Chapter 2
Design Theories, Models and Their Testing: On the Scientific Status of Design Research

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2.1 Introduction

In design research there is a general concern about the scientific status of the discipline. Design research is about observing existing and created design practices, about formulating design theories and models for describing and improving design practices, and about evaluating these design theories and models. As such design research is just like any other scientific endeavour: it has a domain, aims and research methods and it has results. Yet there is this concern that design research does not live up to the standards of science: it is creating in a sense too many theories and models, which jeopardises the coherence of the discipline and which indicates that design research does not yet have the means to test and refute design theories and models.

In this chapter I address this concern about the scientific status of design research using the resources of philosophy of natural science. First, I describe in Sects. 2.2 and 2.3 how scientific theories and models are understood in philosophy. It is analysed to what extent design theories and models of design can be taken as scientific, using a typology that groups design theories and models by their descriptive, demarcating and prescriptive aims. Second, I focus in Sects. 2.4 to 2.6 on testing. Testing design theories and models is in design research generally taken as validation, and I argue that this perspective may be one of the roots of the lack of effective testing and of coherence in design research. Philosophy of science provides more means for testing theories and models. Falsification is another possibility and I argue, using Lakatos' work, that falsification may give design research means for arriving at effective testing and coherence of design theories and models.

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Philosophy is a rich and multifaceted source for understanding scientific theories and models, and their testing. This chapter contains a selection of this material, primarily from earlier philosophical work on the natural sciences. This selection is motivated by my aim to address concerns about the scientific status of design research. I start from a fairly traditional characterisation of what a scientific theory is, for showing that design theories can be taken as scientific, even in this traditional sense. The chapter contains a more extensive survey of what scientific models are, for showing that also models of design practices can be taken as scientific. Finally it introduces work on falsification, specifically by Lakatos, for arguing that design research can arrive at effective research methods for testing design theories and models that also strengthen the coherence of the discipline. This perspective on design research is however not meant as a claim that design research should be similar to research in the natural sciences, or that design practices are natural phenomena. The differences are obvious, as is described in the next section: design theories can, for instance, be prescriptive and define novel design practices. Other perspectives on design research are possible as well, say approaching it as a social science or taking it a *sui generis* discipline. Yet, the upshot of this chapter is that already by a more traditional perspective, design research can meet the standards of science.

A second caveat is about the term design. It may refer to the practice of designing or to the outcome of that practice; design theories and models may therefore be about design practices, about the outcomes or about both. In this chapter I understand the term as referring to design practices, and consider only theories and models about these practices. These theories and models can also describe the outcomes of those practices—it may be hard to capture a practice while avoiding saying something about its outcomes—yet I do not consider theories and models about only the outcomes of design practices. Such theories and models may exist, but belong to the classification and metaphysics of technical products.

2.2 Scientific Theory and Design Theories

The characterisation of a scientific theory that I adopt is a handbook description given by Ruse [1] in the *Oxford Companion to Philosophy*:

> 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.

When this description is taken as part of a definition of what a scientific theory is, then a design theory, when taken as a scientific theory, is an attempt to systematically bind together the knowledge we have of experiences of design practices. There is an aspect of the world of experience that we take as consisting of design practices. We conceptualise and describe our experiences of these design practices in terms of, say, actions or reasoning processes by agents, called designers, where the actions or reasoning involve material objects, information, economic funds, technical and cognitive tools, and so on. We develop criteria to evaluate design practices, for instance, as successful or not, as efficient or not or as innovative or not. We have knowledge of design practices in the form of, say, observed regularities between the actions or reasoning of designers in design practices, and the success and efficiency of these practices. Finally we arrive at a design theory of design practices by attempting to systematically binding that knowledge together. We then understand that aspect of the world and can explain design practices and generate predictions about them. We can, for instance, categorise design practices in types, and predict that future design practices of some type are more successful or more innovative than future design practices of another type.

This way of describing design theories may cover some design theories, yet seems not to fully capture the aims of design theories as developed in design research. One reason for this is that in design research there is no full consensus about what is to be taken as design practices. Some design theories can therefore also be aimed at fixing what aspect of the world of experience is to be taken as design practices. Other design theories can advance as designs altogether new practices of which we do not have experiences yet. Especially the latter possibility is relevant to design research since new types of design practices may be advanced as more successful, more efficient or more innovative than existing types. For bringing also those design theories into focus, I introduce a typology of design theories by means of their aims.

Descriptive design theories. Call a design theory *descriptive* if its aims include describing design practices that are regularly taken as design, say engineering and architectural design practices of existing types. If a descriptive design theory binds together our knowledge of these regular design practices, and arrives at understanding, explanation and prediction of and about them, it is a scientific theory by the given definition.

Demarcating design theories. Call a design theory *demarcating* if its aims include fixing the borders of what is to be taken as design practices, say by also taking developing courses of action as designing [2], or by ruling out that searches among off-the-shelf solutions are design practices [3]. If defining what is to be taken as design practices is the sole aim, then a demarcating design theory is not a scientific theory as defined. But if a demarcating theory is also binding together our knowledge of our experiences with design as demarcated, and providing understanding, explanation and prediction of and about these design practices, then it is a scientific theory by the given definition.

