# A domain-independent descriptive design model and its application to structured reflection on design processes

I.M.M.J. REYMEN
*University of Twente, Faculty of Engineering Technology, Department of Construction Management and Engineering, P.O. Box 217, NL-7500 AE Enschede*
I.M.M.J.Reymen@utwente.nl, Tel. +31 53 489 3826, Fax +31 53 489 2511

D.K. HAMMER
*Technische Universiteit Eindhoven, Faculty of Mathematics and Computer Science, Department of Computer Science, P.O. Box 513, NL-5600 MB Eindhoven*

P.A. KROES
*Technische Universiteit Delft, Faculty of Technology, Policy and Management, Department of Philosophy, P.O. Box 5015, NL-2600 GA Delft*

J.E. VAN AKEN
*Technische Universiteit Eindhoven, Faculty of Technology Management, Department of Organisation Science and Marketing, P.O. Box 513, NL-5600 MB Eindhoven*

C.H. DORST
*Technische Universiteit Eindhoven, Faculty of Industrial Design, P.O. Box 513, NL-5600 MB Eindhoven*

M.F.T. BAX
*Technische Universiteit Eindhoven, Stan Ackermans Institute, Center for Technological Design, P.O. Box 513, NL-5600 MB Eindhoven*

T. BASTEN
*Technische Universiteit Eindhoven, Faculty of Electrical Engineering, Department of Information and Communication Systems, P.O. Box 513, NL-5600 MB Eindhoven*

## Abstract

Domain-independent models of the design process are an important means for facilitating interdisciplinary communication and for supporting multidisciplinary design. Many so-called domain-independent models are, however, not really domain independent. We state that, to be domain independent, the models must abstract from domain-specific aspects, be based on the study of several design disciplines, and be useful for many design disciplines and for multidisciplinary design teams. This paper presents a domain-independent descriptive design model that is developed by studying similarities and differences between design processes in three design disciplines and that is based on the general theory of state-transition systems. Main concepts of the descriptive model are a design situation and a design activity. The descriptive model is applied in a domain-independent prescriptive model that supports designers with structured reflection on a design process; reflection provides an important possibility to improve the effectiveness and efficiency of design processes.

## Keywords

*Design situation, design activity, state-transition system, prescriptive model, reflection process, design session*

# 1 Introduction

Much design research is performed in single design disciplines, like mechanical engineering, software engineering, and industrial design. Many similarities between design processes in several disciplines can, however, be recognized. Common characteristics of a design process are, for example, the occurrence of design phases and the ill-defined nature of design problems. Ways to improve design processes are often similar in many disciplines. Design research based on several design disciplines can combine research efforts and its results can be useful for designers in many disciplines at a time.

For facilitating interdisciplinary communication and for supporting multidisciplinary design, *domain-independent models* of the design process are very important. Because this kind of models abstracts from domain-specific details, it can be used in multidisciplinary teams as a common representation of the design process. The domain-independent concepts and terminology of such a model can be the basis for a dialogue between the members of a design team. The need for domain-independent design theory has been discussed since the beginning of design research. A primary goal of the Design Research Society since its founding in the 1960's has been a domain-independent theory of design within the context of a science of design. A discussion meeting on the question whether the search for domain-independent theory of designing is a reasonable or realistic goal [39] led to the issue of the aim of design research. The discussion showed a clear division between those who want to study design per se and those who want to improve design practice and design education. We share the second viewpoint: We believe that domain-independent design models are worth developing if they are aimed at improving design practice and design education in many design disciplines and multidisciplinary teams. This means that the model should have the right generality, i.e., the general concepts used for describing design processes must be recognizable by designers in a number of disciplines.

We define the following three criteria for design knowledge to be domain-independent: it should be based on the study of several design disciplines; it may not contain domain-specific aspects; and it should be useful for supporting several design disciplines and multidisciplinary teams. Knowledge based on only one discipline can be domain independent when it fulfills the second and third criterion and when it is recognized as general knowledge by many design disciplines in the field. We include the first criterion to encourage cross-disciplinary research, and more important, because we believe that there is a bigger chance on domain independence when the knowledge is based on a study of several disciplines (the chance of focusing on domain-specific aspects is then reduced). Domain-independent models, are, for example, given in Hybs and Gero [27], Korn [33], Newell and Simon [42], Schön [55], and Takeda, Tomiyama, and Yoshikawa [61].

Many design models, however, are said to be domain independent but in our opinion do not deserve to be called so. Some theories, for example, do not abstract from all domain-specific aspects and examples given to illustrate these theories are often taken from only one discipline. For example, Hubka and Eder [26] take all examples from mechanical engineering and do not consider the existence of non-material products like software. (Theories related to the one of Hubka and Eder do, however, abstract from domain-specific aspects and include examples of several disciplines, resulting in the acceptance of these theories as domain independent.) Many general design theories are also often based on the study of one design discipline or are made with no practical goal in mind and are thus too general to be useful for supporting designers or design researchers.

We have chosen to develop domain-independent design knowledge by studying similarities and differences between design processes in three design disciplines. This paper describes the resulting domain-independent descriptive design model. Our model includes a unique combination of domain-independent concepts, which is useful for design researchers to learn from each others discipline and for designers in interdisciplinary communication. Because the domain-independent design model offers insight into main concepts of design processes, it can also help (student) designers from several disciplines with reflecting on their design process.

The descriptive design model is used as a basis for the development of a prescriptive model supporting reflection on the design process, which is also discussed in this paper. Reflection is important since it is indispensable for the faster learning of designers, it can contribute to a smoother design process, and to an improved product being designed. Reflection has already proven to be useful for improving, for example, the learning process of managers, as described by Daudelin [13]. Studying the usefulness of reflection for designing received, however, little attention. Important starting points are given by Badke et al. [5], Lauche [34], Reymen [46], Schön [55], and Valkenburg [65]. Our objective is to stimulate designers from several design disciplines to improve their own process by reflecting on their design process. More specific, we focus on structured reflection, systematic reflection that is performed in a regular way.

The paper starts, in Section 2, with the research set-up. Section 3 describes the model for describing design processes in a domain-independent way. Section 4 summarizes the prescriptive model for supporting structured reflection. The paper ends, in Section 5, with some conclusions.

# 2 Research set-up

We defined the following main research question: "How to describe design processes in a domain-independent way?". To apply the resulting model, we defined a second research question, namely "How to support structured reflection on a design process in a domain-independent way?". We chose to develop domain-independent design knowledge based on the following three disciplines: software engineering, mechanical engineering, and architecture. We chose architecture because it has already played an important role in design research and it is the discipline the first author is most familiar with. Mechanical engineering has also contributed much to design research and it is a typical engineering discipline. Software engineering is a new evolving discipline that started to reflect on its design processes. Together, these three disciplines are responsible for a wide range of products and for many different design approaches.

