Journal of the Indian Institute of Science
A Multidisciplinary Reviews Journal
ISSN: 0970-4140 Coden-JIISAD

REVIEWS

A Review of Theories and Models of Design

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Abstract | This paper intends to provide an overview of the rich legacy of models and theories that have emerged in the last fifty years of the relatively young discipline of design research, and identifies some of the major areas of further research. It addresses the following questions: What are the major theories and models of design? How are design theory and model defined, and what is their purpose? What are the criteria they must satisfy to be considered a design theory or model? How should a theory or model of design be evaluated or validated? What are the major directions for further research?

1 Introduction

The purpose of this paper is to provide an overview of the rich legacy of models and theories that have emerged in the last fifty years of the relatively young discipline of design research, and identify some of the major areas of further research. This is done by addressing the following questions:

- What are the major theories and models of design?
- How are design theory and model defined, and what is their purpose?
- What are the criteria they must satisfy to be considered a design theory or model?
- How should a theory or model of design be evaluated or validated?
- What are the major directions for further research?

This paper is primarily a summary of four sources: (1) the first chapter by the same authors (Chakrabarti and Blessing, 2014a)[29] in the book "An Anthology of Theories and Models of Design" (Chakrabarti and Blessing, 2014b)[30]; (2) the chapters in the above book; (3) Discussions during 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 (summarised in Chakrabarti and Blessing, 2014a Appendix A); and (4) the extensive review of literature from Ranjan et al. (2015).

2 A Summary of Major Theories and Models of Design

This section provides a summary of some of the major theories and models in design, in chronological order. The summaries are not meant to be comprehensive, but only as a pointer to more detailed sources.

2.1 *Development of theories and models of design initiated before this century*

The prescriptive design process model by Asimow (1962)[8] has three main stages: feasibility study, preliminary design and detailed design. The activities are analysis, synthesis, evaluation, decision, optimisation, revision, and implementation, and outcomes are engineering statement of the problem, potentially useful solutions, the most promising concept, and engineering descriptions.

French (1971,[37] 1985,[38] 1999[39]) proposed a prescriptive model of designing with the following stages: analysis of problem, conceptual design, embodiment of schemes, and detailing. French argued that the evaluation activity should be present in each stage. The outcomes are problem statement, selected schemes, general arrangement drawings, and working drawings.

Pahl and Beitz (1977,[71] 1984,[72] 2007[73]) proposed a more detailed prescriptive model comprising task clarification, conceptual design, embodiment design, and detailed design stages, with detailed activities and outcomes within each stage, and connection among the systemic elements through a system-hierarchy.

Design (Designs, Designing): "Design is a purposeful activity aimed at changing existing situations into preferred ones. The word design has two meanings: as verb and as noun. The verb describes the act of designing; the noun specifies its outcomes. A design is taken here as a plan for intervention which, when implemented, is intended to change an undesirable situation into a (less un-) desirable one. Designing is the process of identifying these situations, as well as of developing designs to support the transition." (Chakrabarti 2015 in Papalambros 2015)

Design research (Design Science): Design Research develops descriptive knowledge providing understanding of phenomena associated with design (design phenomena), and, based on this, prescriptive knowledge, i.e., support in the form of approaches, guidelines, methods or tools, for improving design practice and education (Blessing & Chakrabarti 2009).

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Design Stages: Periods within the design process distinguishible by the level of abstraction and detail of the outcomes developed. The most commonly cited design stages (Pahl and Beitz 2007) are: Task Clarification, Conceptual Design, Embodiment Design and Detail Design.

Prescriptive Theory/Model of design: A Theory/model of design that prescribes some aspects of design phenomena 'as should be'.

Technical Systems: Man-made tangible object systems that can be used to deliver effects to perform one or more operations in a transformation process (of energy, materials and/or information). (Hubka and Eder, 1988)

Descriptive Theory/Model of designing: A Theory/model of design that describes some aspects of design phenomena 'as is'.

Hubka (1974),[56] and then Hubka and Eder (1988[57]; 1996[58]) developed the Theory of Technical Systems (TS) in which a TS is expressed using five connected, systemic levels of abstraction: purpose, transformation process structure, function structure, organ structure and component structure. Hubka and Eder subsequently combined the theory of technical systems with a prescriptive design process with the following activities: elaborate and clarify the specification, and establish process structure, function structure, organ structure, and component structure.

Domain theory (Andreasen 1980[6]; Hansen and Andresen 2002[50]; Andreasen et al. 2014[7]) evolved from the Theory of Technical Systems (Hansen and Andresen 2002). Domain theory uses three domains—transformation, organ and part domain and three principal synthesis steps: two in each domain (detailing and concretization) and one connecting one domain to another. The outcomes are characteristics (in the step of detailing) and their values (in the step of concretization). The theory uses the chromosome model as a means of connecting the domains.

