or proof. Likewise, vice versa, a model displays the integration of distinct parts into a whole—'the larger picture'. In design research the purpose of a model is to explicate the process of designing or elements thereof from one or another standpoint'.

The discussions in the workshop highlighted a lack of clarity concerning theories and models. A major agreement emerged: it was felt that any proposal for a model or theory should be accompanied with its purpose (what it does) and context (where it applies)—its 'system boundary'.

## 1.5 Criteria to Satisfy to be Considered a Design Theory or Model

The authors in this book largely agree about the criteria that a theory or model should satisfy in order to be called a design theory or model of design.

A theory should 'refer to actual and existing phenomena' [29], Chap. 10, to 'real design processes at a level that is not trivially true for all processes' [28], Chap. 19, and 'contain a set of propositions to describe or explain some characteristics of (one or more facets of) designing (and design success)' [59], Chap. 15.

Its coverage should be broad: 'It must account for both the similarities and the differences between them, across products, companies and industries' [28], Chap. 19, 'provide a *broader* set of aspects of designing […] explaining communication in design as an activity by many individuals covering various possible *types* of *reasoning* in design (e.g. plausible reasoning), making sense of the *never complete* particular starting point of design, and providing *aesthetical* considerations in design' [46], Chap. 14, be as complete as possible [29], Chap. 10, have 'generativity, that is, the capacity to model creative reasoning and to relate to innovative engineering in all its aspects' and 'generality, i.e. 'the capacity to propose a common language on the design reasoning and design processes' [1], Chap. 11. Sonalkar et al. add that the 'perception–action dimension needs to be an integral part'. The perception–action dimension 'does not explain, but rather gives reflection of the theoretical constructs in situations relevant to practice'. This dimension 'accounts for the human agency in design' and lets 'the theory be rooted in situations relevant for professional practice'. This results in a 'much higher coupling between logical relationships and the situational relationships of constructs that design theory uses to explain phenomenon'.

As discussed in Sect. 1.4, a theory should be able to fulfil its purposes, that is, being able to describe, explain, predict. A theory should be as complete and logically consistent as possible [29], Chap. 10, empirically accurate [82], Chap. 2, based on testable hypotheses [34], Chap. 20, have clarity of explanation [46], Chap. 14, and be accessible by and meaningful to both researchers and practitioners (Sonalkar et al. [72], Chap. 3). For example, 'theories and models should be tools for practice' [46], Chap. 14, that lead to 'hypotheses on how designers should work [that] are the basis of the prescriptive part of design methodology' [7], Chap. 17, and indicate how design processes in industry can be influenced [28], Chap. 19. Weber [85], Chap. 16 points out that the usefulness of theories and models depends on the stakeholder: 'there may be different 'stakeholders' who pose requirements on models and theories of designs and designing', such as 'scientists, designers in practice, students, and tool/software developers'.

Finally, Koskela et al. [46], Chap. 14 add that a design theory should provide directions for further research. Some of the questions posed are: What is the core of a design theory? What is the scope of the phenomena of design? What are the main constructs that describe design?

Goldschmidt [35], Chap. 21 focuses on the criteria for a model: 'The criteria to be satisfied by a model include the presence of all essential components and links in the modelled process (or other phenomenon) and the possibility to extract any portion of it and develop it in more detail. Contraction and expansion must not undermine the integrity of the model, and the expectations from each level of detailing must be clearly defined'.

According to Maier et al. [54], Chap. 7 a good model should make it 'appropriate to enable design cognition and collaboration'. Note that they focus on models for use in design. 'The specific issues in determining the goodness of a model depends on the perspective: explanatory models should be able to accurately explain underlying mechanisms, predictive models should accurately predict patterns in observations. For a synthetic model it is 'not so much the goodness of fit, but rather the degree to which it enables decision-making that turns out to add value given a certain purpose and context'.

Lindemann [49], Chap. 6 includes models in design and models of design. He lists three important *characteristics* of models [73]: reduction (the model contains less attributes than the original), transformation (some attributes may have been modified or may have been additionally added, such as a coordinate system in CAD), and pragmatism (addressing purpose, users and time frame of usage), which influences reduction and transformation. He further refers to *conventions* to be considered during modelling and provides a first set of requirements for a model from [45]: *accuracy* (correspondence between original and model), *clarity* (how clear the purpose and limits are to the user), *relevance* (where is it relevant), *comparability* (can it be compared with original or with other models), *profitability* (what are the benefits of using the model), systematic *settings* (how to set up the model for using it).

From the discussions in the workshop, a strong consensus emerged across the teams in the criteria to be considered a theory or model of design: theories should be testable and refutable (i.e. falsifiable).

## 1.6 How Should a Theory or Model be Evaluated or Validated?

A design theory or model not only has to meet ‘the usual criteria of a descriptive science (e.g. truth, completeness, level of detail) but also the criteria of usefulness and timeliness’ [85], Chap. 16 ‘Usefulness needs testing’ [82], Chap. 2 and ‘should be the focus of the validation of methods, models and theories in design [as validation] is a process of building confidence in their usefulness’ Gero and Kannengiesser [33], Chap. 13. For Lindemann [49], Chap. 6 too, purpose plays the most significant role in validation of theories and models, but at the same time the purpose limits validity. Validity depends on stakeholders [85], Chap. 16.

Andreasen et al. [6], Chap. 9 see ‘two dimensions in a theory’s goodness, namely its range and productivity. Range is the breadth of related phenomena that the theory is able to describe based upon a shared set of concepts. The productivity of a theory shall be found in its suitability for teaching its applicability for designers’ practice and its utility for researchers to understand and analyse the phenomena of design’. Albers and Sadoswki [2], Chap. 8 also mention these criteria: the variety of problems and domains that can be addressed in industry and research, and the impact on education. Eckert and Stacey [28], Chap. 19 stress the importance to indicate where a theory applies when validating these: ‘Theories about the nature of design or how designing is done are typically presented with insufficient consideration of how much of designing they actually cover’.