We answered the first research question by developing domain-independent descriptive knowledge about designing. For this purpose, we inventoried characteristics of design processes in the literature and we did empirical research in design practice. These studies have been the basis for the development of a domain-independent descriptive model of the design process. This model, in turn, has formed the basis for developing a prescriptive model for supporting structured reflection on a design process. At the end of the project, we confronted the descriptive and prescriptive knowledge with the design practice in another empirical study to get feedback on the results; we also compared the results to the design literature. An overview of the research project is given in Figure 1.

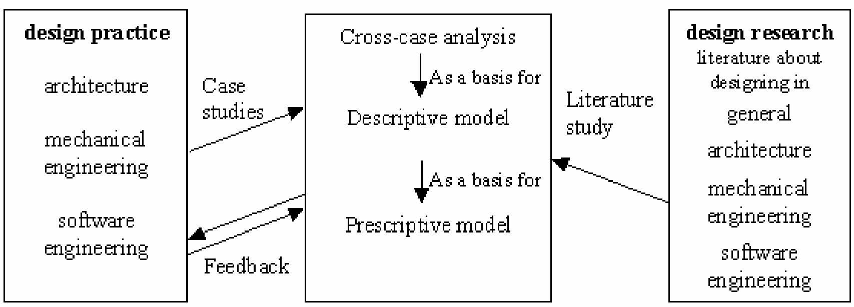


Fig. 1. Overview of the research project.

The research project can best be characterized as a broad exploratory study. The study is broad because it contains empirical research in several disciplines, the development of some theoretical results, the development of support for the design practice, and the confrontation of the results with design practice. An exploratory study was necessary because the study of design across several disciplines is relatively new. The exploration helped to find out which concepts, terminology, and kinds of support are useful for answering the research questions.

The research project can be described in more detail as follows. We started the project with a *literature study* in which we explored general design literature and literature specific for the three design disciplines. The goal of the literature study was to find domain-independent characteristics of design processes. Because the authors are already familiar with architecture (first and fifth author) and software engineering (second and seventh author), literature about designing in mechanical engineering got extra attention. References to the literature studied are given in Section 3.2.1. To explore design practice, we performed *case studies* in the three chosen disciplines. Case studies were chosen to get insight into a complete design process. An advantage of cases studies was also that not that much pre-structuring of important aspects of design processes was necessary compared to other data-gathering methods. We performed twelve case studies, four in each discipline. The case studies consisted of interviews about one specific design project and an analysis of documentation of the design project. The interviews were performed at the end of the design project, so that the designers could look back on the complete design project. To limit the scope of the research, we collected only data of individual designers. In each discipline, two junior and two expert designers were interviewed. We selected junior designers that just finished their first large design project in practice. Expert designers were chosen for their design expertise in a certain discipline; their design projects were more complex than those of the junior designers. Since most of the expert designers fulfilled the role of design-team leader, they had a good overview of important aspects of the project. We expected that junior designers experienced certain aspects explicitly, whereas expert designers would experience some of these aspects already implicitly, and vice versa (based on Cross et al. [11]). We first interviewed the six junior designers and we analyzed the documents made during their projects. In a cross-case analysis, we compared all junior cases. Then, we performed the same activities for six expert designers: interviewing the expert designers, analyzing their documentation, and performing a cross-case analysis. Results of the case studies and cross-case analyses are presented in Section 3.1.

The literature and the case studies were the basis for the development of the descriptive design model. The developed descriptive knowledge, in turn, has formed the basis for developing a prescriptive model, consisting of a method and a prototype software tool supporting the use of the method. In the empirical study we performed at the end of the project, expert designers gave *feedback* on all results in another interview. In the interviews, we explained the results briefly and asked feedback in the form of open questions. Junior designers used the method and the prototype software tool in two design sessions of half a day each. After a brief introduction to the method and tool, they worked on one of their design tasks while using the method and tool. The designers evaluated the method at the end of the first session and the tool at the end of the second session: They were asked to write down, on an evaluation sheet, positive and negative experiences on the following six topics: general impression of the support, time spent on reflection in relation to the duration of the design session, support offered by the forms and checklists/software, relevance of the support, usefulness of the support, and suggestions for improvement. Afterwards, all designers came to the blackboard to cluster their feedback (written on yellow memos) with respect to the six topics. In front of the black board, we had a group discussion on each of the topics.

The feedback of the expert designers was synthesized in several iterations. The individual feedback of the junior designers was first integrated, then, added to the group discussion (structured according to the six topics), and finally, synthesized. Suggestions for improvement of the descriptive model and the method are taken into account in the further development of these results. The feedback was a first confrontation with design practice, to judge the generality (domain independence), the relevance, and the potential usefulness of the results for design practice. The results must be tested more extensively in a follow-up study. Suggestions for improvement of the descriptive and prescriptive model are taken into account in the further development of these results. At the end of the research project, we performed again a *literature study* in order to position our results.

# 3 A descriptive model of a design process

The main question we have to answer, namely “How to describe design processes in a domain-independent way?”, can be split into the following two sub-questions: “What are important concepts and terms for describing design processes in a domain-independent way?” and “How to structure the description of a design process?”. We answer the first sub-question in Sections 3.3 to 3.5 by describing the main common concepts for describing a design process we found in practice and in the literature. We answer the second sub-question by explaining, in Section 3.6, the domain-independent design description structure we developed. A discussion of the feedback received on the descriptive model and a comparison of the model with the literature can be found in the discussion in Section 3.7. A more extensive description of the design model can be found in [46]. Section 3.1 describes the empirical basis of the descriptive model. The theoretical basis is summarized in Section 3.2.

## 3.1 Empirical basis

The empirical basis of the model lies in the case studies performed. In this section, an example of a case (which is used as running example further on in this paper), our case-study protocol and the approach of the cross-case analyses, and some results of the cross-case analyses are summarized. More about the performed case studies can be found in [48].