Yoshikawa (1984)[104] proposed General Design Theory (GDT); Yoshikawa and Tomiyama (1987)[95] expanded the theory. It is one of the pioneering design theories at the knowledge level. Knowledge level was proposed originally by Newell (1982): as a level of abstraction in computer and cognitive systems. "Knowledge, according to Newell, is a capacity for rational action" (Smithers, 2000).[81] GDT describes design as a transformation between function space and attribute space when complete design knowledge is available; Extended GDT explores the nature of this transformation when knowledge available is incomplete.

The FBS (Function-Behaviour-Structure) model of designing by Gero (1990)[42] represents the descriptive process for transforming a set of functions F into a design description D of an artifact so that the artefact can exhibit these functions. The transformation process from F to D involves the following activities: formulation, synthesis, analysis, evaluation, reformulation, and production of D. The resulting ourcomes are functions, expected behaviour, structure, derived behaviour and design description.

Visser (1991)[99] proposed a descriptive model of designing that explains how the two approaches typically used in designing are carried out: how one proceeds iteratively when working out problems in depth; and how one moves progressively from a global problem specification to a detailed solution by decomposing problems and integrating solutions.

VDI 2221 (1993)[97] is a prescriptive process model for designing technical systems, with seven stages: clarify the task; determine functions and function structure; develop solution principles for sub-functions and combine to form a principal solution; divide the principal solution into realizable modules and develop its module structure; develop key modules into preliminary layouts; develop preliminary layouts into a definitive structure; and produce final product documents. The outcomes are specification, function structure, principal solution, module structure, preliminary layouts, definitive layout, and product documents.

Stauffer and Ullman (1991)[87] prescribe a six-stage mechanical design process. In *product discovery*, the need for the product is established. In *product planning*, resources are allocated and the tasks and their sequence are developed. In *product definition*, the design problem is decomposed into manageable sub-problems. In *conceptual design*, a functional model of the problem is developed, and concepts are generated, evaluated and selected. In *product development*, these concepts are refined, and technical documents are developed for manufacturing. *Product support* focuses on how to retire the product.

The core of PROSUS (PROcess-based SUpport System)—a prescriptive model for designing developed by Blessing (1994)[12] is a design matrix that is a structured set of issues, proposals and activities. Each matrix is applicable to a component, assembly and/or product. Several matrices are used in designing. The issues consist of problems, requirements, functions, concepts and detailed designs. The activities of generate, evaluate and select are used to resolve the issues. PROSUS is intended for guiding designing and capturing its rationale.

Maher et al. (1996a; 1996b[67]) propose a descriptive model of problem-design exploration, which is used for developing a prescriptive genetic algorithm for designing. The activities of selection, crossover, mutation, and evaluation are performed on the problem spaces consisting of 'genotypes', which then lead to the creation of 'phenotypes' of designs that are part of the solution space.

Umeda et al. (1996)[89] proposed a computer based framework called Function-Behavior-State (FBS) Modeler to support functional design. The framework uses a prescriptive model of designing with three constructs: function, behaviour and state. These together provide the modelling scheme that supports the conceptual design process.

The prescriptive model for conceptual design of micro-sensors proposed by Chakrabarti et al. (1997)[27] has three steps: generation of a design concept, identification of potential behavioral problems with the concept, and modification of the concept to alleviate these. The outcomes are functions, solution principles and embodiments. Functions are represented using an input-output description, and solution principles using concatenated laws and effects. Designing involves decomposition of each function into sub-functions, and developing solutions for each as a combination of physical effects and elementary devices.

Axiomatic Design Theory was proposed by Suh (1998,[90] 2001[91]). 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.

Smithers (1998,[80] 2000) proposed $K^LD^E_0$, a Knowledge Level theory with six types of design knowledge: 1. of how to form requirements, of the requirements descriptions actually developed and of their justifications; 2. of how to develop well-formed problem descriptions, of well-formed problem descriptions developed and their justifications; 3. of how to solve well-formed problems, and of solutions and justifications actually formed; 4. of how to analyse and evaluate problem solutions, of analyses and evaluations actually performed and their justifications; 5. of how to form design descriptions, and of actual design descriptions and justifications; 6. of how to construct design presentations, and of presentations actually formed and their justifications.

Grabowski et al. (1998)[48] proposed Universal Design Theory (UDT) to integrate knowledge about design from various disciplines in a consistent and compact form (Lossack and Grabowski 2000)[65] that would serve as a scientific basis for rationalizing interdisciplinary product development. The process of design is taken as a "mapping of a set of requirements onto a set of design parameters" that constitute a design solution, proposed to be carried out by transition through four, linked levels of abstraction: modelling requirements, modelling functions, modelling effective geometry, and embodiment design. The scope of UDT is limited to those types of design where new designs can be seen as a combination of old, basic elements.