For Andreasen et al. [6], Chap. 9 it is important ‘whether the theory lead to new theories or to new models and methods that can support design’. They see rigour ‘in the efforts to link a theory to design practice’. Similarly, Eckert and Stacey [28], Chap. 19 emphasise the role of validation in supporting the development of theory fragments into a more coherent theory of design by ‘comparing pieces of theory with the reality of particular design processes, and explaining failures to observe the phenomena the theory fragments predict either in terms of the falsification of the theory, or by elaborating the theory fragments to cover a wider range of causal factors and distinct situations’. That is, ‘developing design theory involves constructing pieces of theory, assessing their validity, assessing their limits of applicability, and progressively stitching them together to make a larger coherent whole’. Badke-Schaub and Eris [7], Chap. 17 add that evaluation and validation can extend the theoretical considerations or show that ‘existing theories in other domains (that were considered generic) did not always apply in the design domain’.

Referring to models, Lindemann [49], Chap. 6 distinguishes verification and validation: ‘Verification has to guarantee that all requirements are fulfilled in a correct way, and validation has to show that the purpose of the model will be fulfilled. Usability checks should ensure that the subject (the user of the model) will be able to use the model in a correct way’.

Vermaas [82], Chap. 2 argues for falsification rather than validation to address ‘two deficiencies that lower the scientific status of design research’: ‘the lack of generally accepted and efficient research methods for testing design theories and models', and a 'fragmentation in separate research strands'. He suggests naive Popperian falsification as a swifter way of testing, and sophisticated falsification as described by Lakatos to compare rival design theories and models'. The need to focus on falsification is mentioned by several other authors: a design theory should make falsifiable predictions [34], Goel and Helms, Chap. 20, a model or theory should be falsifiable rather than verifiable [85], Weber, Chap. 16, 'researchers need to infer hypotheses that test the theory by being amenable to falsification' (Sonalkar et al. [72], Chap. 3), and 'theory development should involve deliberate falsification of arguments' [28], Chap. 19. The development of the E-IMoD—the model of designing proposed by Ranjan et al. [59], Chap. 15 is a case of Lakatosian falsification, where extension of the scope of the model beyond conceptual design leads to the need for further elements in the model.

Ranjan et al. [59], Chap. 15 propose two ways to test propositions: first, using empirical data, and second, using 'logical consistency with other theories or models, that are already validated'. Vermaas [82], Chap. 2 emphasises that testing cannot be done independently of rival design theories and models.

Examples of *testing using empirical data* are given by various authors. Ranjan et al. [59], Chap. 15 use protocol analysis of existing protocols to identify whether all constructs of the model are present. Badke-Schaub and Eris [7], Chap. 17 could confirm and extend their theoretical considerations based on a qualitative analysis of the data gathered by interviews of professional designers from different disciplines. Goel and Helms [34], Chap. 20 mapped data from a large number of cases to an initial coding scheme from an earlier knowledge model and added new conceptual categories as they emerged from the data. Based on additional sets of data, the new model was refined and relationships added. This model was validated using a third data set. Gero and Kannengiesser [33], Chap. 13 validated the utility of their ontology both conceptually and empirically by using it to code hundreds of design protocols in various design disciplines and for various tasks, allowing comparison 'across protocols independent of the designers, the design task and all aspects of the design environment' and thus 'provide insight into designing'. The results imply 'that the FBS ontology provides a robust foundation for the development of a generic coding scheme. Cavallucci [21], Chap. 12 verified his IDM framework through case studies in industry in which he moderated the use of the framework by company experts. Albers and Wintergerst [2], Chap. 8 analysed the results of design projects of students who had received training in the approach as well as the results of the application of the approach in a variety of problems and domains.

Agogué and Kazakçi [1], Chap. 11 focus on *logical consistency with other theories and models* that are already validated when they speak about 'relatedness to contemporary knowledge and science (i.e. the capacity to relate to advances in all fields even when they seem far from the design community, such as mathematics or cognitive psychology: a design theory enables a dialogue that either benefits from or contributes to other disciplines)'. They compare data of CK-theory with a similar approach on the developments of axiomatic theory. They propose further ways of validating a theory: looking at the impact in practice, both in the own field and in other fields; using a theory to interpret or lead to a deeper understanding of existing models and methods, and as a framework to model very diverse issues. Koskela et al. [46], Chap. 14 evaluated the validity of the aristotelian proto-theory as a theory of design by looking whether its explicit and implicit features can be found in modern, corresponding ideas, concepts and methods. They also verified whether it provides an explanation of design. Weber [85], Chap. 16 confronted his own approach 'with a multitude of questions in order to fathom its limits or even find at least one falsification'.

From the discussions in the workshop, validation was found to have a spectrum of meanings, from checking for internal consistency, through truth, to utility. Testing the limits of a theory or a model was considered important and lead to a strong consensus on falsification as an approach.

Several challenges to validation were also identified: difficulty or lack of repeatability of phenomena, the large number of factors blurring clear and identifiably strong influences, difficulty of finding statistically large number of appropriate subjects or cases, and difficulty of generating reliable data about the phenomena under investigation. Furthermore, the lack of clarity of purpose and intended context of many theories and models (see Sect. 1.4.2) is considered a hindrance for proper validation.

## 1.7 Future Work

The various tasks ahead that were formulated by the authors clearly show that design research is still a rapidly developing field. Apart from tasks related to their own research programme, the authors in this book also propose more fundamental tasks for the research community that should contribute to the maturity of our field. These are:

### *1.7.1 Coverage*

- Agreeing on the boundaries of the phenomenon of design [46], Chap. 14.
- Acknowledging that engineering design is distinct from other forms of designing [29], Chap. 10.
- Learning from history as a fertile legacy for understanding design [46], Chap. 14.
- Developing genuine system adaptation, evolution, and reproduction theories [42], Chap. 5.
- Developing new system abstraction, modelling, prototyping, and testing theories [42], Chap. 5.