One junior case in the field of mechanical engineering concerned the design of a photo-voltaic (PV)/thermal hybrid solar panel. The designer, D.W. De Vries, followed the post-graduate program in technological design, “Computational Mechanics” at the Technische Universiteit Eindhoven. The first part of the design project was done during this post-graduate design program, the second part at the Faculty of Mechanical engineering, Department Mechanical Energy Technology in co-operation with Shell Solar Energy B.V. At the moment of the interview, the designer was in the last part of his project. The designer had to design and build a prototype of a photo-voltaic/thermal hybrid panel that can be placed on the roof of a house. The combi panel converts solar energy into both heat and electricity. It was a multi-disciplinary project, in which thermodynamic, optical (physics of PV-systems), mechanical, architectural, production-technical, and economical problems had to be solved. No overall design method was chosen. First, concepts were generated using a list of demands. Then, a model was developed to estimate the yearly electrical and thermal yield of a hybrid panel. A prototype was built to check the model. After doing experiments, the design was optimized.

The course of a single case study is described in a *case-study protocol*. We followed the guidelines of Yin [73] to design the protocol. This is a document that contains all procedures and general rules that are followed to execute a single case by the researcher. This instrument increases reliability and continuity between cases, and guides in carrying out the case studies. Our case-study protocol includes a description of the following main activities: preparing and executing a first interview (about one of the design projects of the designers), processing data of the first interview (called transcription), analyzing the documentation received from the designer, making a summary, preparing and executing a second interview (to check and correct the summary of the first interview), processing data of the second interview and correction of the summary, and making a summary report of the case. The protocol was tested in two pilot case studies, then used for junior designers, and then for expert designers. *Questions* in the interviews concerned the product that was designed, the design process, bottlenecks in the project, and things learned from the project. Examples of questions are “What is characteristic for designing in your opinion?”, “Describe important aspects of the product you designed.”, “Describe important aspects of the design process you performed.”, “What were main design activities?”, “What were the most important design skills for the project?”, “What were important parties in the design project?”, “What did disturb the design process? How? When?”, and “What did you learn from the design project?”. A *transcription scheme* was used to classify the raw material of the interviews and the analysis of the documents. The transcription scheme included the following broad categories, based on the main topics of the interview scheme: product (sub-categories environment, system, specification, documentation), design process (activities, resources, people, documentation), designing (definition), and design management aspects.

After the cases with junior designers, a summary of characteristics of design processes in each discipline was made based on a brief cross-case analysis of the junior cases and on the literature we studied, as further explained in Section 3.2.1. Then, the cases with the expert designers were performed. As stated in Section 2, we expected that junior designers would experience certain aspects explicitly, whereas expert designers would experience some of these aspects already implicitly, and vice versa. These differences were found in the empirical study. Expert designers focused, for example, on more aspects of the product lifecycle, they gave more attention to controlling the design process, and they gave higher importance to interaction with different stakeholders at the beginning of a design process.

Finally, a real cross-case analysis was performed in which the cases were compared for similarities and differences within one discipline and in different disciplines. This resulted in descriptions of important common aspects of design processes in architecture, software engineering, and mechanical engineering. These descriptions were compared to derive important general concepts of design processes. Important differences between the descriptions in the three disciplines are the following (they concern mainly differences in terminology). Designing in software concerns designing an immaterial product, namely a software system. The system interacts with its environment through an interface. The design process consists often of the following activities: defining specifications, defining the software architecture, designing the system, implementing the system in source code, and verifying and testing the software. Designing in architecture concerns creating a material product that creates immaterial space. The environment of the created building has often direct influence on the public space around it and may then be part of a public debate. The design process often consists of defining a program of demands, making a sketch design, making a preliminary design, and making a realisation design. A design process in mechanical engineering often consists of the following activities: generating concepts, modelling, making estimations, building a prototype or making simulations to check the model by doing experiments, evaluating the results and optimising the resulting concept.

The important general concepts are the following: First of all, we noticed that the combination of the product being designed, the design process, and the design context was important in all cases. This observation resulted in introducing the concept of a design situation (see Section 3.3). Second, we learned that designers change both characteristics of the product being designed *and* of the design process. Designers make decisions about both continuously during the design process. An example of changing the design process in the case of De Vries is the fact that he asked an expert to design the production process of the combi panel. Our definition of a design activity is based on this observation (Section 3.4). Third, we noticed that interaction between designers and stakeholders in the design context is crucial for a design project because of the influence of changes in the design context on decisions about the design process and the product being designed (for example, in the case of De Vries, changes in production technology of solar cells highly influence the design of the combi panel). Interaction between designers and stakeholders is introduced in our model in Section 3.4. Fourth, we observed that design phases are the major structuring principle of design processes in practice; design phases take long periods in time (usually several months). Design methods guiding designers during a design process are very often based on these phases. The phases are also often part of norms and standards (ISO norms, building norms, software standards, etc.); the standards also often justify their use. Shorter periods in time are almost never used for structuring a design process, although there appeared to be a need for such a short-term structuring mechanism. This last observation directly inspired us to introduce the idea of subtasks (in Section 3.5) and design sessions (in Section 4.3).

To describe the inventoried concepts of design processes in general terms, a choice of terminology had to be made, because the disciplines used several synonyms and because some terms were shared between disciplines, while they had a different content or meaning in the different disciplines. To make a general description of design processes, the terminology of state-transition systems has been used (as explained in Section 3.2.2). The general description of design processes resulted in the descriptive design model, presented in Sections 3.3 to 3.6.

## 3.2 Theoretical basis

References to general design literature studied and to literature studied specifically for the three chosen disciplines are given in Section 3.2.1. Section 3.2.2 introduces the domain-independent theory on which the descriptive model is based.

### *3.2.1 Design literature*

Table 1: Overview of the literature studied

| **Author(s)** | **Domain** | | | |
|---|---|---|---|---|
| | **general** | **architecture** | **softw. eng.** | **mech. eng.** |
| 1. Akin [1] | x | | | |
| 2. Evbuomwan [16] | x | | | |
| 3. Blessing [8] | x | | | |
| 4. Cross [10] | x | | | |
| 5. Hybs and Gero [27] | x | | | |
| 6. Korn [33] | x | | | |
| 7. McDonell [40] | x | | | |
| 8. McMahon et al. [41] | x | | | |
| 9. Roozenburg et al. [53] | x | | | |
| 10. Cross et al. [11] | x | | | |
| 11. Dorst [14] | x | | | |
| 12. Maher et al. [38] | x | | | |
| 13. Newell and Simon [42] | x | | | |
| 14. Schön [55] | x | | | |
| 15. Simon [58] | x | | | |
| 16. Takeda, Tomiyama, Yoshikawa [61,62,74] | x | | | |
| 17. Alexander et al. [2] | | x | | |
| 18. Bax [7] | | x | | |
| 19. Jones [30] | | x | | |
| 20. Lawson [35] | | x | | |
| 21. Le Cuyer [36] | | x | | |
| 22. Avison [3] | | | x | |
| 23. Jalote [29] | | | x | |
| 24. Pressman [44] | | | x | |
| 25. Rechtin [45] | | | x | |
| 26. Rumbaugh et al. [54] | | | x | |
| 27. Sodhi [59] | | | x | |
| 28. Sommerville [60] | | | x | |
| 29. Winograd [72] | | | x | |
| 30. Dym [15] | | | | x |
| 31. Finger [17,18] | | | | x |
| 32. Hubka et al. [26] | | | | x |
| 33. Pahl et a. [43] | | | | x |
| 34. Ullman [63] | | | | x |
| 35. VDI Guidelines [67] | | | | x |