Prescriptive design theories. Call, finally, a design theory *prescriptive* if its aims include singling out particular types of design practices and positing favourable properties about these practices. These particular types of design practices may be types that already exist and are regularly taken as design practices, say when design as described by Pahl and Beitz et al. [4] is proposed as efficient. But the prescribed types of design practices may also be new ones, say, types of design practices that did not yet exist but are proposed to improve sustainability (e.g., [5]). A prescriptive design theory is a scientific theory as defined if it singles out types of design practices that already exist and if it binds together our knowledge about these practices, arriving at understanding, explanation and prediction; in fact, the claim that the singled out design practices possess the favourable properties, may be taken to be knowledge or prediction about these design practice. If, however, a prescriptive design theory singles out new types of design practices, the assessment whether it may be a scientific theory becomes more involved. One may take such a prescriptive design theory as a scientific theory as defined by arguing that the favourable properties it posits are predictions about design practices. Yet they are not predictions about practices that already exist; they are predictions about designs of types that are defined by the theory and that are not yet part of the world of experience. At best one could take a prescriptive design theory that defines new types of designs and posits favourable properties for them as a *hypothetical* scientific theory: it puts forward claims of the form "*if* design practices of the new type were an aspect of the world of experience, *then* the claim that they have the posited favourable properties is part of the knowledge about that aspect of the world of experience."

The design theories that are generated in design research are typically not pure descriptive, demarcating or prescriptive theories; they are amalgams. First, a regular approach to arrive at a design theory is by analysing a specific set of actual design practices, *describe* the structure of the actions or reasoning in these practices, and they *prescribe* this structure for novel design practices. For instance, the way expert designers have proceeded in successful design projects is described, and then as a design method or strategy prescribed to other designers, the prediction being that the favourable properties of successful expert projects are by mimicking also realisable by non-expert designers (e.g., [6, 7]). Second, a design theory that prescribes new types of design is demarcating as well, since it advances those new types of design as design practices whereas they were not yet taken as design practices. Third, a prescriptive theory becomes also descriptive when the tool is adopted. Say QFD [8] may have been a pure prescriptive design theory at the time it was introduced, as it was proposing a new reasoning scheme for design and thus defining new design practices. By being adopted QFD describes today practices that are regularly taken as design, making it also a descriptive theory. Finally, a demarcating design theory can be descriptive as well. C-K theory [9], for instance, describes both practices that are regularly taken as design practices, and practices that are not regularly taken as cases of design.

Not all amalgams of description, demarcation and prescription are possible. For instance, a design theory that describes or prescribes a particular type of design practice but by its demarcation does not acknowledge this practice as design, is contradictory. In [10] a more systematic analysis of possible and impossible amalgams is given.

The distinctions between descriptive, demarcating and prescriptive design theories are relevant to the question of whether design theories are scientific theories as defined. Descriptive design theories are reasonably candidate scientific theories, since the step from describing design practices in terms of processes of actions and reasoning, to knowledge, understanding, explanation and prediction of and about these processes seems rather feasible. Demarcating design theories need not be scientific theories since they may merely define what is to be taken as design. Prescriptive design theories may be scientific theories but need not be so. Design methods and tools are, for instance, all prescriptive design theories, since they all single out particular types of design practices and posit favourable properties about them. From a practical point of view, this singling out of preferred design practices may be sufficient. Yet, for counting as a scientific theory, a design method should minimally add understanding and explanation to the prediction that the singled out design practices have the posited properties. In Sect. 2.5 I argue that these distinctions are also relevant for the testing of design theories. For instance, the possibility to test demarcating design theories depends on the character of the definition of design practices these theories are advancing.

2.3 Scientific Models and Models of Design

A general description of what a scientific model is and of what a model is aimed at, is not so easily found in philosophy. Scientific models come in different types and have various aims. Taking my cue from [11], the following types of entities can be scientific models.

Physical objects. Scientific models can be physical objects, such as technical scale models of ships and buildings, Eisinga's orrery of the solar system and the sticks-and-balls model of DNA by Watson and Crick.

Fictional objects. Scientific models can be fictional objects in the mind, such as frictionless pendulums, the Carnot model of a heat-engine and the model of a rational agent in economics.

Set-theoretical structures. Scientific models can be set-theoretical structures consisting of a set of entities, operations on the entities and relations between the entities, where these entities can represent, for instance, numbers, probabilities or data as in database design.

Descriptions. Scientific models can be linguistic descriptions of objects, of systems, of practices and of experimental phenomena.

Equations. Scientific models can consist of equations, such as $F_x = -kx$ for the harmonic oscillator.

Models in science are generally taken to have the aim of representing something else, where there can be differences between what is represented and how strict the representation is.

First, a model is taken as representing features of a target system in the world. The scale models of ships or buildings are representing those ships and buildings, and these representations concern some but typically not all features of the target system: the dimensions of the ships and buildings are represented, but not, say, their material constitution. Models can represent target systems moreover in an idealised way. Orreries represent the movements of the planets around the Sun, and do so in an idealised way, say, by ignoring the gravitational influences of the various moons in the solar system. The idealisation part of models can even be such that the target system is at best an imaginary system. The Carnot model of the heat-engine [12] and the model of the rational agent in economics are not models that represent systems in the world, but are at best non-existing idealisations of them.