### 1.7.2 Concepts

- Clarifying the terminological problems [46], Chap. 14.
- Developing an ontology of key concepts to enable a clear distinction of concepts and how they can vary [28], Chap. 19.
- Developing irreducible foundational concepts of design and designing and ontologies as frameworks for the knowledge in the field of designing [33], Chap. 13.
- Compiling a common conceptual and theoretical core for the various design and production sciences, and develop associated ways of contextualizing it to specific situations [46], Chap. 14.
- Fusing heterogeneous bodies of disciplinary knowledge into a holistic body of trans-disciplinary knowledge (Horváth [42], Chap. 5).
- Linking different theories and models to cover multiple domains [85], Chap. 16.

### 1.7.3 Multiplicity

- Using different paradigms to provide different perspectives on design [34], Chap. 20.
- Explaining or predicting the differences and similarities that we observe when studying design processes across a range of product and domains [28], Chap. 19.
- Developing fundamentally different theories of design to engender fundamentally different methods and tools for design [21], Chap. 12.
- Development of a tradition to let design theories and models compete to avoid proliferation of theories and models [82], Chap. 2.
- Rationalising, consolidating and integrating the ideas behind the heterogeneity of models and methods [54], Chap. 7.
- Reducing the large number of different types of models and languages and to have them meet the requirements of usability and purpose orientation [49], Chap. 6.
- Developing an integrating framework of the several models that exist in parallel, each explaining certain aspects [85], Chap. 16.
- Reducing the fragmentation in separate research strands [82], Chap. 2.

### 1.7.4 Validation

- Differentiating between descriptive, prescriptive and demarcating aims of design theories [82], Chap. 2.
- Developing design theories that display scientific rigour while being useful to professionals [72], Chap. 3.
- Developing generally accepted and efficient research methods for testing design theories and models [82], Chap. 2.

- Testing design theories and models by naïve and sophisticated falsification for effective testing and for coherence of design theories and models, respectively [82], Chap. 2.

### 1.7.5 Impact

- Ensuring impact in academia and in empirical contexts by fulfilling three criteria: generality, generativity and relatedness [1], Chap. 11.
- Development of theories rooted in the pragmatics of professional practice by including a perception–action dimension in addition to the event-relationship dimension [72], Chap. 3.
- Addressing transfer to industry to reduce effort and risk of full implementation [85], Chap. 16.
- Developing methods or process models that allow guidance for different situations [54], Chap. 7.
- Using design theory as a framework for disciplines outside of design, whenever there is a need to model and understand creative reasoning [1], Chap. 11.

### 1.7.6 Presentation

- Presenting models explaining design with a clear statement of their purpose, their subject, and the time frame to help recognise the limits of its validity [49], Chap. 6.
- Presenting theories with sufficient consideration of how much of designing they actually cover [28], Chap. 19.

Many of the issues raised in the individual chapters, as reflected in the individual statements above, coalesced during the workshop into a number of major, common issues. One of these is the general lack of a common understanding that can act as the underlying basis for the discipline of design research. A need for an overview, or even consolidation, of research carried out so far has been strongly emphasised. As a discipline, we need good ‘demarcating theories’ that provide a clearer understanding of what constitutes (and what does not constitute) part of the phenomena of designing (e.g. designing is demarcated by intentionality), the different types of designs and designing that form our discipline; and position the models and theories with respect to these.

This base, it was suggested, might be initiated by including the following (see details in Appendix):

- The philosophies of the discipline, including what design means, and what the ‘phenomena of designing constitute’. ‘We need a philosophy of design, like a philosophy of science’.

- A list of 'demarcating theories' that provide an understanding of the different types of designs and designing that form our discipline.
- A list of models and theories of design, along with their context and purpose.
- A list of agreed upon concepts that are used within the discipline, including theory and model, along with their contexts and purpose.
- A list of agreed upon research methodologies and methods for use within the discipline, along with their contexts and purpose.
- A list of empirical results, along with their context and purpose.
- A list of influences of results of design research on practice.

Another major issue raised was the need to clarify the common purpose of design research, and to identify what the pressing, concrete questions are that the discipline needs to address. Also emphasised was the need for investigating the specific characteristics, benefits and complementarities across the various theories and models, rather than discussing only about which one might be superior.

Towards addressing the above, several suggestions were made in the workshop (see details in Appendix A):

- Have more events at various levels, e.g. students, researchers, educators, etc., to discuss these issues. Getting together is the first step to 'form the discipline'. Developers of theories and empirical results should interact more with one another.
- Like in other disciplines, teach the common understanding reached to those (intending to be) in this discipline. This knowledge should be taught in a context-specific manner, i.e. 'make explicit what is applicable in which specific situation'.
- Interact with other disciplines with similar goals, such as management, and learn from their perspectives.
- Carry out more empirical studies that are unbiased, of high value, high-quality, and are clearly explained, as we still do not understand in sufficient depth why design processes happen the way they do.
- Have 'grand debates' where specific models are discussed and contrasted together.
- Work more on developing research methods that are appropriate for serving the specific needs of design research. A major issue is: how to develop and validate testable, refutable theories and models of adequate accuracy within the constraints of complexity of the phenomena observed and within the limited availability of appropriate cases and subjects? A starting point can be to form Special Interest Groups (SIG) to work on these, e.g. on research methodology.

## 1.8 Conclusions

With each theoretical development new concepts and/or relationships between concepts were introduced, earlier ones revived, and existing definitions refined or modified so as to become coherent with the set of concepts covered by the new theory or model. This introduced new perspectives on design, allowed increased understanding, and resulted in richer models and theories of design, and of models and theories for design. These developments were fuelled by an increase in results from empirical studies, a desire to better understand and/or support design, an openness to look into existing theories in other fields, and the need to do so in the light of an (perceived) increased complexity of both the product and the process. The increasing complexity is a combination of reality and, foremost, of our perception: the richer models with their increased number of concepts and relationships allow us to see more (depth), and/or consider more (width). The latter has also been fuelled by a change of perception as to what influences design and what is influenced by design (e.g. taking into account users (user-centred design), environment (eco-design), services (product-service systems) and society (socio-technical systems)). Theories, models and their concepts co-evolve with our understanding of design (and with the development of design support), i.e. theoretical and empirical (and applied) research should go hand-in-hand.