Takeda et al. (1999)[92] argued that knowledge for synthesis in design needs physicality, unlikeness, and desirability, which respectively ensure possibility of existence, newness and value. Their theory of synthesis takes design as an iterative, logical process of abduction and deduction on design solutions, their properties and behaviors, and knowledge of objects. Synthesis is seen as a process of reconstructing design experiences, where each experience contains a logical 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."

Based on their empirical study of co-evolution of requirements and solutions in designing, Nidamarthi et al. (1997,[69] 1999[70]) proposed a descriptive model of designing with two phases: problem understanding (PU), and problem solving (PS) In PU, designers develop a clear and concrete view of requirements; in PS, they develop the design from vague or incomplete descriptions of artefacts. For each phase, the activities are divided into primary and secondary levels. Requirements and solutions co-evolve through these phases. While co-evolution is not a new idea, and several models of co-evolution in design were proposed earlier, e.g. by Chakrabarti (1991)[26]; Koza (1992)[62]; Watabe and Okino (1993)[103]; Maher and Poon (1996a),[66] etc., Nidamarthi et al. (1997) were the first to report empirical observation of co-evolution in designing.

Concept-Knowledge-Theory or C-K Theory (Hatchuel and Weil, 2003[51]; 2011) is a knowledge level, descriptive theory of designing based on two expandable spaces: a space of concepts (undecidable propositions), the C-space, and a space of knowledge (decidable propositions), the K-space. The process of design is defined as the co-evolution of C and K through four types of independent operators: C-C, C-K, K-C, K-K. C-K Theory proposes to explain how design creativity occurs, and provide a framework for unification of design theories and for linking scientific discovery and the design process. It has been applied in several industrial contexts to improve the innovative capacity of organisations.

Based on UDT (Lossack and Grabowski 2000), Lossack (2002,[63] 2006[64]) proposed the foundations of a Domain Independent Design Theory that describes design knowledge, design process knowledge and system-theoretical approaches for processing this knowledge system. The foundations consist of object patterns, process patterns and design working-spaces. Lossack stressed that "design is not a workflow [...] workflows represent processes in a deterministic manner, whereas design is intrinsically indeterministic". The design approach is based on solution patterns to support indeterministic design processes, which include solution finding and creativity.

Dorst and Cross (2000) developed a descriptive model of designing with the following activities: problem-space exploration, concept generation, concept evaluation, and communication of the final design to manufacture. Problems and solutions co-evolve through various levels of abstraction. Further, they developed a prescriptive, symmetrical problem-solution model of designing with seven stages: clarify objectives, establish function structures, set requirements, determine characteristics, generate alternatives, evaluate alternatives, and improve details. Using these, a problem is divided into sub-problems, sub-solutions are generated, and these are integrated into an overall solution.

2.2 Development of theories and models of design initiated during this century

Bhatta and Goel (2002)[10] developed a prescriptive model of conceptual device design called model-based analogy (MBA). MBA takes a design problem as functional requirements and structural constraints on the desired design, and generates the output in the form of a Structure-Behavior-Function (SBF) model of the solution that realizes the functions and the constraints. Function is represented as a schema that specifies its pre- and post-conditions, and contains references to the behaviour that accomplishes the function (Goel et al., 2009).[45] Behaviour is represented as a sequence of states and state transitions. Structure is represented hierarchically in terms of the constituent structural elements and their relations that realise the behaviour and hence the function.

In an attempt to establish a unified understanding by formalising and modelling synthesis, Tomiyama et al. (2002)[96] developed a knowledge operation model of design. The prescription is a multiple-model based framework, which includes models of both synthesis and analysis, each of which is carried out using logical and modelling operations. The core of synthesis is considered to be abduction, which is proposed to be realised by a model-based abduction algorithm. The model is verified empirically.

Ulrich and Eppinger (2003)[88] prescribed a product development process that comprise the stages of planning, concept development, system-level design, detail design, testing & refinement, and production ramp-up. Each stage consists of activities and outcomes at various abstraction levels. Needs are developed into a hierarchy of needs. Problem is decomposed into sub-problems; sub-solutions are developed and combined to form concepts, followed by concept selection and testing. The concept is subsequently laid out, detailed, tested, refined, and ramped up for production.

In the prescriptive model for computational design synthesis by Campbell and Rai (2003),[32] a design problem is described using constraints and objective functions. The activities of representation, generation, evaluation and guidance are performed on solutions, resulting in candidates, generated solutions, evaluated solutions, objective values, and new and better solutions.

To support functional design during the conceptual phase, Deng et al. (2000)[33] proposed using four aspects of functional information: function, behaviour, structure and working environment. Information about the working environment is demonstrated to be useful for exploring functional design solutions. The physical behaviour is represented by an input-output flow-of-action, as opposed to the commonly-used input-output flow-of-object approach (where object refers to material, energy or signal), which the authors argue is only a physical-level design abstraction, incapable of capturing design intention.