Table 1 indicates the literature we studied. As already mentioned in Section 2, the goal of the literature study was to find domain-independent characteristics of design processes. We studied the descriptive models described in Akin [1] and Evbuomwan et al. [16] and looked in detail at the Prosus model described in Blessing [8], the design model of Cross [10], the evolutionary process model of design as presented in Hybs and Gero [27], the domain-independent design theory of Korn [33], the descriptive model of McDonell [40], the transformation models in McMahon et al. [41], and the basic design cycle described in Roozenburg and Eekels [53]. We also found important general aspects of design processes in Cross et al. [11], Dorst [14], Maher et al. [38], Newell and Simon [42], Schön [55], Simon [58], and Takeda, Tomiyama, and Yoshikawa [61, 62, 74]. Note that some of the cited literature also includes domain-specific aspects. Models studied that include domain-specific aspects are the following. For architecture, we got an impression of designing by studying table entries 17 to 21. Literature studied in software engineering includes, among similar books, the table entries 22 to 29. Literature that was studied about designing in mechanical engineering is table entry 30 to 35.

### *3.2.2 State-transition systems*

We have chosen to describe design processes in a domain-independent way using the theory of state-transition systems. General literature about state-transition systems can, among others, be found in Lewis and Papadimitriou [37]. This theory has been chosen (1) because it is a very general theory (which was necessary because similarities between design processes in several disciplines could only be found on a high level of abstraction) and (2) because this theory appeared to be the most appropriate to describe the two main concepts of design processes we recognized in the case studies, namely design situations and design activities. In the theory of state-transition systems, a state is defined as the situation at a certain moment in time; a state is changed by transitions. A 'design situation' corresponds to a state; a 'design activity' corresponds to a transition. The descriptive model presented here uses the concept of state-transition systems to describe design processes. Only the observable behavior of designers is described. Also, only the basic concepts of state-transition systems are used to describe design behavior; the mathematical notation and definitions of state-transition systems are not used. The basic terminology of state-transition systems (state and transition) is extended with terminology commonly used in technical sciences (like property, factor, representation, relation, and process).

## 3.3 A design situation

This section introduces the concept of a design situation building on a number of related concepts, namely a product being designed, a design process, a design context, a property and a factor, a design relation, a representation, a state, and a state description. After defining a design situation, the coherence between the introduced concepts is briefly explained. Finally, the important related concept alternative is introduced.

We use the concept of a *product being designed* to indicate the product during the design process because the product itself does not yet exist during this process. A *design process* is defined as a finite sequence of design activities, necessary to obtain the design goal (see also Section 3.5). A *property* describes a characteristic of the product being designed or of the design process. A *factor* describes an external influence on the characteristics of the product being designed or of the design process. Properties and factors can be described by sets of values. The distinction between properties and factors is based on who 'determines' the property or factor and who can 'influence' the property or factor. A designer cannot determine factors, but a designer might be able to influence some design factors by interaction with the design context. A *design context* is described by the set of factors influencing the product being designed and the design process at a certain moment. Properties of a product being designed describe, for example, the dimensions of a hybrid solar energy panel and its type. Values for these properties are '0.25m high', '1.2m wide', and '1.5m long' and 'photo-voltaic/thermal combi panel'. In architecture, a property of a new museum describes, for example, the main volume of the building with the values 'cone', 'cylinder', or 'cube'. Properties of software for mobile phones describe, for example, the execution time of the software and the energy and memory usage. Other properties of a product being designed describe, for example, characteristics of the problem, a solution, or an alternative solution. Properties of a design process describe, for example, members and characteristics of a design team, characteristics of a designer, and design aids like methods and computer support. Examples of factors are other processes than the design process in the lifecycle of the product being designed, stakeholders, a company quality handbook, competitors, laws, patents, and the situation of the market.

A *design relation* is defined as a relation between properties and/or factors. Design relations exist between properties of the product being designed, of the design process, and/or factors in the design context. A design relation between two properties and/or factors describes the way in which one property or factor influences another property or factor. Possible relations are, for example, hierarchical, causal, and dependency relations. An example of a design relation is the relation between the dimensions of the production machines and the dimensions of the combi panel: the first 'limit' the latter.

A *representation of an entity*, i.e. of a product being designed or a design process, is a reproduction of a relevant subset of the properties and factors of this entity in a mental image, a picture, a textual description, a drawing, a model, a graph, a computer visualization, a prototype, or in some other way. For example, a representation of an energy panel is a textual description or a drawing of the energy panel; a representation of software is a flow diagram or source code. Many different representations can be made of one entity because different subsets of properties and factors can be represented and even the same subset can be represented in different ways. Different representations of the same entity are not always consistent with each other; for example, a mental representation can be different from the existing physical representations. A *state of an entity* is the set of values for all properties and factors describing and influencing this entity at a certain moment in time. The state of an entity can be seen as a special property of an entity; it also describes a characteristic of the entity; its value is a set of values. A *description of the state of an entity* is a specific representation of a relevant subset of the state using the general terminology of state-transition systems. For example, consider the following description: "The set of properties of an energy panel is its type and its surface; the set of values for these properties is 'photo-voltaic/thermal combi panel' and '1.8 square meter'". To make a description, concepts are needed; a state description can thus be seen as a conceptualized representation of the entity. An example of a representation that is not a description is, for example, a photograph.

For properties, a distinction can be made between current and desired properties. *Current properties* are properties of the product being designed or the design process at a given moment; *desired properties* are related to the design goal. Current properties are determined by a designer and can be influenced by a designer. Desired properties can be determined by a designer or by the design context. A designer can influence some of the desired properties; other desired properties can only be influenced via interaction between a designer and the design context. Desired properties correspond to the concepts constraint, requirement, and specification that are often used in design literature and practice. A *current state* of a product being designed or design process is a set of values for all current properties. A *desired state* of a product being designed or design process is a set of values for all desired properties.