Second, and in addition to representing target systems, a model can represent a scientific theory. Orreries represent the movements of the planets in the solar system *and* represent Newtonian physics by being cases that comply with Newtonian physics; they are models of the solar system and of Newtonian physics.

The value of scientific models is not only that they represent target systems or scientific theories; they also have epistemic value. The creation of models, their analysis and their development, allow scientists to understand the target systems and the theories represented. With physical models such as scale models, knowledge about the target systems and theories can be collected by carrying out tests on the models in laboratories or in the field. With models consisting of fictional objects or of equations, such knowledge can be collected by derivation or computer simulation.

In philosophy there are two competing positions about the relationship between the aims of scientific models to represent and to have epistemic value, and here I take my cue from [12]. By the *semantic position* on models, the representation of target systems and of theories is the immediate aim of scientific models, and are the epistemic advantages secondary and due to this representation. By the *pragmatist position* on models, having epistemic value is an immediate aim of scientific models as well, and is the way in which models represent target systems and theories dependent on their epistemic value. The epistemic values of models may even compete with their aim to represent. The idealisations made in scientific models such as the Carnot model of the heat-engine and the rational agent model are useful for acquiring knowledge about thermodynamics and economics, yet are detrimental to the accuracy by which these models are representing real target systems in the world.

There are three general views in philosophy about how scientific models are related to scientific theories. In the first *syntactic view* scientific theories are taken as formal and axiomatised sets of sentences, and models of theories are then taken as providing rules for interpreting the terms and sentences of the theory they represent. An orrery is by this view not a model of Newtonian physics, since as a physical object it does not explicitly give an interpretation of terms of Newtonian physics as physical properties of the Sun and the planets. In the second *semantic view* a scientific theory is seen as a set of models, in particular of the more abstract types such as set-theoretic models. All theoretical models of Newtonian physics define together the contents of Newtonian physics, making the formulation of a formal and axiomatised set of formal sentences capturing all these models a possibly interesting but eventually unnecessary affair. Orreries as physical objects are by this second view probably still not models of Newtonian physics, but only so if it is added how they represent the physical properties of the Sun and the planets. In the third view, associated with [13], the link between models and theories is weakened. In this view models are not taken as closely representing the content of theories, but seen as means to understand that content. And in line with the pragmatist position that models have epistemic values as well, models allow this understanding of scientific theories by introducing elements that are not part of these theories. Models add, for instance, real and imaginary cases to theories, and introduce idealisations. Orreries are by this final view models that are not derivable from Newtonian physics but still means that enable us to understand this theory.

In design models are used for various reasons. Models are used to represent the investigated or final outcomes of design practices, to represent the objects, theories and data employed in finding these outcomes, and to represent the design practices themselves. These models in design typically count as scientific by being of the types of scientific models described above, as is illustrated by scale models and the Carnot model of a heat-engine. Given all the types of scientific models discerned, and given the different philosophical positions about their aims and relation to theory, a full discussion of design models will easily diverge into extensive classification and commentary. Yet when considering only models used in design research for representing design practices, the discussion becomes again focussed and of use to an analysis of the testing of the results of design research (see [14], Part IV) for broader discussions of models in engineering and design).

A discussion of the aims of models of design practices in design research reiterates much of the above discussion of the aims of scientific models.

First, abstracted descriptions of actual design as given in design research (e.g., [15]) may be taken as models that primarily aim at representing design practices in the world, that is, as models that are relatively independent of design theory. Diagrams of design practices as they are often given in design research, ranging from the VDI [16] flowcharts for activities in engineering design, to the reasoning schemes of design thinking (e.g., [17]), are not straightforwardly models. Diagrams are in philosophy not seen as models themselves but as means to express models ([18], p. 2). Accepting this point, diagrams of design practices are minimally expressions of models aimed at representing these design practices.

Second, diagrams and descriptions of design practices as advanced in design theories (e.g., [9, 19]) may be taken as (expressions of) models aimed at representing design practices and at representing the design theories concerned.

Finally, diagrams of design practices as advanced in more prescriptive design theories (e.g., [6, 17]) may be taken as expressing models that also have the epistemic value of making clear to designers how to improve on their design practices. And given the often made observation that actual design practices are typically more complex than the prescribed flow charts and reasoning schemes, these diagrams are typically expressions of models representing idealised design practices. So, in line with the pragmatist position on models, the epistemic value of design models of making clear how to improve on design practices may overrule their aim of representing design practices in the world.

There are design theories that strive toward formalisation and axiomatisation (e.g., [19, 20]), yet typically design theories are not meeting the logico-philosophical ideal of being formulated as axiomatised sets of formal sentences. The syntactic view on the relation between models and theory seems therefore not plausible for most design theories; at best the semantic view can be adopted, meaning that the models of design practices as advanced by a design theory together define the content of the design theory.