Infused Design (Shai and Reich 2004[78]; Shai et al. 2013[79]) is a prescriptive model of design in which the design problem is represented at a mathematical meta-level common to all engineering disciplines. Problem solving is carried out by using tools that, due to their generality, are also common across 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."

Integral Design Methodology (IDM) by Zeiler et al. (2007)[105] is a prescriptive model for designing, with generate, synthesize, select and shape as activities, and need, design problem, functional specification, physical solution process, module structure, prototype structure, engineering aspects and material properties as outcomes. Zeiler et al. also proposed that design problem and its solutions co-evolve during the design process.

The Integrated Model of Designing (IMoD) by Srinivasan and Chakrabarti (2010a,[84] 2010b[85]) was developed to describe designing up to the conceptual stage. It combines Generate-Evaluate-Modify-Select (GEMS) of activities (Srinivasan and Chakrabarti, 2009),[83] SAPPhIRE model (Chakrabarti et al., 2005) of outcomes, and co-evolving model of requirements and solutions (req-sol). GEMS activities are performed on SAPPhIRE outcomes, which evolve as requirements or solutions. IMoD was validated empirically. Ranjan et al. (2012,[75] 2014,[76] 2015[77]) developed this into an Extended, Integrated Model of Designing" (e-IMoD) to extend its scope to later stages. e-IMOD adds a system-environment model to the activity, outcome and req-sol models of IMOD.

Contact and Channel Approach (C&C2-A) (Albers et al., 2009[3]; Albers and Wintergerst 2014[2]) is a prescriptive model for supporting embodiment design that uses two main elements: *Working Surface Pairs* (WSP) "are pair-wise interfaces between components, or between a component and its environment"; *Channel and Support Structures* (CSS) "are physical components or volumes of liquids, gases or spaces which connect exactly two WSPs". The following activities are prescribed: Decompose concept into sub-systems and main components, decompose requirements into functions and localise start/end points, identify machine elements to satisfy functions, and complete design using other simulation and analysis approaches.

Combining a modular system hierarchy and a design activities process, Howard et al. (2009)[55] prescribed a design process model in which the types of activities carried out for a design task are independent of the systems level at which the task is set. In this model, task clarification, conceptual design, embodiment design, and detailed design form the design activities process. The outcomes of the design activities process from a design module at one system level are used by other system level modules, each of which should go through every design activity.

Munich Model of Product Concretization (Ponn and Lindemann 2011[74]; Lindemann 2014[62]) is a prescriptive model composed of four, partial, outcome models: requirement models, function models, working element models, and component models. The model has three process 'dimensions': 'abstraction and concretization'; 'vary and constrict', and 'fractionize and assemble'. Lindemann (2014) also presents the Munich Procedural model, which consists of the following activities: goal planning, goal analysis, generation of solutions and ideas, properties assessment, ensuring goal achievement, decision making and task structuring.

Environment Based Design (EBD) methodology, developed by Zeng (2011),[106] consists of three main activities: environment analysis, conflict identification, and solution generation. According to Zeng, "in the design process, any previously generated design concept can be treated as an environment component for the succeeding design, as a result, a new state of design can be defined as the structure of the old environment (Ei) and the newly generated design concept (Si), which is a partial design solution".

The Characteristics-Properties Modeling/ Property-Driven Development or Design (CPM/ PDD)—a prescriptive model of designing developed by Weber (2014)—uses CPM and PDD respectively to describe the product and process aspects of design. "Characteristics (Ci) are made up of the parts structure, shape, dimensions, materials and surfaces of a product. Properties (Pj) describe the product's behaviour (Verhalten), e.g. function, weight, safety and reliability, aesthetic properties, but also things like manufacturability, assemblability, testability, environmental friendliness and cost". Only characteristics can be influenced directly by the designer; characteristics and properties are linked together by 'analysis' and 'synthesis' activities.

Inventive Design Methodology (IDM) developed by Cavallucci and others (Cavallucci et al. 2008[21]; Zanni-merk et al. 2011[22]; Cavallucci 2014)[23] is a prescriptive model for creative design based on an extension of TRIZ—the Theory of Inventive Problem Solving (Altshuller, 1961; 1984),[4,5] to rapidly arrive at a reasonable number of inventive solution concepts to evolve a complex initial situation. IDM has the following steps: Initial Situation Analysis, Formulating contraditions, Generation of solution concepts, and Selection of solution concepts. The central notion of IDM and TRIZ is *contraditions*, in which two aspects (e.g. requirements) are dependent and opposed to each other at the same time, and the resolution of which leads to solutions that are highly creative.

Koskela et al. (2007,[60] 2014[59]) argue that the first prescriptive theory—proto-theory—of design was proposed by Aristotle, and later developed by Galen. The argument is based on the claim that design is similar to 'geometric analysis', which uses two types of analysis: proposing a solution, and proving a proposed solution. These, it is argued, are what are currently called, respectively, synthesis and analysis. The authors further argue that the two stages in Aristotle's analysis: "of selecting a means among different alternatives" and "completing the analysis regarding the selected means" correspond respectively to "conceptual design and embodiment/detail design".