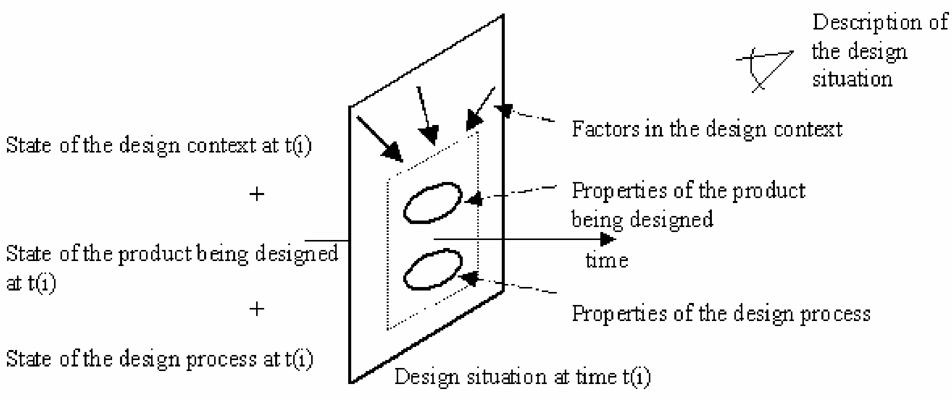


Fig. 2. A design situation as a state.

A *design situation* at a certain moment is defined as the combination of the state of the product being designed, the state of the design process, and the state of the design context at that moment. This means that it is (1) the set of values of all properties describing the product being designed, (2) the set of values of all properties describing the design process, and (3) the set of values of all factors influencing the product being designed and its design process. This definition is illustrated in Figure 2. During a design process, designers make representations of the product being designed, the design process, and the design context. Making representations implies modeling the reality from a particular point of view, i.e., neglecting certain irrelevant characteristics. We define *a description of a design situation* as a specific representation of a relevant subset of the set of values of all properties describing the product being designed and the design process and of the set of values of all factors influencing the product being designed and its design process, which is made using the terminology of state-transition systems applied to the field of designing (as defined above). An example of a (partial) description of a design situation is given in Section 3.6. The description of a design situation may include a description of the design relations between the properties and factors of the design situation.

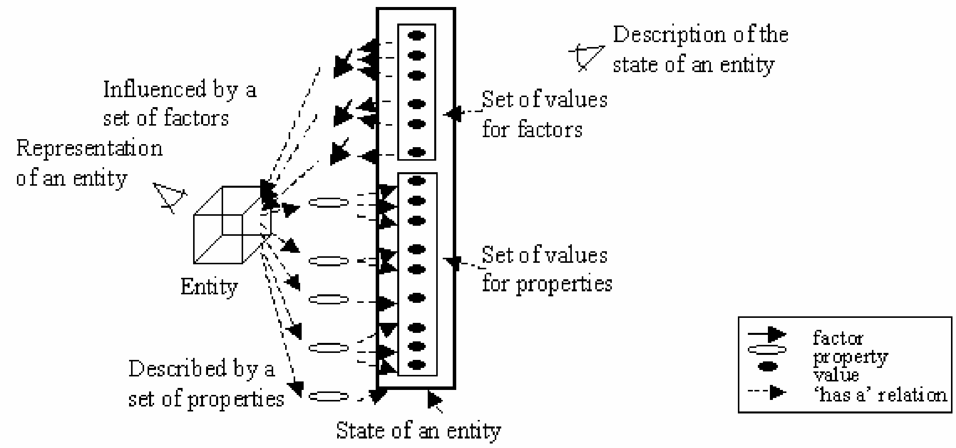


Fig. 3. The concepts entity, representation, state, and state description

The difference between an entity, its representation, the state of an entity, and a state description can also be explained as follows (and is also illustrated in Figure 3, summarized in Table 2, and further explained in Section 3.5). An entity exists in reality. We have chosen to model (an entity in) reality by the concept of a state, including values for properties and factors. An entity has only one state at a certain moment; a state includes values for all properties and factors; a state is 'objective'. An entity can be represented in many different representations. A representation of an entity consists of a limited set of properties and factors and is made by someone or something. Which properties and factors are included and made explicit depends on the purpose of the representation, its designer, and on conventions; a representation is partly 'subjective'. The state of an entity can be described in many different descriptions, possibly including only a subset of the set of values of the state; a description of the state of an entity is made using the general terminology of state-transition systems.

In design processes, the concept of 'a proposal' or 'an *alternative'* is very important. This concept is modeled as shown in Figure 4. Values of different properties can, together, describe an alternative for the product being designed or the design process. For each alternative, different properties of the entity can be important. Sets of alternatives can occur for current as well as for desired properties.

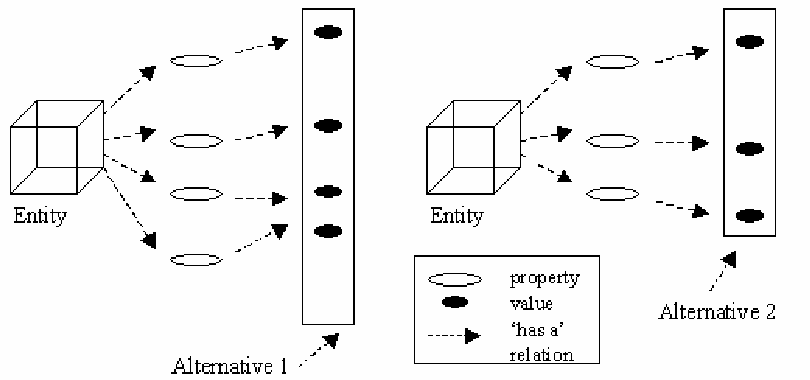

Fig. 4. The concept of an alternative or a proposal.

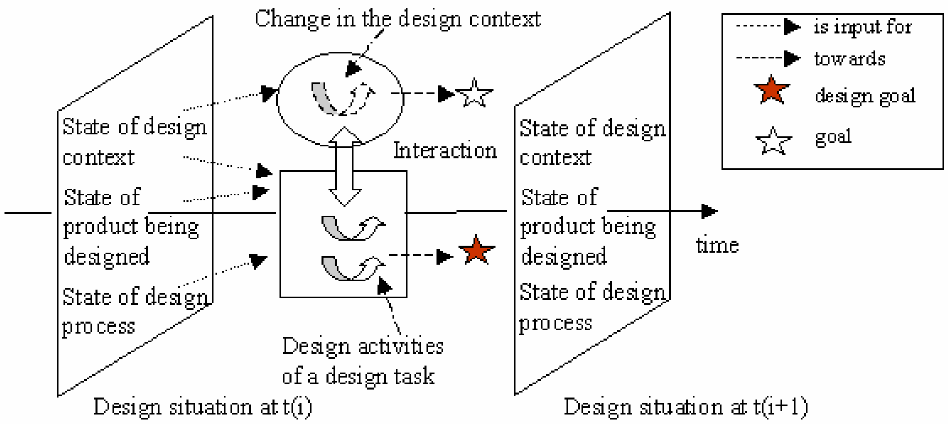

Fig. 5. Actions changing one design situation into another.