In the previous section, I took distance from understanding all types of design theories as scientific theories. Design theories can have descriptive, demarcating and prescriptive aims, and specifically demarcating and prescriptive design theories did not straightforwardly fit the characterisation of scientific theories. 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.

Models representing actual design practices and models representing a descriptive design theory may be taken as *descriptive models* of design, meaning that they are models with the aim of representing practices that are regularly taken as design. The abstracted descriptions of actual design practices as given in, e.g., [15] may be taken as such descriptive models, and they are scientific models of the type *descriptions*. Design diagrams aimed at capturing actual design practices are expressions of descriptive models, which are also scientific; the diagrams are expressions of scientific models of the types *fictional objects*, *descriptions*, or maybe even *set-theoretical structures*.

Models that represent an aspect of the world that is to be understood as design practices and models that represent a demarcating design theory, may be taken as *demarcating models* of design, meaning that they have the aim of representing practices that are to be taken as design practices. The diagrams and characterisations of design practices as advanced in C-K theory [9] may be seen as, in part, (expressions of) demarcating models, and they are scientific models of the types *fictional objects*, *descriptions*, or *set-theoretical structures*.

Finally, models representing real or imaginary design practices with favourable properties and models representing a prescriptive design theory, may be taken as *prescriptive models*, meaning that they are models for singling out design practices for having those favourable properties. The diagrams of design practices as advanced by Lawson and Dorst [6] are expressing such prescriptive models, and these models are scientific models of the types *fictional objects* or *descriptions*.

Again, models of design practices can be amalgams. The models of C-K theory [9] are both demarcating and descriptive, and the models by Lawson and Dorst [6] are both descriptive of particular expert design practices and prescriptive to other design practices. And, again, not all amalgams are possible. Models can represent cognitive processes as they take place in the mind of designers, and models can represent more rationalised cognitive processes of thinking in design practices [21]. A prescriptive model may by its pragmatic aim of characterising favourable design practices represent the thinking of designers in this more rationalised way, which blocks the possibility that this model can also have the aim to represent the way actual designers think during design practices.

2.4 Testing Design Theories and Models by Validation

Design theories and models of design advance a diversity of claims about design practices: they describe and demarcate design practices, and they prescribe design practices as having favourable properties. For evaluating design theories and model these claims are to be tested for determining the empirical accuracy and practical usefulness of the design theories and models. For instance, descriptive design theories aim at describing actual design practices, and are to be tested on whether they give accurate descriptions of these practices. And prescriptive models aim at representing design practices that have specific favourable properties, and are to be tested to determine whether these practices indeed have the posited properties. (In the next section it is more systematically discussed how to test descriptive, demarcating and prescriptive design theories and models.) In philosophy of science different approaches to testing theories have been advanced and criticised, and for the discussion in this chapter it is relevant to distinguish two rather opposite approaches. The first is testing a theory by *falsification* and consists of tests of individual observational statements derived from the theory. If such a test yields that the statement does not hold, the theory is refuted. And if the test confirms the statement, the theory is corroborated and accepted provisionally, since a new test may in the future still refute the theory. The second approach is testing a theory by *validation* and consists of tests of all (main) observational statements derivable from the theory. If one such test yields that a particular statement does not hold, the theory is refuted. If the tests confirm all statements, the theory is accepted. And as long as the tests are not yet all done, it remains open whether the theory can be accepted. In design research, as will be illustrated in this section, testing is typically taken as validation, whereas, as I will argue, testing by falsification may improve the scientific status of design research.

Design research may have known periods in which more theoretical work was done and testing was less prominent. But certainly today it is saturated by empirical studies in which design theories and models are discussed in close connection to analyses of actual design cases, to outcomes of design experiments and to statistical data gathered about design experiences in industry and academia. Yet, despite this ongoing empirical focus there is in design research a general concern about the quality of the testing of design theories and models. In work reflecting on the results that design research has produced, it is complained that generally accepted and effective research methods for testing design theories and models are lacking in design research, and that the discipline is fragmented in separate research strands (e.g., [22–25]). Hence, efforts are made in design research for strengthening testing (e.g., [23, 26, 27]), for arriving at coherence, and for thus improving the scientific rigour of the discipline.

When considering design research from a philosophical perspective it can be argued that the two complaints of weak testing methodology and fragmentation may have a common root in the very assumption that testing of design theories and models is taken as validation. First, by understanding this testing as validation it is assumed that all claims of design theories and models should be confirmed by empirical observation or other means. This assumption makes testing quite open-ended and rather difficult (e.g., [24, 26]). Prescriptive design theories, for instance, are ultimately meant to improve design practices in industry. Testing of design theories that posit that particular design practices lead to innovative products (e.g., [7, 28]), then requires years-long experiments in which sufficiently large numbers of engineering firms abandon their established design practices in favour of the prescribed practices, and in which relevant contextual factors like international economic growth and the behaviour of competitor firms are kept controlled. Given the unrealistic nature of such experiments, it seems not surprising that design research does not yet have effective research methods to carry them out.