Taura and Nagai (2014)[94] proposed a systematized theory of creative concept generation in design, proposed as a theory on the thinking process at the "very early stage of design"—the phase that "includes the time just prior to or the precise beginning of the so-called conceptual design." They divided concept generation into two phases—the *problem-driven phase* and the *inner sense-driven phase*. They categorised the concept generation process 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.

Futher reviews from existing literature can be found in Blessing (1995)[14]; Lossack (2006); Pahl and Beitz (2007); Heymann (2005)[53]; Gericke and Blessing (2012)[41]; Weber (2014); Chakrabarti & Blessing (2014a); and Ranjan et al., (2015).

2.3 *Reflection*

Wallace and Blessing (2000)[100] divided development in design research in the last century into three overlapping phases: Experiential, Intellectual, and Experimental. The theories and models developed during these phases were often considered pre-theoretical, pre-paradigmatic (Cantamessa 2001)[20] or pre-hypothesis (Horváth 2001),[54] and only few have been regularly used.

Around the turn of the century a new phase in design research, the Theoretical Phase (Blessing 2002)[16] began. Not only was earlier work revalued, several new theories of a very different nature were proposed in a rather short period of time. At the same time, earlier work was further developed. For details see (Chakrabarti and Blessing, 2014a). In (Chakrabarti and Blessing 2014a) we described how the many existing theories and models are partially competing, and how many are partially complementing one another. Some (e.g. Buchanan 2004[19]; Hatchuel et al. 2011[52]) consider this a strength and a sign of work in progress, while others (Galle, 2006[40]; Vermaas 2014[98]) worry that this might prevent coherent theory development, in particular as "design research does not yet have means to test and refute design theories and models" (Vermaas 2014). For yet others, such as Eckert and Stacey (2014),[35] this is only a transitional phase needed to accumulate understanding.

In (Chakrabarti and Blessing 2014a), we described the differences between developments in the new Theoretical Phase and developments in the earlier phases, which we summarise below:

- New theories and models have become more widely known and rather quickly.
- Theories and models started to be built upon one another, rather than growing independently, and design researchers engaged in more fundamental discussions about design research.
- The new theories and models are richer in the number and variety of concepts used.
- Validating theories and models using empirical data has become a focus of attention, driven by an increased demand for rigour.
- Explicit attention is paid to linking theory to practice.

3 Definitions and Purpose of Design Theories and Models

Design literature reveals a considerable variation in the definitions of design theory and model, and the overlap between these (Ranjan et al., 2014; Lindemann, 2014; and Vermaas, 2014). Concerning the purpose of a design theory or model the literature is less explicit, but equally diverse. This section summarises the definitions and purposes we discussed in (Chakrabarti and Blessing, 2014a).

3.1 *Design theory*

The majority of definitions, in particular early ones, refer to theory as a description of a phenomenon, in this case of design. An example is the definition of Eder (2014),[36] "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". Another example is from Badke-Schaub and Eris (2014),[9] where a theory is "a body of knowledge which provides an understanding of the principles, practices and procedures of design". Such definitions reflect the observation of Gero and Kannengiesser (2014)[43] that 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". As for any other theory, the purpose of design theory is to describe, explain and predict.

In current literature, many authors emphasize that the ultimate purpose is to create support to improve practice, based on the understanding obtained. This, in our view, is based on the assumption of design research that many of the observed phenomena can be changed, i.e. design practice and education can be improved (Chakrabarti and Blessing, 2014a). This brings an additional purpose to design theory: to be useful, to contribute to improvement. Eckert and Stacey (2014), for instance, 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." Taura (2014)[93] 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. (2014), 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 Albers and Wintergerst (2014), a design theory should be "explaining, or predicting certain phenomena", but also "facilitating designers to analyse design problems and to create appropriate solutions". "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". Cavallucci's view (2014) adds that "a theory or model of design is supposed to provide designers with answers to their everyday professional difficulties." Finally, Andreasen et al. (2014) stress the concepts introduced in a theory 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".

It has to be noted that these authors do 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 or "provide the basis for the prescriptive part of design methodology".

In our view, "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" (Blessing et al., 1995).[13] The distinction between descriptive and prescriptive theories, or at least components of theories, is emphasised also by more recent literature, such as (Koskela et al. 2014) and (Vermaas, 2014). Design research is about "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)" (Weber, 2014).[102]

Vermaas (2014) distinguishes not only descriptive and prescriptive theories, but also demarcating theories, based on the purposes of the theory:

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

According to Vermaas, design theories developed in our area typically are not pure theories but combine aims. He points out that only those that include the aim to "systematically bind together the knowledge we have of experiences of design practice", i.e. include a descriptive aim, can be considered scientific theories. In his view, e.g. "prescriptive design theories that single out *new* types of design practices and posit favourable properties", i.e. are not descriptive, are at most *hypothetical* scientific theories. The same is true for demarcating theories that do not have a descriptive component.