## 3.4 A design activity

A design situation can be changed into another design situation by one or more actions. Designers can change the state of the product being designed and of the design process. Stakeholders can change the design context. Stakeholders are actors in the design context that have an interest in the product being designed or the design process, like customers, users, production managers, and logistic managers. The design context can also be changed by interactions between designers and stakeholders. Our design model illustrating the actions changing a design situation into another is represented in Figure 5.

We call a goal-oriented action a *transformation*. An action without a goal is called a *mutation*; a mutation occurs spontaneously. A *design activity* is a transformation towards the design goal at that moment, carried out by a designer, causing a transition of the state of the product being designed or of the design process. The definition of a design activity is illustrated in Figure 6. For the case of a combi solar energy panel, a design activity can be the estimation of the yearly electrical and thermal yield of the panel, based on a model of the panel. Two new properties are then added to the previous design situation, namely 'yearly electrical yield' and 'yearly thermal yield'. Transitions in the design context can be described by transformations or mutations.

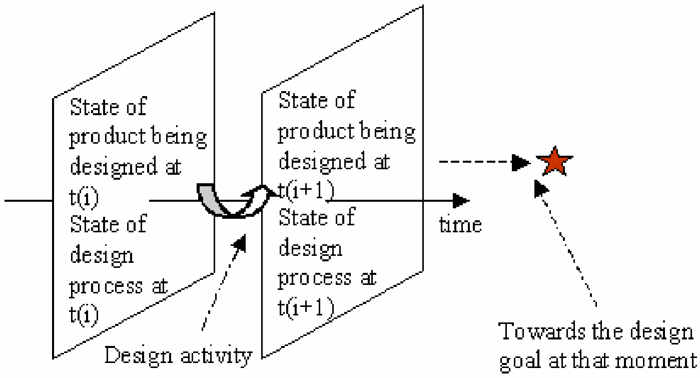


Fig. 6. A design activity causing a state transition.

Designers can change the properties of the product being designed and of the design process. Current as well as desired properties can be changed and alternatives can be formulated. The latter may be 'experiments' to see if an idea will work and will meet the design goal; these experiments sometimes include calculating risks. New properties can arise by new insights of the designer or existing properties can be combined or split into several properties. Actions changing the state of the product being designed or the design process result in a representation of the product being designed or design process with changed properties and/or changing factors influencing the product being designed or the design process. The design process can also be changed by executing changes in the design process itself. Producing a representation means creating a new representation or modifying an existing representation; it is a transition from one representation to another. For example, it is making a complete drawing of an energy panel, drawing just one additional line, or changing the organization scheme of the design team. An example of changing the design process is the recruitment of a new team member.

The *goal of a design activity* is to create a desired representation of the product being designed having a desired state; the product being designed must thus fulfill the desired properties for the product being designed and the representation must fulfill the desired properties for a representation. A representation must thus fulfill some demands about the medium of representation (for example, mock-up or 3D presentation) and/or about usefulness for stakeholders. The goal of a design activity is usually not explicitly defined. An example of the goal of a design activity is determining the dimensions of a combi energy panel. For the desired state, a value for the property 'dimensions of a combi energy panel' must be defined. The desired representation can be a textual description.

## 3.5 A design process

So far, the term design process has been used rather informally. This section starts with defining the design process in some more detail. Also the related concepts of a design goal, a design task, and a design space are introduced. Then, a definition of designing is given. Finally, the different concepts and terms defined in the descriptive model are positioned against each other.

A *design process* is modeled as a finite sequence of design activities, necessary to obtain the design goal. Thus it is a sequence of transitions as shown in Figure 6. One or more designers can execute the design activities, in sequence or in parallel, using one or more design aids. Examples of design aids are theories, methods, tools, time, space, money, skills, and knowledge. The design process is, at the same time, subject to changes (properties of the design process can be changed by designers) and the cause of these changes (as the sequence of design activities). During a design process, designers can concentrate alternately on the product being designed, the design process, and the design context and on current and desired properties. Sets of properties and values (alternatives) can be added, deleted, or changed, based on new experiences. Developing and evaluating proposals and alternatives are ways of experiential learning in a design process. To proceed, designers can also look back at changes made earlier in the design process. As stated in Gero and Maher [21], creative design involves exploration (i.e., finding new goals, new states, and new state-transition processes).

The *goal of a design process* is to create one or more desired representations of the product being designed having a desired state; the product being designed must thus fulfill the desired properties for the product being designed and the representation must fulfill the desired properties for a representation. Often, the goal of a design process also induces desired properties of the design process. These can be desired properties about the final state of the design process (like budget and time) or desired properties about the state of the process during the design process (like moments for presentation of intermediate results and guidelines for documentation). The design goal can then be formulated as creating a specified product being designed during a specified process. The design goal is defined by stakeholders, usually, in co-operation with the designers. Both can define desired properties of the product being designed and can determine the desired representations. Notice that desired and current properties can be added and deleted during the complete design process. This means that the current as well as the desired state continuously change during a design process. In the literature, this simultaneous evolution of desired and current properties is called co-evolution (of problem and solution); see, for example, Maher et al. [38].

Compared to the goal of a design activity, as discussed in the previous subsection, the goal of a design process can consist of the creation of more than one representation. Multiple representations must, for example, be made for communication with the different stakeholders. Important representations are those for the realization of the product being designed. The desired state of the product being designed can be reached after a sequence of design activities. The goal of a design activity in a design process is a sub-goal of the goal of the design process; it can be defined as decreasing the gap between the current and the desired state of the product being designed. The goal of a design process is, for example, creating a new type of hybrid energy panel that is also highly esthetical. Desired representations are a textual description, drawings, and a prototype. The desired state of the product being designed is ‘ready for production’. The desired state of the design process is ‘finished in two years’.

A *design task* at a certain moment is a task to meet the design goal at that moment, starting from the current design situation. One or more designers perform a design task by executing design activities. An alternative formulation of a design task is a task to transform the current state of the product being designed and/or the design process into a desired state, taking into account the design context. Our concept of a design task is similar to the concept of a design task in Dorst [14]. At every moment during a design process, a design task can be defined by a description of the current design situation and the design goal. At the beginning of a design process, the goal of a design process is often vague and ill defined. During the design process, designers and stakeholders can refine the design goal. At the end of the design process, the state of the product being designed and its representations must conform to the design goal. In practice, a design task is not always explicitly defined.