Intensive debates and dialogues, increased, richer sets of empirical studies as a basis, testing using established means, as well as endeavours to develop new, appropriate research methods as enablers are required to ensure a gradual movement towards an established set of core concepts and their definitions (which may change over time as understanding progresses) and to 'progressively stitching them (the pieces of theory) together to make a larger coherent whole' [28], Chap. 19. Whether we are working on the same puzzle or multiple puzzles remains to be seen.

The chapters in this book show that the development of theories and models may in name be linked to one person, the 'originator', but is in fact a joint effort taking many years of generating and evaluating, of discussion and comparison, of modification and refinement, of creating and rejecting concepts and relationships, of criticism and support, and of including concepts and relationships of other theories also outside one's own field. Even though we did not manage to obtain a contribution from all researchers who developed a theory, we hope this book can further theoretical progress by bringing together a wide range of thoughts, approaches, assumptions, concepts, scopes and foci developed in our research community, and in doing so inspire readers and provide them with a broader basis for their own research.

## Appendix A: Summary of Discussions from the International Workshop on Models and Theories of Design

Discussions in the workshop, carried out primarily in three, parallel breakout sessions that continued through the days of the workshop, and culminated in a subsequent, common, final discussion session on the last day, focused on the four questions discussed below. This appendix provides a summary of the outcomes from these discussion sessions, which, we hope, will add to the richness of the knowledge already encapsulated in the individual chapters. As will be seen, while it is far from being conclusive, some major similarities in (lack of) understanding about theories and models, their purposes and criteria, and as to how they should be validated, have already began to emerge, and a number of common directions for further activity in this area have been proposed.

1. What is the distinction between a theory and a model?

*Team 1: Rapporteur: John Gero; Scribe: Sonal Keshwani*. The team took a broad approach of decomposition, and looked at the elements that constituted a model. A model was taken as a representation (i.e. away in which a language is used to describe something) of some observable phenomena. It had been noted that some phenomena may not be observable, and observation of phenomena may sometimes change the phenomena themselves. It was noted that the point of view of the observer plays an important role in what will be observed and how it will be interpreted: 'what you come up with is always limited by how you see the world and your output is evaluated by how the world looks at it'. All representations, it was felt, are limited, ideally by the purpose of the representation; hence, all models are also purposively limited. Models have generality and causality. Models project or predict, and can be used to explain. The team defined a theory to be an abstract representation of a generalisation of phenomena; a theory may have axioms that explain how a world behaves. Three views on the distinction between a model and a theory emerged: (i) a theory may be composed of multiple models; (ii) a model may be more concrete and specialised in its context than a theory, which is more abstract and general; (iii) a model may embed explanation of phenomena, while a theory may allow for such explanation. A theory may be represented by different models. There may be theory-driven and phenomena-driven models.

Overall, the team summarised its findings as follows. A model is a representation of some phenomena and relationships among these phenomena. With features that are operationalisable, a model provides some generality with respect to the phenomena, which can be causal, speculative and dynamic, and independent from theory. A theory is an abstract generalisation of phenomena, which can be modelled in multiple ways. Models, but not theories, can change with time. Phenomena are things that have regularity and are directly or indirectly observable, and are interpretable. A representation is an externalisation of a description of phenomena. Any representation leads to a reduction in some aspects of the phenomena and its granularity. What is represented is limited by the purpose or intention of the representation.

*Team 2: Rapporteur: Udo Lindemann; Scribe: S Harivardhini, Praveen Uchil*. The team distinguished between two types of models: research-based (driven by truth) and practice-based (driven by utility). The team raised the question: should models and theories in design be able to explain only (as in natural sciences) or should they also be useful, since the purpose of design research is to improve knowledge to improve design practice? The team also discussed what constituted goodness of a model, and argued that the goodness of a model depends on understanding of its system boundary, i.e. the context and purpose of the model. The team felt that there is an overlap in meaning between models and theories. A model may simulate a part of the world, but does not necessarily explain it. A model could be a subset of a theory, in that a theory provides explanation at a higher level than a model does.

*Team 3: Rapporteur: Lauri Koskela; Scribe: Boris Eisenbart*. The team distinguished between two types of models: models of design (i.e. of outcomes of design activity), and models of designing (of design activity). The latter is often used synonymously to theories of design. The team distinguished between a model and theory in the following. A model is an abstraction of reality created for a specific purpose, and the purpose includes representation of a theory; a model is helpful: it may serve multiple purposes and may be applied in multiple ways. A theory, on the other hand, may involve a number of hypotheses, each of which should be possible to be falsified. They recognised that describing something as a theory is sometimes a cultural issue; for instance, in some fields of research, less comprehensive approaches, frameworks etc. are called theories for the only reason that the term 'theory' added some kind of value to the proposition. The team recognised that while taxonomies are typically not considered theories in natural sciences, design research should consider theories as a spectrum with various levels of maturity in its context and purpose of use.

Overall, the team felt that a model and a theory have several aspects in common: both models and theories serve a (set of) specific purpose(s) that are useful for researchers and/or practitioners; both are explanatory in character which facilitates prediction and prescription. A goal of theories that is distinct from those of models is to provide an explanation of what design and designing mean within the context of use of the theory.

2. What is a model or a theory expected to describe, explain or predict? What criteria must it satisfy?

*Team 1: Rapporteur: John Gero; Scribe: Sonal Keshwani*. The purpose of a model is to transform something (e.g. produce an output given an input, which can form a prediction), to explain something. Explanatory power of the model comes from the result produced when using the model. A theory is a set of beliefs that are proposed as a generalisation of some phenomena, which are intended to give an explanation for the phenomena. Models have to be useful; theories have to be falsifiable. A model may help in prediction or exploration. A theory has to be testable/refutable. A model has to be usable in design, if this is a model for design. A theory cannot be evaluated directly, but can be evaluated only after its implementation. Theories contain rules and principles which together form their explanatory framework; this characteristic (i.e. of being constituted of rules and principles) is one of the criteria that a theory should satisfy.