As discussed in (Chakrabarti and Blessing, 2014a), researchers such as Eckert and Stacey (2014), Koskela et al. (2014), Taura (2014), Horváth (2014), Gero and Kannengiesser (2014) and Badke-Schaub and Eris (2014) contribute to 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 (2014), for instance, criticize 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" and "are typically presented with insufficient consideration of how much of designing they actually cover". They therfore 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.

Our conclusion was that "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 … need for a common ontology or agreed set of main concepts".

Ontology is considered not only an important basis for theoretical development but also an important aid in analysis of empirical data and in

Design Phenomena: Design Phenomena are phenomena associated with design that govern the relationships between design and its facets (Chakrabarti 2011)

Ontology: Ontology is the philosophical study of the nature of being, becoming, existence, or reality, as well as the basic categories of being and their relations (Wikipedia). In the context of knowledge sharing, an ontology is an explicit specification of a conceptualization (Gruber 1993).[49]

making a theory comprehensible and transferable to design practice and education. Yet, our analysis of the concepts used in various theories (Chakrabarti and Blessing, 2014a) shows a strong diversity and lack of consistency in terminology: often the same term is used for different concepts, or different terms are used for the same concept. The need for a common ontology or agreement about the main concepts in design has been argued for several decades (e.g. in Chakrabarti et al., 1995).[31] Several authors developed ontologies describing the concepts used in their theories and models, e.g. Agogué and Kazakçi (2014),[1] Albers and Wintergerst (2014),[2] Andreasen et al. (2014), Cavallucci, (2014), Goel and Helms (2014),[44] Gero and Kannengiesser (2014), and Ranjan et al. (2014), but a commonly accepted ontology is still lacking. This issue needs urgent attention.

Having this dual aim of describing and prescribing influences both the research process and its outcomes: scientific rigour and practicality. To resolve this dichotomy, Sonalkar et al. (2014)[82] propose a two-dimensional structure for design theory that "displays scientific rigor while being useful to professionals". Our own attempt to resolve the dichotomy has been to propose a research methodology, DRM, as a structure for design research that aims to address both aspects (Blessing et al. 1992,[11] 1995, 1998[15]; Blessing and Chakrabarti, 2002,[17] 2009[18]).

In summary (adapted from Chakrabarti and Blessing, 2014a) a design theory:

- is a body of knowledge, typically a set of propositions (hypotheses), consisting of a set of constructs and their relationships. The propositions are relationships among constructs representing specific aspects of designs, designing, their facets, and success factors.
- aims at understanding design so as to provide description, explanation or prediction about some aspects of phenomena related to designs and designing.
- can be descriptive or prescriptive.
- has a clear boundary of what it can describe, explain or predict, and with what level of generality, and the propositions are testable and falsifiable.

Design Facets: Facets are the baskets of factors that influence and are in turn influenced by design. Common facets (Blessing and Chakrabarti, 2009) are people, products, processes, knowledge and tools, organization, microeconomy and macro-economy.

Falsifiable: "A statement is called falsifiable if it is possible to conceive an observation or an argument which proves the statement in question to be false." (Wikipedia)

3.2 *Design model*

The phrase 'design models' can have two meanings: models that are used in designing, such as scale models, CAD models, sketches etc., which could be referred to as 'models *in* design'; and models that are used to describe or prescribe how design is or should be (carried out), which we call models *of* design, We focus on the latter.

Definitions vary from succinct "simplified, idealized representation" (Maier et al., 2014),[68] "an interpretation of a target system, process or phenomenon" (Goel and Helms, 2014), to the more elaborate, such as those from (Stachowiak, 1973[86] in Lindemann, 2014), who describe models as having 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 of purpose, users and time frame of usage.

Several authors link the term model to theory, e.g. a model "is a simplified and schematic representation of the essence of a theory" (Goldschmidt 2014)[46] or "represents features of a target system in the world or a scientific theory (Vermaas 2014). Note that the latter includes models in design and models of design.

Vermaas (2014) points out that "Models of design practices may also be differentiated as models with descriptive, demarcating and prescriptive aims" "depending on what they represent".

Several authors do not distinguish between theory and model and, hence, consider a model to have the same purposes as a theory. Some, however, were explicit in the purpose of models (Chakrabarti and Blessing, 2014a). For Goel and Helms (2014) a model should "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". According to Vermaas (2014) "Scientific models also have epistemic value: their creation, analysis and development allow scientist to understand the target systems and the theories represented". Goldschmidt (2014) describes the purpose of model as "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".

3.3 *Discussion*

Discussions among researchers at IWMT Workshop (see Section 1.1) led to the following understanding of the distinctions and overlaps in meaning and purposes of theories and models of design (Chakrabarti and Blessing, 2014a).