A design task can be decomposed into several subtasks. A subtask at a certain moment is a task to meet a sub-goal of the design goal at that moment. A subtask can, for example, be the creation of a representation of the product being designed on a certain level of detail by concentrating on certain aspects of the product being designed and by concentrating on a certain process in the product lifecycle (see also Section 3.6). Different subtasks can be executed in parallel or in sequence; iteration between subtasks can also occur. Various subtasks can be defined at the beginning of a design process or during a design process. The latter can be necessary when the complete design task reveals too many problems or is too complex, when more subtasks can be executed in parallel, when subtasks can be delegated to other, more specialized, designers, when factors describing the design context change, or when the design goal changes. Also at the end of the design process, new subtasks can be created as part of a new design process. The creation of a subtask can be an action of a project manager or of an individual designer. The execution of a subtask is influenced by its duration in time, the composition of the design team, the available aids, and the responsibilities. The general division of subtasks over a design process and the sequence of subtasks in a design process are defined in a design strategy.

Each design task has a specific design context; a design context is defined relative to a design task. Designers performing a design task can interact with stakeholders in the design context to exchange information about the design situation, i.e., to get to know desired properties of the product being designed and possibly also of the design process, to refine and validate the desired properties, to get to know the important factors, and to influence factors by discussion and negotiation. Our prescriptive model, described in Section 4, helps designers to take into account all relevant factors describing the design context (by means of checklists).

A *design space* at a given moment is the set of all possible next states, towards the design goal, of the product being designed and of the design process. The concept of a design space is illustrated in Figure 7. The definition of a design space refers to all 'possible next' states 'towards the design goal'. The latter limitation is useful because a design process is directed. Possible next states are the states of the product being designed and the design process that can be derived from the current state by changing or adding properties and values. The states of the design context do not belong to the design space, because the designer cannot influence these.

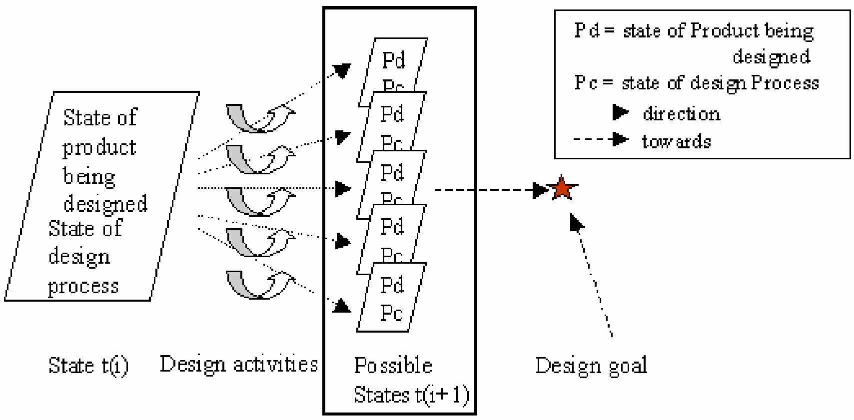


Fig. 7. The concept of a design space.

*Designing* is the activity of transforming the state of the product being designed or of the design process into another state towards the design goal. To perform a design task, designers start thus from the design situation at a certain moment and perform design activities to meet the design goal at that moment. Interaction between designers and stakeholders in the design context is necessary so that designers are informed about the important factors in the design context and to discuss their influence on the characteristics of the product being designed and the design process. These discussions may result in a changed design goal. The design context can also change, but in a direction that does not necessarily conform to the direction of the design goal (illustrated in Figure 5 with different 'stars').

We developed a model of the design process, thereby modeling some concepts and terms as part of reality and others as representations of reality. A classification of our concepts and terms in reality and representations of reality is given in Table 2. The main choices we made in this respect are briefly explained below. Making a distinction between reality and representations of reality is closely related to our use of language for speaking about reality, which is a non-trivial issue. We have chosen to categorize commonly used words in the daily practice of designers (like product being designed, design process, and design context) in *reality*. Terms like property, factor, and state are less commonly used and are in a sense more abstract; they are classified in the design model, which is seen as a *representation of reality*. The model includes three types of representations of reality. The first type consists of concepts like property, factor, state, design activity, and design task. A second type of representations is the type that designers make of entities during design processes (representations of entities). (Our descriptive model represents the process of making representations.) A third type of representations, namely descriptions of the state of an entity, combines the concepts and terms of our descriptive model with concrete values for different properties and factors.

Table 2: Classification of the concepts and terms of the descriptive model.

| | CONCEPTS AND TERMS |
|---|---|
| Reality | entity, object<br>product being designed, design process, design context<br>actor, designer, stakeholder |
| Representations of reality | property, factor,<br>state of the product being designed,<br>state of the design process,<br>state of the design context<br>design situation<br>design activity, design goal<br>design relation design space<br>design task, design session |
| | representation of an entity<br>representation of the product being designed,<br>representation of the design process,<br>representation of the design context |
| | description of the state of an entity<br>description of the state of the product being designed,<br>description of the state of the design process,<br>description of the state of the design context,<br>description of the design situation |

## 3.6 Description structure

In Section 3.3, a design situation is defined in terms of properties and factors. A structure for positioning the various properties and factors can be very helpful for making descriptions of a design situation and for analyzing these descriptions. The description structure presented in this subsection is a domain-independent aid for positioning properties and factors. It connects the descriptive model of the previous sections to design practice. It is the structure formed by the combination of three dimensions for each subject. *Subjects* are the three parts of a design situation, namely the product being designed, the design process, and the design context. The three *dimensions* are ‘level’, ‘perspective’, and ‘time’. Each dimension is specified by a set of *values*. The resulting structure is a three-by-three matrix, as represented in Table 3.