*Team 2: Rapporteur: Udo Lindemann; Scribe: S Harivardhini, Praveen Uchil*. The team argued that a major distinction in the nature of phenomena dealt with between natural sciences and design research is that, design research focuses on design processes that are unique and operate within incomplete information and uncertainty. It is important to distinguish between different models in terms of their system boundary (i.e. scope of application) and their purpose. The purpose can be truth (in research) or utility (in practice). For a model to be good for truth, it should be true at least with the scope of its application. Goodness criteria for models for utility include: usability, ease of use, how quickly it can be used, system boundary, and limits of the model. Many theories and models are not used well in practice because it is hard for practitioners to understand the terms used in these theories and models. A theory or a model should be able to provide insight. A theory must be falsifiable.

*Team 3: Rapporteur: Lauri Koskela; Scribe: Boris Eisenbart*. The team felt that theories need to be useful: they can be curiosity-driven where the goal is to understand the nature and characteristics of objects, entities and their relationships, or problem-driven where the goal is to support practitioners and provide utility, or to support education. Understanding is necessary for predicting an outcome, and eventually prescribing how to perform design to achieve an expected outcome. Theories in design may be more probability-driven rather than being strictly causal, given the large number of influences, and may take the form of narratives rather than strict propositions. The team asked for whom theories are to be developed, and felt that these would be primarily for researchers or managers. The team discussed what phenomena a theory should address. While it noticed there may not be a single phenomenon of designing, there might be something fundamental to designing that every designer or design team does or shares, e.g. similar activities, aspects etc. appear across different design projects and disciplines. Overall, it was agreed that there are similarities and differences across designing in different contexts, and a theory of design should explain both similarities and differences across the contexts. It was strongly felt that 'We do not have a thorough understanding of all the assertions we make about designing. We ought to have theories about how to differentiate between different types of design'.

The team felt that phenomena of designing essentially refer to 'how design works'; various aspects (e.g. people, process, product, knowledge etc.) play a role in this, and therefore, designing may look very different as these aspects change. There are also many partial activities within designing (e.g. the work of an FEM engineer), i.e. there is 'designing within designing', which theories currently do not capture. Design processes are seen as a major aspect, and therefore, need to be comprehensively understood. Since human reasoning is an essential part of the phenomena of design, and since there is a variety of different kinds of reasoning that exist in design (e.g. logical, informal etc.), a theory should account for these differences and their influences.

Overall, the team argued that the criteria which a theory should satisfy is its amenability to validation and testing, where correspondence between what can be concluded from the theory and the phenomena it tries to explain are assessed. Another criterion is that a theory helps prediction which is useful; this can also be in the form of justification in a historical context. Theories are evolutionary rather than stationary. All assumptions underlying a theory should be made explicit, and one should be aware, as a researcher, about the process by which is a theory is developed.

3. How should a theory or model be evaluated or validated?

*Team 1: Rapporteur: John Gero; Scribe: Sonal Keshwani*. The team felt that all theories have to be falsifiable. The team defined evaluation as assessment of usefulness, and validation as assessment of consistency. It noted that a model that has so far always given correct results can still give incorrect results: theories are never tested to be true, but with more evidence, confidence in the theory grows. A model has to be validated (checked for internal consistencies) followed by evaluation (checked for usefulness). A difference between models and theories is that, ‘hypotheses are derived from theories, while hypotheses are derived from application of models’. A causal model is a network of hypotheses. In evaluating, one has to test each of these hypotheses. To evaluate a theory, one has to operationalise its hypotheses and test these.

Two aspects are critical to pay attention to, when discussing validation: the first is, what should be taken as true and false, and what the process of refutation is whereby truth and falsity should be adjudged. According to this team, validation involves application of the theory or model in design, checking for their internal and external consistencies, and checking them against other, already validated theories or models.

*Team 2: Rapporteur: Udo Lindemann; Scribe: S Harivardhini, Praveen Uchil*. Validation, the team argues, is about finding the limits of a theory. A major difficulty in validating theories and models of design is that, unlike much of natural sciences, being able to carry out repeatable experiments is hard to impossible. The team proposes that one way of validating a model or theory would be in terms of the level of reliability of the model or theory to achieve its purpose. The team proposed several ways of validation e.g. by comparative studies, by comparing and reducing gaps between research and practice models, by comparing multiple practice based models, or by referring to an existing theory which is already validated.

*Team 3: Rapporteur: Lauri Koskela; Scribe: Boris Eisenbart*. No design is ever repeatable; however for many areas of natural sciences too. There are various levels of variation across so called repeatable phenomena (e.g. the breaking stress of no two samples of the same material is exactly the same, the effect of the same medicine on no two people is exactly the same, etc.). If the discipline looks into a vast number of design projects in various fields, it might find the phenomena at some level of repeatability (as both material science and medical science already do by taking a statistically large set of samples or subjects). However, two distinct challenges for our discipline are: (i) comparable data in our discipline is currently missing, and (ii) such data is hard to generate. For instance, designers may not be aware of what they do during designing, or may distort certain aspects of their work (e.g. to hide failure, due to miscommunication, post facto rationalisation, forgetting, etc.).