Second, by understanding testing of a design theory or model as validation, it is suggested that this testing can be done independently of rival design theories and models. The claims of a design theory or model are to be confirmed as stand-alone claims or, in the case of a prescriptive theory or model, at best as claims relative to some design-practice benchmark; the claims of the tested design theory or model need, however, not be compared to the claims of rival design theories or models. By this suggestion design research arrives at series of stand-alone evaluations of individual design theories and models, supporting that design research indeed develops in separate research strands associated with these theories and models.

These arguments are not directed against testing design theories and models by validation; they are rather meant to provide room to taking this testing not only as validation. In the next section I drop the assumption that testing means confirming all claims of design theories and models, and consider swifter testing of design theories and models by falsification in a Popperian [29] manner. In Sect. 2.6 I also drop the suggestion that design theories and models should be assessed in isolation by discussing sophisticated forms of falsification as proposed by Lakatos [30] by which rival design theories and models are compared. Considering testing by falsification may seem a spurious return to what has already been discarded in philosophy of science. Yet, it can be shown that current work in design research on testing design theories and models by validation contains ample points of contact with also testing them by falsification.

A first example of a design research method for testing design theories and models is the validation research method developed and brought together by Blessing and Chakrabarti [23]. This research method, called DRM (Design Research Methodology) is aimed at helping design researchers at formulating and validating theories and models for understanding design and for supporting improvements. In terms of the terminology used in this chapter, DRM is a research

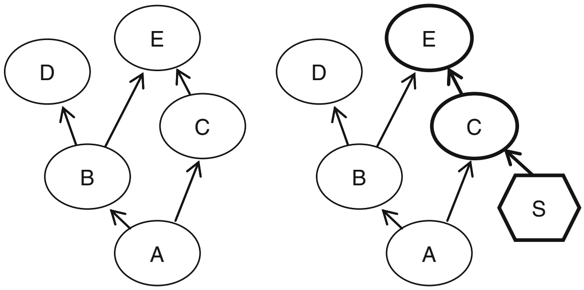

Fig. 2.1 Examples of a reference model (*left*) and an impact model (*right*) in DRM; the hexagonal node in the impact model represents the added support S and the *bold arrows* and nodes represent the causal chain leading to the improvement of E

method for formulating and validating descriptive and prescriptive design theories and models.

Abstracting from the many elements and subtleties, DRM consists of four stages: clarification, description of current design practices, formulation of the planned improvements, and testing of these improvements.[1] In these stages two models play a central role: the *reference model* and the *impact model*. Both these models are *networks of influencing factors*, containing nodes that represent factors, being aspects of design that influence other aspects of design, and containing arrows that represent how the factors causally influence each other (see Fig. 2.1). The reference model is representing the existing situation in design and acts as a benchmark to the improvements. The impact model represents the desired situation and adds the planned support for creating the improvements as an additional factor relative to the reference model.

The description of the causal influences in the reference model should be confirmed by a thorough literature study (which is one of the ways in which Blessing and Chakrabarti aim to overcome fragmentation; researchers are by DRM required to study the literature from all design research strands). And when information about influences between factors is lacking, this information should be created by empirical research. The supporting factor that is added to the impact model is meant to change one or more (downstream) factors in the reference model, and then to improve other (upstream) factors by means of the causal influences given in the reference model. This improvement may however not merely be assumed on the basis of the causal influences part of the reference model, but should be confirmed by separate empirical research.

A second example is the research method proposed by Seeparsad et al. [27] for validating design methods by means of a *validation square*. By this proposal a design method is taken as constituted by *constructs*, which are loosely speaking the building blocks of the method, and as aimed at resolving design problems of a specific class. Yet, by the proposed research method a design method is not tested

[1] In DRM these stages are called, respectively, *Research Clarification*, *Descriptive Study I*, *Prescriptive Study* and *Descriptive Study II*. These stages comprise more tasks than described here; in the Descriptive Study II-stage, for instance, it is also evaluated whether designers can effectively manipulate the planned support for improving design practices [23].

for all the design problems in the class of problems the design method aims to resolve. Rather, a few *example problems* are introduced that have the characteristics of the class of design problems, and in that sense represent the design problems for which the design method is intended. Validation by means of the validation square consists then of four steps (these steps are graphically represented by the four quadrants of the evaluation square). First, the constructs of the design method are accepted separately and as an integrated whole. Second, the example problems are accepted as appropriately characterising the design problems the design method aims to address. Third, it has to be established that application of the design method to the example problems resolves them, and that this resolution is due to applying the method. Fourth, in a 'leap of faith' the usefulness of the design method should be accepted for all the design problems the example problems represent.

Finally, Frey and Dym [26] explore possibilities to validate design methods in a similar manner as medical treatments are evaluated. Frey and Dym are critical about taking the analogy too close; they observe, for instance, that it is hard to imagine what it would mean to let designers follow a 'placebo design method' without that the designers become aware of this. And the costs of letting a sufficiently large number of companies implement new design methods may be too high. Yet they propose to consider tests consisting of applying design methods on models of engineering design processes, in analogy with test of medical drugs on animal models, and to consider evaluating design methods by collecting data about the use of design methods in the 'field', in analogy with clinical trials.