A theory is an abstract generalization of phenomena, which can be modelled in multiple ways. A model is a representation of some phenomena and relationships among these phenomena; an abstraction of some reality. A model may describe or 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.

A theory may involve a number of hypotheses, each of which should be possible to be falsified. Participants at the workshop recognized that describing something as a theory (rather than a model) is sometimes a cultural issue; for instance, in some fields of research, approaches, frameworks etc. are called theories for the only reason that the term 'theory' added some kind of value to the proposition. The participants recognized 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 participants felt that a model and a theory have several aspects in common: both models and theories serve a set of specific purposes that are useful for researchers and/or practitioners; both can be explanatory in character which facilitates prediction or prescription. A goal of theories that might be distinct from those of models is to provide an explanation of what design and designing mean within the context of use of the theory; this however was not felt uniformly across the participants.

Given this overlap in meanings between, and the 'spectrum of meanings' for models and theories of design, a consensus amongst the participants was on the 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.

The participants emphasised the importance of distinguishing theories in terms of *boundary* (i.e. scope or application) and *purpose*. A theory should serve its purpose at least within the scope of its application. Theories can be curiosity-driven—aimed at understanding a phenomenon, or problem-driven—aimed at supporting practitioners or students and providing utility.

The participants felt that the phenomena of designing essentially refers to "how design works"; various aspects (e.g. people, process, product, knowledge, human reasoning, etc.) play a role in this, and therefore, designing may look very different as these aspects change. The participants agreed that there are similarities and differences across designing in different contexts, and concluded that a theory of design should explain these. There are also many partial activities within designing (e.g. work of an FEM engineer), i.e. there is "designing within designing", which theories currently do not capture. 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.

The discussions in the workshop highlighted a lack of clarity as to how the existing theories and models compared or complemented one another. A major agreement emerged: it was felt that any proposal for a model or theory should be accompanied by its purpose (what it does) and context (where it applies)—its "system boundary".

4 Criteria to Satisfy to be Considered a Theory or Model

Our overview and the discussions in the aforementioned IWMT workshop (both reported in Chakrabarti and Blessing, 2014a) showed a strong agreement on the criteria that a theory or model should satisfy in order to be called a design theory or model of design. Design theories and models should describe, explain or predict some aspects of design phenomena, have generativity, generality and breadth in scope, and should be testable and refutable (i.e. falsifiable) for the given scope and purpose. Finally, a design theory or model of design should be useful for research, as well as for practice and/or education.

Generativity: The capacity of a theory to model creative reasoning and to relate to innovative engineering in all its aspects (Agogué and Kazakçi 2014).

Generality: The capacity of a theory to propose a common language on the design reasoning and design processes (Agogué and Kazakçi 2014).

A theory should "refer to actual and existing phenomena" (Eder, 2014), to "real design processes at a level that is not trivially true for all processes" (Eckert and Stacey, 2014), and "contain a set of propositions to describe or explain some characteristics of (one or more facets of) designing (and design success)" (Ranjan et al. 2014).

A theory or model should have broad scope: "It must account for both the similarities and the differences between them, across products, companies and industries" (Eckert and Stacey 2014), "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" (Koskela et al. 2014).

The participants discussed goodness criteria for utility. These should include usability, ease of use, how quickly the theory or model can be used, and its limits. A theory or a model should be able to provide insight.

The participants emphasized that theories are evolutionary rather than stationary, which requires all assumptions underlying a theory to be made explicit, and awareness, as a researcher, about the process by which is a theory is developed.

5 How Should a Theory or Model be Evaluated?

A theory should be as complete and logically consistent as possible (Eder 2014), empirically accurate (Vermaas 2014), based on testable hypotheses (Goel and Helms 2014) and have clarity of explanation (Koskela et al. 2014). In addition, a design theory or model not only should meet "the usual criteria of a descriptive science (e.g. truth, completeness, level of detail) but also the criteria of usefulness and timeliness" (Weber 2014). "Usefulness needs testing" (Vermaas 2014) 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 (2014). For Lindemann (2014) 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 (Weber 2014).

Andreasen et al. (2014) distinguish "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 Wintergerst (2014) emphasise the variety of problems and domains that can be addressed in industry and research, and the impact on education. Eckert and Stacey (2014) stress the importance of considering where a theory applies when validating a theory.

Validation can play an important role 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" (Eckert and Stacey, 2014).

Referring to models, Lindemann (2014) 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 (2014) observes "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". For this reason he and others (e.g. (Goel and Helms 2014), (Weber 2014), (Sonalkar et al. 2014) and (Eckert and Stacey 2014)) recommend falsification (à la Popper) rather than validation.

Ranjan et al. (2014) 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 (2014) emphasises that testing cannot be done independently of rival design theories and models.