A major issue in validation is that, while some researchers develop theories and others develop empirical results, the two rarely discuss their results with one another to bootstrap their work. A platform to support such discussion is necessary. Another issue is that, many empirical studies are carried out with students only; as a consequence, what can be learnt from these about design in practice is relatively limited. In these studies, and even more so for studies of practice, sample sizes are small due to lack of availability of subjects and constraints on time for detailed analyses. There is a strong need for developing appropriate design research methods to tackle these issues. Another issue is the lack of information of the contexts in which a theory of design is applicable. Given the complexity and variety of designing, it may be too ambitious to develop one theory of design; the community needs to develop many theories, each of which applies in a particular context for a particular purpose. These may then form the basis for developing more comprehensive theories. Another challenge is the difficulty of validating prescriptive theories in practice, e.g. asking practicing designers to change their thinking or process of designing may be hard. Validation need not be done only via practice, but also via teaching, training budding designers into preferred ways of thinking and processes of designing. A possible, new direction for validating theories is theory-driven prediction of new, hitherto non-existing, types of design or design fields.

**Overall conclusions about these three questions**

Regarding the definition of models and theories, two main points emerged. One is that the term ‘model’ has multiple meanings. In one meaning, models are used as a means to carry out design, e.g. a digital model of the product; we may call these models for design. In the other meaning, models describe, explain or predict how designs and designing are, and how aspects of these are related to various criteria that are of importance to practice, e.g. how designing relate to costs of designs. We may call these models of design.

The second point is that there is considerable overlap between the meanings of models of design and theories of design. A spectrum of meanings emerged, starting from having ‘no distinction in how these terms are currently used in our area’, to one where ‘Theory defines a framework from which multiple models could be derived’. A consensus emerged that there is need to understand ‘theory as a spectrum’, with terms such as taxonomies, models and theories having varying degrees of maturity in context, purpose and explanatory capacity.

The purpose of the need for understanding these terms was also discussed. It was felt that for a practitioner, it made no difference as to what these terms meant. However, for a discipline of research such as design, understanding of these terms is crucial, since this forms the basis for research. Overall, it was agreed that a clear understanding of the terms model and theory in the context of design research is necessary. It is also felt that any proposal for a model or theory should be accompanied with its purpose and context.

A strong consensus arrived at across the teams is in the criteria to be considered a theory: theories should be testable and refutable (i.e. falsifiable), and this should be possible to be carried out within the context and purpose of the theories, i.e. where it applies, and how well.

Validation was seen to be testing the limits of a theory or a model. Validation, too, emerged to have a spectrum of meanings, from testing for internal consistency, to truth and usefulness, in terms of providing explanation or insight in the form of predictions or post-dictions.

Several challenges to validation were identified: difficulty or lack of repeatability of phenomena, the large number of factors blurring clear and identifiably strong influences, difficulty of finding statistically large number of appropriate subjects or cases, and difficulty of generating reliable data about the phenomena under investigation.

4. What are Gaps in our Current Understanding and What are the Directions for Further Research?

Several directions emerged.

One major issue identified in the discussions is the general lack of a common understanding that can act as the underlying basis for the discipline. One symptom or a possible cause of this lack is the poor citing of each other's work in the discipline. A need for an overview, or even consolidation, of research carried out so far was strongly emphasised. As a discipline, we need good 'demarcating theories' that provide a clearer understanding of what constitutes (and what does not constitute) part of the phenomena of designing (e.g. designing is demarcated by intentionality), the different types of designs and designing that form our discipline; and position the models and theories with respect to these.

This base, it was suggested, might be initiated by including these:

- The philosophies of the discipline, including what design means, and what the 'phenomena of designing constitute'. 'We need a philosophy of design, like a philosophy of science'.
- A list of 'demarcating theories' that provide an understanding of the different types of designs and designing that form our discipline.
- A list of terms that are used within the discipline, including theory and model, along with their contexts and purpose.
- A list of research methodologies and methods within the discipline, along with their contexts and purpose.
- A list of empirical results, along with their context and purpose.
- A list of models and theories of design, along with their context and purpose.
- A list of influences of results of design research on practice.

Another major point was the need to clarify the common purpose of design research, and identify what the pressing, concrete questions are that the discipline needs to address. Also emphasised was the need for investigating the specific characteristics, benefits and complementarities across the various theories and models, rather than discussing only about which one among these.

A further major point was the challenge of validating theories of models of phenomena of design, which pointed to the need to develop research methods that are appropriate for scientific studies within the constraints and expectations of design research: how to develop and validate testable, refutable theories and models of adequate accuracy within the constraints of complexity of the phenomena observed and within the low availability of appropriate cases and subjects?

Towards addressing the above directions, several suggestions were made:

- Have more discussion events at various levels, e.g. students, researchers, educators, etc., to discuss these issues. Getting together is the first step to 'form the discipline'. Developers of theories and empirical results should interact more with one another.
- Like in other disciplines, teach the common understanding to those (intending to be) in this discipline. This knowledge should be taught in a context-specific manner, i.e. 'make explicit what is applicable in which specific situation'.
- Interact with other disciplines with similar goals, such as management, and learn from their perspectives.
- Carry out more empirical studies that are unbiased, of high value, high-quality, and are clearly explained, as we still do not understand in sufficient depth why design processes happen the way they do.
- Have 'grand debates' where specific models are discussed and contrasted together.
- Work more on developing research methods that are appropriate for serving the specific needs of design research. A starting point can be to propose Special Interest Groups (SIG) to work on these, e.g. on research methodology.

## Appendix B: Major Theories and Models not Contained in this Book

This appendix provides a summary of some of the major theories not contained in this book, but are necessary to point to for the sake of completeness. The summaries are not meant to be comprehensive, but only as a pointer to more detailed sources.

General Design Theory (GDT) was proposed by Yoshikawa [86] and later expanded by Tomiyama and Yoshikawa [79]. It is one of the first design theories at the knowledge level—a concept originally proposed by Newell [56] in the context of computational theories. GDT describes design as a transformation between two spaces—function and attribute, and discusses the nature of this transformation in relation to availability of complete and incomplete knowledge.

Axiomatic Design Theory was proposed by Suh and colleagues [74, 75]. It describes design as a transformation between functions and parameters, and argues that good designs can be described by two axioms: axiom of independence and axiom of information content. According to Axiomatic Design Theory, the less coupled the functions are in a design and the less information content the design has, the better it is.