What the first two validation research methods have in common is that they limit validation from confirmation of *all* claims of a design theory or model, to confirmation of only specific *key claims* of the design theory of model. For Blessing and Chakrabarti [23] these key claims are the causal influences of factors in their reference and impact models. For Seeparsad et al. [27] the key claims include that example problems are resolved. If these key claims of a design theory or model can be confirmed by research on design practices, the design theory or model is taken as validated. And if some key claims are not confirmed, then validation is absent, what may mean that these key claims can still be confirmed by further research on design practices, or that the key claims are in contradiction with design practices. In the latter case the conclusion should be that the design theory or model has to be rejected. The exploration of Frey and Dym [26], in turn, opens the possibility of a *step-wise* testing of design methods, first by applying them on models of engineering design processes, and then by data about their use in industry and academia, and possibly by other steps in analogy to the step-wise evaluation of medical treatments. This step-wise testing is already part of design research, when new design ideas and design theories are tested first in the design lab and then in the field, before being proposed in say product design (e.g., [31]). And again this step-wise testing may lead to rejection when a design theory or model does not pass one of the steps.

Hence, existing validation research methods for design theories and models are in addition to being useful for validation, also good starting points for falsification of the design theories and models. The validation research methods single out key claims of design theories and models, and testing of design theories and models may then consist of pilot studies in academia and industry in which these key claims are either confirmed or rejected. Hence, only a few design projects are to be carried out for testing a design theory or model, which is a lot more feasible also because they may be short projects that can be done under more controlled conditions.

2.5 Testing by (Naïve) Falsification: Towards Effectiveness

In the discussion of validation research methods the focus was on testing descriptive and prescriptive design theories and models. By the typology given in Sects. 2.2 and 2.3, design theories and models can also have the aim of demarcating design practices. So, let us consider design theories and models generally, and explore the possibilities to test them using Popperian falsification. The general advantage of falsification is that not all claims of design theories and models need to be considered, and not even all their key claims. Hence, testing more effective than validation is possible, be it testing that singles out provisionally acceptable design theories and models by elimination.

Descriptive design theories and models. A descriptive design theory is as a scientific theory that binds together knowledge of what we regularly take as design practices as they occur in the world, and that aims at understanding, explanation and prediction of and about these design practices. Descriptive models of design represent descriptive design theories, or define the content of these theories.

In principle it is clear how to falsify a descriptive design theory or model. If one practice that we regularly take as design does not fit the theory or model, or if one of these predictions is not correct, the design theory or model should be rejected as a descriptive one. This testing is possible already by considering more simple practices that are regularly taken as design; all other claims and predictions of a descriptive design theory or model about more elaborate design practices in industry can initially be ignored, thus avoiding waiting for the outcomes of years-long experiments before being able to say something about the acceptability of descriptive design theories and models. For instance, if one has for a descriptive design theory a reference model as defined by Blessing and Chakrabarti [23], key claims of that theory are represented as a network of influencing factors. A literature study or a simple empirical observation may then falsify one of these key claims and thus refute the descriptive design theory.

Demarcating design theories and models. For demarcating design theories and models the aim is to determine what practices can be taken as design, and falsification is in principle not possible. Demarcating design theories and models are similar to definitions and can as definitions only be rejected or falsified under specific further assumptions.

If it is assumed that a demarcating design theory or model singles out practices that are *essentially* design practices—a rather metaphysical assumption—then that theory or model is aimed at saying something about reality and can be true or false, just as an *essentialistic definition* can be true or false. Falsification is now possible: by finding one practice that is essentially a design practice but not identified as such by the demarcating design theory or model, or by finding one practice that is not essentially design, but identified as such by the theory or model, the demarcating design theory or model is refuted.

If it is assumed that a demarcating design theory or model singles out how design practices are identified in common or expert language, then that theory or model is aimed at saying something about how people give meaning to the term design. The theory of model can then again be true or false, as a *lexical definition* can be true or false. Falsification is possible: by finding one practice that is generally accepted as design but not identified as such by the demarcating design theory or model, or by finding one practice that is not accepted as design, but identified as such by the theory or model, the demarcating design theory of model is refuted.

Yet, if these assumptions are not made, then demarcating design theories and models have other overall goals. A demarcating theory or model may define design practices as part of a larger effort at analysing, say, engineering curricula or national economies. The goal of demarcation is then usefulness to that analysis, like the goal of a *stipulative definition*. Typically this usefulness implies that practices that are generally accepted as design practices are acknowledged as such by a demarcating theory or model. But if some borderline cases either fall inside or outside the demarcation, or if practices that typically are not taken as design become design, then the demarcating design theory or model is not refuted. Consider, for instance, Simon's [2] well-known characterisation of design:

> Everyone designs who devices courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produced material artifacts is no different fundamentally from the one that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state.

If this characterisation is meant as singling out the essence of design practices, metaphysicians may be called in for trying to falsify it. If the characterisation is meant as lexical, the second sentence of the citation provides ample reason to reject Simon's view. Yet if the characterisation is meant as stipulating what design is in the research program Simon envisaged, observing that prescribing medical treatment is typically not seen as a design practice, is beside the point; one may at most attempt to refute the characterisation of design by trying to argue that it is not particularly helpful to Simon's research program to take prescribing medical treatment as design.