Various authors describe how they tested their theories *using empirical data*. Ranjan et al. (2014) analysed protocols to identify whether all constructs of the model were present. Badke-Schaub and Eris (2014) did a qualitative analysis of the data gathered by interviews with professional designers from different disciplines. Goel and Helms (2014) coded data from a large number of cases using a coding scheme from an initial knowledge model. In the process new conceptual categories emerged, which were used to refine the model. This process was repeated twice, each time with a new data set. Gero and Kannengiesser (2014) evaluated their ontology by using it for coding hundreds of design protocols in various design domains and for various tasks. Cavallucci (2014) used case studies in industry in which he moderated the use of his framework by company experts. Albers and Wintergerst (2014) verified their approach by evaluating the results of design projects of students who were trained in the approach, and the results of the application of the approach in a variety of problems and domains.

Agogué and Kazakçi (2014) focused on *logical consistency with other theories and models* that are already validated. They proposed further ways of validating a theory: looking at the impact on 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. (2014) used a similar approach and evaluated the validity of the aristotelian proto-theory as a theory of design by asking whether its explicit and implicit features can be found in modern, corresponding ideas, concepts and methods.

The discussions during the aforementioned IWMT workshop highlighted the breadth in meaning of the term validation, the different ways of validating and the related reliability and repeatability.

Validation was seen to be testing the limits of a theory or a model, where the criteria for validation spanned from testing for internal consistency, to truth and usefulness, in terms of providing explanation or insight in the form of predictions or postdictions, and the level of reliability of the model or theory to achieve its purpose. Two aspects were identified as critical: what should be taken as true and false, and which is the process of refutation whereby truth and falsity should be adjudged.

Several challenges to validation were highlighted: difficulty of repeatability of phenomena, the large number of factors obscuring "clear and identifiably strong" influences, difficulty of finding statistically large samples of subjects or cases, and difficulty of generating reliable data about the phenomena under investigation, lack of specification of intended focus and application area of the theory or model. Repeatability too is often seen as a major issue: no design is ever repeatable. However, this is true for many areas of natural sciences too, where there are various levels of variation across so called repeatable phenomena. If the discipline looks into a large number of design projects in various fields, it might find the phenomena at some level of repeatability.

Overall, the participants 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.

6 Summary, Conclusions and Directions for Future Work

The review of literautre and the discussions at the IWMT Workshop have focused on understanding the concepts of theory and model in the context of design, and in assessing progress in their development, validation and influence on practice and education.

Overall, the article demonstrates a rich legacy of theory development in design research. A distinct feature of design research is that its theories can be *descriptive* (describing phenomena of design as is), or *prescriptive* (i.e. prescribing phenomena of design as should be).

In terms of meanings, it was found that the term 'model' can have multiple meanings: models used for carrying out design may be called *models for design*; while models used for describing, explaining or predicting how designs and designing are or should be, and how these relate to criteria of importance to practice or education, may be called *models of design*. The primary focus of this paper has been on models of design.

Another significant finding has been the considerable overlap between what models of design and theories of design mean. Participants felt that a theory of design should be understoood as having a spectrum of meanings, and should encompass terms such as taxonomies, models and theories that may have various levels of maturity in context, purpose and explanatory power.

Validation was also seen as having a spectrum of meanings, from checking for internal consistency, through truth, to utility in terms of explanation or insight as predictions or post-dictions, thereby testing the limits of a theory or a model. Theories should be testable and refutable (i.e. falsifiable), and this should be possible to be carried out within their context and purpose, i.e. where they apply, and how well.

From the review and the discussions, it is clear that theory development in design is highly complex. This is primarily because design phenomena—the focus of research—is highly complex, being a confluence of factors arising from the multiple facets of design, e.g. of the characteristics of people involved, products developed, organisations involved, process, knowledge and tools used, and the economy and ecology within which it operates, thereby influencing and being influenced by all these factors.

Notwithstanding the complexity of the endeavour, it is heartening to see the increasing maturity in research in this area. There is clear progress in development of richer theories and models, that are better linked to and built on one another, better grounded empirically, better validated, and better connected to applications in practice.

A number of major, common issues and associated directions for future research emerged.

One is the need for greater consolidation of existing research. Good "demarcating theories" are necessary to provide a better understanding of what constitutes design phenomena, what types of designs and designing are included; and how to situate the various models and theories within these.

Another major point is the challenge involved in validating theories or models of phenomena of design. Many challenges were highlighted: issue of repeatability of phenomena, the numerous factors that made it difficult to identify clear and strong influences, difficulty of finding statistically large number of cases—especially experienced designers as subjects for study, the amount of time and data involved in observational studies of design processes and their influences, etc. This pointed to the need for developing research methods that are appropriate for scientific studies within design research.

Finally, given the complexity and variety of designing, it is too ambitious to develop, in one shot, a single theory to explian or predict all aspects of all types of design. Many theories, each working in a particular context and purpose should be developed. These may then form the basis for developing more comprehensive theories, or even their unification.

Received 18 December 2015.

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