Another Knowledge Level theory—$K^L D_0^E$—was proposed by Smithers [69, 70]. This theory was tested by the author on design of a new font that the author himself designed. $K^L D_0^E$ distinguishes six types of knowledge needed in design: 1. knowledge needed to form *requirements*, knowledge of the requirements descriptions actually developed, and their associated justifications; 2. knowledge of how to develop *well-formed problem descriptions* and knowledge of the well-formed problem descriptions developed and their justifications; knowledge needed to *solve well-formed problems*, and the knowledge of the solutions and justifications actually formed; 4. knowledge needed to analyse and evaluate problem solutions, knowledge of the *analyses and evaluations* actually performed together with their justifications; 5. knowledge needed to *form design descriptions*, and the knowledge of the actual design descriptions and justifications; 6. knowledge needed to *construct design presentations*, and the knowledge of the presentations actually formed and their justifications.

A quest for a Universal Design Theory (UDT) was made by Grabowski et al. [37, 53]. UDT is attempted to be a design theory containing findings and knowledge about design from different engineering disciplines in a consistent, coherent and compact form [52]. It is aimed at serving as a scientific basis for rationalizing interdisciplinary product development. The aim of UDT is to provide models of explanation and prediction of artefacts and away of designing them. The theory takes the 'process of design as the mapping of a set of requirements onto a set of design parameters' that constitute a design solution. The process is proposed to be carried out in by transition through four linked, abstraction levels: modelling requirements, modelling functions, modelling effective geometry, and embodiment design. A design solution is a specification of information sets associated with levels of functions, effective geometry, and embodiment. UDT proposes three axioms: the first states that there is a finite number of levels of abstraction; the second axiom states that the 'the set of well-known basic elements on each level of abstraction is finite at a certain point of time'; the third axiom states that 'the number of transitions between the different levels of abstraction is also finite'. Based on these axioms, the authors considered that 'Elements of a design theory…can only include the components currently known to us whereas the invention of new effects etc. has to be the concern of research work'. In line with this, they hypothesised the following: 'The invention of a product is always a new combination of known basic elements', and that 'Discovery, achieved through research, is defined as the finding of new basic elements'. In this sense, the scope the universal design theory is limited to those types of design where new designs can be seen only as a combination of old basic elements.

Based on the methodological framework used for the development of Grabowski's universal design theory [52], Lossack [50, 51] proposes the foundations of a Domain Independent Design Theory. The theory describes design knowledge, design process knowledge and system theoretical approaches for processing this knowledge system. The underlying concept consists of three elements: object patterns, process patterns and design working-spaces. Lossack emphasises that 'design is not a workflow […] workflows represent processes in a deterministic manner, whereas design is intrinsically indeterministic'. He therefore proposes an approach based on solution patterns to support indeterministic design processes, which include solution finding processes and creativity. A solution pattern is an aggregation of an object and a process pattern, although an object pattern can be used without process patterns. Object and process patterns describe design knowledge with which a mapping between properties of the design stages is defined. To define the design context, design working-spaces are introduced [36]. A design working space is a system (with elements, relationships and boundaries) which builds a framework to support the solution finding processes with object and process patterns. The approach is regarded to be general enough to support designing in mechanical, electrical and software engineering.

The theory of synthesis by Takeda et al. [76] focuses on the properties that the synthesis process should have as a thought process and propose a theory for synthesis. Knowledge for synthesis in design, they argue, 'needs physicality, unlikeness, and desirability'. Physicality ensures possibility of existence, while unlikeness and desirability ensure newness and value. The theory is based on the assumptions that a design process is an iterative logical process of abduction and deduction on design solutions, their properties and behaviours, and knowledge of objects. The synthesis theory for design is defined as a process of reconstruction of design experiences, where each experience contains a logical design process having three steps: 'collecting design experiences, building a model that includes the collected design experiences, and minimizing an element that designers want to find newness'.

Infused design [66] is an approach for 'establishing effective collaboration between designers from different engineering fields'. Infused design provides representation of the design problem at a mathematical meta-level that is common to all engineering disciplines. The problem solving is carried out by using mathematical terminology and tools that, due to generality, are common across design disciplines. The meta-level proposed consists of general discrete mathematical models termed combinatorial representations (CR). In particular, Infused design demonstrates 'how methods and solutions could be generated systematically from corresponding methods and solutions in other disciplines', and 'guarantees the correctness of results by relying on general ontology of systems that is embedded in the different representations'. Taura and Nagai [78], in their systematised theory of creative concept generation in design, proposed a theory on the thinking process at the 'very early stage of design', they define as the phase that 'includes the time just prior to or the precise beginning of the so-called conceptual design'. They segregate concept generation into two phases—the problem-driven phase and the inner sense-driven phase. They found that the concept generation process could be categorised into two types: first-order concept generation, which is related to the problem-driven phase, and high-order concept generation, which is related to the inner sense-driven phase.

## Appendix C: Overview of Theories, Models and Key Concepts Proposed by the Authors

As discussed in Sect. 1.3.5 some authors have proposed ontologies for the development of their theories and models, others have defined their main concepts but not yet put these together into an ontology. In this section, we summarise the proposed theories or models and the related key concepts. What is immediately visible is the differences in concepts used, as well as the difference in their number. Some overlap in key concepts exists. As expected, this is the case where a theory or model has been built on other theories and models. The differences suggest that the phenomenon of design is (as yet) too large, or maybe its boundaries not fixed enough, to be treated as a whole, as also suggested by Eckert and Stacey [28], Chap. 19.

Agogué and Kazakçi [1], Chap. 11: Concept-Knowledge-theory of C–K theory, a theory of creative design reasoning.

Key concepts: K-space, C-space, logical status, properties, restrictive and expensive partitions, co-evolution of C- and K-spaces through operators (conjunction, disjunction, expansion by partition/inclusion, expansion by deduction/experiments), d-ontologies, generic expansion, object revision, preservation of meaning, K-reordering.

Albers and Wintergerst [2], Chap. 8: Contact and Channel (C&C) Model and Approach to integrate functions and physical structure of a product in a shared representation using product models that are widely spread in practice.