Prescriptive design theories and models. Prescriptive design theories posit favourable properties of particular types of design, and can be falsified for that. Prescriptive models represent prescriptive design theories, or define the content of these theories.

Falsification of a prescriptive design theory or model is in principle possible. If there exists one design practice of the prescribed type that does not have the favourable properties posited, then a central prediction of the prescriptive design theory or model is not correct. One can then refute this theory or model as a prescriptive one. This testing is again possible already with more simple design practices in a controlled lab context; the predictions of a prescriptive design theory or model also concern long-lasting design practices in industry, yet with falsification the testing of prescriptive design theories and models is already possible without considering these claims. For instance, one can construct for a prescriptive design theory the example problems as defined by Seepersad et al. [27] and determine if designers following the prescription arrive at practices having the posited favourable properties. Or one can test a prescriptive design theory stepwise as envisaged by Frey and Dym [26] thus creating ample opportunities to test the theory by more controlled and simpler experiments. This testing by falsification of prescriptive design theories and models can again focus on their key claims, say when an impact model is constructed for it as defined by Blessing and Chakrabarti [23]. This impact model has the additional advantage for falsification by analysing the overall favourable properties of the prescribed design practices in terms of separate claims that supporting one factor of design has an effect on another effect. One can arrive at such separate claims also by spelling out in detail what types of design practices are prescribed by prescriptive design theories and models. For instance, if the methodological steps to be followed by design methods are formulated in a SMART manner, where SMART is the management acronym of *Specific*, *Measurable*, *Assignable*, *Realistic* and *Time-related* [32], then prescriptive design theories and models advance predictions about what each of these methodological steps has to result in [33]. These predictions can be tested separately, leading again to an effective way to determine the acceptability of prescriptive design theories and models.

2.6 Testing by Sophisticated Falsification: Towards Comparison

The position that evaluation of scientific theories takes place through only direct falsification has been abandoned in philosophy of science. The original position by Popper [29] was criticised by authors such as Lakatos [30], Kuhn [34] and Feyerabend [35], who considered more empirically how theories are accepted or rejected in science. The received view in philosophy is currently that science progresses by paradigm changes in which theories get replaced by other theories. These paradigm changes may still be motivated by empirical observations, yet theoretical argument and social processes play a decisive role as well, in part because observations are depending on theory and social considerations.

Given this abandoning of Popperian falsification, the analysis given in the previous section may seem spurious. Yet, as I argue in this section, the results of the philosophical critique of falsification may still be of interest to design research. Specifically Lakatos' criticism has resulted in a more sophisticated form of falsification, which opens up the possibility to design research to test design theories and models in comparison to each other, and thus to overcome fragmentation due to the validation of the theories and models in independent strands. Only if one holds that the critique has shown that theory evaluation is an entirely social affair in science, then it does not make sense to look further into what falsification could offer to design research. Yet, if this is the conclusion to be drawn from philosophy of science, also a larger part of design research work done on the validation of design theories and models becomes spurious. A social-constructivist view of evaluation undermines the very assumption that observations of design practices can validate design theories and models; on that view, it makes more sense to analyse validation sociologically as a negotiation process between design researchers. Hence, when current validation research methods in design research make sense, it equally makes sense to look at what sophisticated falsification as envisaged by Lakatos may mean for testing design theories and models.[2]

Lakatos [30] makes a distinction between *naïve* and *sophisticated falsification*. Naïve falsification comes close to the standard view of Popperian falsification: it concerns a single scientific theory *T*, which is falsified when one observational statement[3] is counterevidence to it. Lakatos argues that naïve falsification is typically circumvented in science: by adjusting auxiliary hypotheses in the *protective belt* of *T*, the *hard core* of *T* may be saved (later more about this protective belt and hard core).

What does happen in science, according to Lakatos, is what he calls sophisticated falsification. In sophisticated falsification one has two theories T and T', where the second is a rival to the first. Theory T is now falsified according to Lakatos if three conditions hold, which all refer to the rival theory T'. The conditions are that (1) T' has excess empirical content over *T*, (2) T' explains the previous success of *T*, and (3) some of the excess content of T' is corroborated

[2] This argument also holds if it is assumed that the observations that design researchers collect about design practices are interpreted as judgements of the designers carrying out the practices. The observations then concern social facts and are depending on social processes among designers. But these observations are not depending on social processes among the design researchers engaged in evaluating design theories and models. Hence, the observations can still be taken as objective facts, allowing an objective evaluation of design theories and models by only these observations, either by validation or falsification. On a social-constructivist view the judgements of designers about their design practices are also depending on the social processes taking place between the evaluating design researchers, undermining validation research methods as envisaged by, e.g., Blessing and Chakrabarti [23].

[3] I describe only a few elements of Lakatos' [30] analysis of falsification and ignore others. Lakatos, for instance, does not talk about observational statements simpliciter, but about 'observational statements', where the parentheses are reminders that observations in science typically depend on scientific theory.