Key concepts: Channel and support structures, working surface pairs, connectors, Wirk-Net, Wirk-structure, operation mode, input parameter characteristic, environmental conditions system state property.

Andreasen et al. [6], Chap. 9: Domain Theory as a systems approach for the analysis and synthesis of products.

Key concepts: Activity, organ, part, structure, elements, behaviour and function, state, property, characteristic, technical activity, need, operands, effects, surroundings, use function, wirk function transformation.

Badke-Schaub and Eris [7], Chap. 17: Understanding the role intuitive processes play in the thinking and acting of designers, to inform their Human Behaviour in Design (HBiD) framework which aims to understand the complex interplay between the designer, the design process, design output, and the related patterns and networks of influencing variable.

Key concepts: Intuition (physical, emotional, mental and spiritual), un/subconsciousness, reasoning.

Cavallucci [21], Chap. 12: Inventive Design Method based on and an extension of TRIZ theory, to rapidly arrive at a reasonable number of inventive solution concepts to evolve a complex initial situation that is currently unsatisfactory.

Key concepts: Contradiction (administrative, technical, physical), problem, partial solution, action parameter, evaluation parameter.

Culley [24], Chap. 18: An information-driven, rather than task-driven, design process to manage and control design activity.

Key concepts: 'Information as thing', knowledge (embedded, encoded, encultured, embrained, embodied).

Eckert and Stacey [28], Chap. 19: Identifying the causal drivers of design behaviour as a first step to generate partial theories of design.

Key concepts: Constraints (problem, process, solutions and meeting constraints), causal drivers (characteristics of classes of products or processes, conditions in which they are created), and requirements.

Eder [29], Chap. 10: Theory of Technical Systems and an engineering design methodology based on this theory.

Key concepts: Transformation process (operands and related states, effects, operators, technology, assisting inputs, secondary inputs and secondary outputs, active and reactive environment) and Technical System (function, organ, organ connector, constructional parts and their relationships: functional structure, constructional structure), life cycle of a technical system (a sequence of transformation systems), properties of transformation processes and technical systems (observable, mediating, elemental) and their related states.

Gero and Kannengiesser [33], Chap. 13: The Function-behaviour-structure (FBS) ontology to describe all designed things, irrespective of design domain, the FBS and the situated FBS (sFBS) frameworks to represent the process of designing, and its situatedness, respectively, irrespectively of the specific domain or methods used.

Key concepts: Function, behaviour (expected, derived from structure), situatedness (interactions between external, expected and interpreted world), interaction (interpretation, focussing, action), function, requirements, structure, design description, transformation (formulation, synthesis, analysis, evaluation, documentation, reformulation types 1–3), comparison.

Goel and Helms [34], Chap. 20: A knowledge model of design problems called SR.BID, derived from the Structure-Behaviour-Function knowledge model, and grounded in empirical data about biologically inspired design practice to capture problem descriptions more deeply than with the SBF knowledge model.

Key concepts: Function, performance criteria, solution, deficiencies/benefits, constraints/specification, and operating environment, structure, behaviour and function.

Goldschmidt [35], Chap. 21: A model of the role of sketching in the early, search phase of design.

Key concepts: Problem, search space, internal and external representations, rapid sketch, cognitive benefits and affordances (time effective/fluent, minimal cognitive resources, minimally rule-bound, transformable/reversible, tolerant to incompletion, tolerant to inaccuracy/lack of scale, provides unexpected cues).

Koskelaet al. [46], Chap. 14: The first theory—proto-theory—of design proposed by Aristotle based on the claim that design is similar or analogous to geometric analysis.

Key concepts: Analysis (theoretical and problematical), synthesis, deliberation, science of production, causes (efficient, formal, material and final), types of reasoning (regressive, transformational, decompositional or configurational).

Lindemann [49], Chap. 6: Definition and nature of the variety of models used for design, discussion on quality and requirements for modelling based on important characteristics like transformation and reduction, purpose and subject, and nature of the process of modelling.

Key concepts: Transformation, reduction, pragmatism (purpose, users, time frame), modelling conventions (accuracy, clearness, profitability, relevance, comparability, systematic settings), process of modelling (intention, modelling, validation, usage).

Maier et al. [54], Chap. 7: A cybernetic systems perspective to understand designing as a self-regulated modelling system, i.e. to consider the synthetic role of models in designing.

Key concepts: Sensoring, actuating.

Ranjan et al. [59], Chap. 15: Integrated Model of Designing' (IMoD) for describing task clarification and conceptual design, and for explaining how various characteristics of these stages relate to one another, by combining different views (or models).

Key concepts: Activity view (generate, evaluate, modify, select), outcome view (phenomenon, state change, effect, input, action, organ, part, other), requirement-solution view (requirement, solution, associated-information), and system-environment view (relationships, elements, subsystem, system and environment).

Sonalkar et al. ([72], Chap. 3): Two-dimensional structure for design theory: describing the theoretical constructs and relationships between them, and providing the perceptual field and action repertoire that makes a theory relevant in situations of professional practice.

Key concepts: Perceptual field, action repertoire, event, relationship,

Taura [77], Chap. 4: A framework composed of the Pre-Design, Design, and Post-Design stages is introduced to allow the explicit capture of the *motive of design*, as an underlying reason for the design of highly advanced products, that links the Post-Design and Pre-Design stages.

Key concepts: Pre-Design, Design, Post-Design, deductive, inductive and abductive processes, personal/social motive, inner/outer motive, need, problem, personal inner sense, inner criteria, function (visible/latent), force of a product, standard, field (physical/scenic/semantic; visible/latent).

Weber [85], Chap. 16: The CPM/PDD approach to modelling products and product development based on characteristics and properties (CPM: Characteristics-Properties Modelling, PDD: Property-Driven Development).

Key concepts: Characteristics, properties (current, desired), relations, external conditions, analysis, synthesis, solution elements/patterns.

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