[30]. Counterevidence to T still plays a central role in sophisticated falsification but this role is now twofold: it is part of the excess empirical content of T' over T, meaning that, first, T cannot describe the counterevidence whereas, second, the rival theory T' can. Counterevidence to T does thus not immediately falsify T; as long as there is no rival theory T' that can describe it, the counterevidence is merely set aside as *anomalies* to T.

With sophisticated falsification theory evaluation amounts to successions of accepted scientific theories and Lakatos captures this by talking about *scientific research programmes*. Such a programme consists of a series of scientific theories T, T', T'', T''' …, and is characterised by a hard core of, e.g., basic assumptions and basic natural laws, and a protective belt of auxiliary hypotheses. Initial theories T in a scientific research programme typically are confronted by numerous counterevidence, which is all set aside as anomalies. Successor theories T' in the programme are meant to reproduce the empirical content of their predecessors T and to add novel content which includes some of these anomalies (this novel content is the excess empirical content referred to in the three conditions for sophisticated falsification). All theories in a scientific research programme share the hard core, and the auxiliary hypotheses are adjusted for letting successor theories have new empirical content that includes earlier anomalies. And by finding a successor theory T' with the right novel empirical content, the preceding theory T in the research programme is falsified without changing the hard core of the programme.

Scientific evaluation can also amount to the rejection of a scientific research programme as a whole, and again this takes place only when a rival scientific research programme is available. For this, both programmes should describe a common observational domain. If now a first scientific research programme after repeated attempts fails to generate theories that can describe counterevidence in the common domain, whereas the rival programme has theories available to do so, then the first is defeated (see [30], pp. 69–72).

In design research sophisticated falsification as described by Lakatos would mean doing tests in which design theories and models are taken as rivals and in which theories and models would be rejected relative to other more successful ones. This implication is probably sufficient to conclude that sophisticated falsification does not take place in design research. Design theories and models are proposed, studied, developed and tested relatively independently from each other, which leads to a rich variety of such theories and models (see [23] for a list) and an associated fragmentation of design research. Also there does not seem to exist a tradition in design research to let design theories and models compete. For instance, the question how to define the concept of function in design methods has been answered in different ways and an academic exchange at determining which answer is best is virtually absent [36], creating a development in design research in which theories and models proliferate.

Introducing sophisticated falsification into design research would create competition between design theories and models. It would direct testing towards collecting counterevidence to design theories and models, and it would direct research towards determining whether some of that counterevidence can falsify one theory or model in favour of another. It would raise the question of whether the current design theories and models can be ordered to belong to what may be called a single *design research programme* by sharing a hard core, and it would raise questions about how to evaluate such a design research programme as a whole.

Specifically, research on prescriptive design theories and models may benefit from such a development. There are design methods for engineering design that share common assumptions, say, first formulating design requirements as functional requirements, and then exploring design solutions that meet those functional requirements (e.g., [3, 4, 16]). Such design methods may be construed as prescriptive design theories and models that are part of the same design research programme, leading to the question of whether there is counterevidence in the design research literature that rejects one method in favour of another. Design methods that include the tool of reframing design problems (e.g., [37, 38]) may form another design research programme, and a third may consist of the emerging methods of design thinking (e.g., [7, 17, 28]), leading to the question of whether these programmes have a common domain of design practices by which it can be decided which of these programmes fare best in describing it.

With sophisticated falsification existing work on validating design theories and models can be used to bring design research to a more advanced level than merely separately testing all the claims advanced by the theories and models and then comparing the overall outcomes. With the example problems as defined by Seepersad et al. [27] and with the reference and impact models introduced by Blessing and Chakrabarti [23], already the key claims of, say, design methods can be used to determine the relative merits of these methods and associated design research programs. Hence, the comparison between methods can take place in a more fine-grained manner than the coarse-grained 'my method is better'-way alluded to by Reich [24].

The proposal to start testing design theories and models by sophisticated falsification clearly has a programmatic nature, since, as observed, it does not seem to take place yet. The benefits are clear, however, since doing it would mean a substantial step towards comparing design theories and models and towards overcoming the fragmentation that characterises current design research.

2.7 Conclusions

In this chapter I described how in philosophy scientific theories and scientific models are understood, and applied this understanding to design theories and models as generated in design research. A typology was introduced for distinguishing descriptive, demarcating and prescriptive design theories and models. All types of models of design fitted the philosophical understanding of scientific models, descriptive design theories may count as scientific theories, and demarcating and prescriptive design theories need not do so.

In this chapter I also considered research methods for testing design theories and models. In design research this testing is generally taken as validation, whereas philosophy of science also provides research methods for testing theories and models by falsification. Specific attention was given to sophisticated falsification as formulated by Lakatos to improve on (naïve) falsification associated to Popper.

The description of theories and models in design research and the survey of design research methods to testing them, was set against a discussion of the scientific status of design research. It was argued that using falsification to test design theories and models can help address two general concerns about this status, being a lack of effective research methods to test design theories and models, and a lack of coherence in design research. Popperian falsification gives design research means to more effectively test the claims of design theories and models. Lakatos' sophisticated falsification gives means to overcome fragmentation of design research by broadening testing to the comparison of design theories and models from separate research strands.

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