Table 3: Template with specific positioning spaces for the case De Vries.

| SUBJECT | LEVEL | PERSPECTIVE | TIME |
|---|---|---|---|
| PRODUCT BEING DESIGNED | Combi panel<br>Components of combi panel<br>Details of components | Usage<br>Production<br>Performance | Design process<br>Production process<br>Use process |
| DESIGN PROCESS | Design process<br>Design activities<br>Mental processes | Means<br>People<br>Activity | Conceptual design<br>Embodiment design<br>Detail design |
| DESIGN CONTEXT | Branch<br>Company<br>Product-development department | Juridical<br>Economical<br>Esthetical | Design process<br>Production process<br>Use process |

The choice for the dimensions is mainly inspired by the design theory of Bax and Trum (described in, for example, [5] and [6]). This theory is based on general systems theory and also aims at offering a structure to position important concepts and aspects of designing. We define a dimension as one ordinate of a set of ordinates of a three-dimensional space in which properties and factors can be positioned. The three-dimensional space is called a *positioning space*; the dimensions characterize this space. For each subject, a positioning space of three dimensions is defined. Values are articulations on the ordinates of a positioning space. Value sets for the dimensions specify the dimensions and the positioning space. Value sets for the various dimensions are levels for the level dimension, perspectives for the perspective dimension, and processes for the time dimension. To position a property or factor in a positioning space, values for the three dimensions must be given. Each property or factor can be considered on a certain level, from a certain perspective, and in a certain process in which it is important.

To make a detailed description of a design situation using the description structure, the next two steps can be followed:

*Step 1*: defining, using a template, value sets for the three dimensions for each subject, resulting in a matrix as shown in Table 3. Positioning spaces for the specific product being designed, the design process, and the design context must thus be defined. In Table 3, three positioning spaces are specified for the case De Vries. Each table entry contains examples of values for the corresponding dimension of the positioning space corresponding to one of the subjects. This first step can be performed once, at the beginning of the design process; the template can then be refined during the design process if necessary. The advantage of writing down the value sets for each dimension early in a design process is that important terminology about the design task is documented. Because values for the dimensions can be defined in a domain-specific way, the template can be tailored to the needs of a specific discipline.

*Step 2*: describing a design situation in detail by filling out for each property and factor a value for the dimensions in the positioning space of the related subject, resulting in a table as shown in Table 4. The properties and factors in Table 4 are positioned in the positioning spaces defined in Table 3. For example, the property 'yearly electrical yield' (property of the product being designed) can be positioned in the positioning space defined by the values given in Table 3, on the level 'details of components', in the perspective 'performance', and in the 'use process' in time.

Table 4: (Partial) description of a design situation, using the description structure.

| PROPERTY or FACTOR | SUBJECT | LEVEL | PERSPECTIVE | TIME |
|---|---|---|---|---|
| Yearly electrical yield | Product being designed | Details of components | Performance | Use process |
| Need new software to simulate optics of photo-voltaic system | Design process | Design activity | Means | Detail design |
| Product planning | Design context | Product-development department | Economical | Production process |

Step 2 can be followed by an analysis of the description made. The structure may help designers to compare properties and factors of a design situation in terms of their level, their perspective, the process they focus on, and their subjects. It may also help the integration and co-ordination of important aspects; for example, aspects positioned on several levels can be integrated per level. It can also help comparing views of different designers involved in the same design process. The model may also be useful in several applications. A method to support the generation of new ideas based on the use of the structure of the model is proposed in [46]. In Section 4, the use of the model for developing domain-independent support for reflection on a design process is illustrated.

## 3.7 Discussion

Feedback given by the expert designers on (a preliminary version of) the descriptive model is discussed in Section 3.7.1. A comparison of the model with the literature can be found in Section 3.7.2.

### *3.7.1 Feedback*

Feedback was given on the generality (domain independence), relevance, and potential usefulness of the descriptive design model for design practice. In general, all experts recognized the concepts of the descriptive model and understood its terminology; the concepts and terminology therefore seem to be domain independent.

The relevance of the concepts and terminology of the descriptive model was judged as high. The experts stressed that changing desired properties during a design process is common practice. The architects also stressed the importance of the design context and the interaction of designers with the design context during a design process. The importance of changes and interactions is written down by one of the experts in [36] as follows: "The problem is constantly revised, reshaped, and reframed through interaction with this complex entity called the client.". To improve the model, the experts suggested adding the concepts of risks (uncertainties) and of iterations. These concepts have already been added in the model as described in this paper: The concept of risks can be found in Section 3.4; the concept of iterations is discussed in Section 3.5.

The relevance of the three dimensions of the description structure was judged as follows: One of the experts saw the dimensions as abstractions that can be used in a general language; such a language is necessary to understand designers from different disciplines. Abstractions, together with representations, are very important and their importance will increase in design practice when everything must be communicated faster and more efficiently. An architect said that, not only designers, but also the commissioners have to see the importance of dimensions. Already at the beginning of a design project, it is important to consider different levels, different aspects, and different processes in the product lifecycle. Commissioners must give designers time to do so.

Specific comments we received on each of the dimensions are the following: The architects mentioned that *levels* are very important in architecture: Architects have to look at both the overall structure and the details. They must be trained to think on different levels of abstraction; for example, when an architect works on a high level of abstraction (part of a city), it is also important to consider in detail the functions or the compactness of the buildings. A mechanical engineering expert called the most important *perspective* that of the customer; he said that other viewpoints must be derived from that perspective. The architects support the importance of the perspective dimension. For them, a designer should not concentrate on one aspect in isolation; always multiple aspects are important. The experts agreed that for the *time* dimensions, paying attention to other processes than the design process is very important.

From the feedback as stated above, it can be concluded that the experts see potential usefulness of the descriptive model, especially in communication between designers and between designers and commissioners. This is mainly due to the fact that the model makes explicit a combination of important concepts about design processes.

### *3.7.2 Comparison with the literature*

Our descriptive model is unique in the sense that it combines the concepts design situation, design activity, design task, and design context in one domain-independent model. The role of the design context is often not explicitly taken into account in design models. We modeled the design context as part of the state at a certain moment and interaction with the design context as one of the activities performed by designers. More about our explicit modeling of the design context can be found in [51]. The domain independence of the model (discussed in Section 5) makes the model valid for several design phases in several design disciplines and for several types of design activities.

We based our model on the general theory of state-transition systems. State-transition systems are a special form of transformation systems: the latter transform something into something else; state-transition systems transform a state into another state. In the design literature, the notion of transformation is widely used: In Hubka and Eder [26], a design process is modeled as a process of transforming design information. In [61, 62, 74], a transformation from a functional specification to an artifact specification is suggested. More transformation models in the design literature are summarized in McMahon et al. [41]. The concept of state-transition systems is also already used in the field of design. In Salustri and Venter [57] and Van der Net [66], a design process is defined as a series of time-dependent actions that transform the information through a series of states. A similar definition is given in Section 3.5. The theory of Salustri et al. was, however, not taken as a basis for our model because it formalizes 'design information' rather than concentrating on the description of the 'design situation' and 'design activities'; we preferred concentrating on the description of design situations and design activities.

In the remainder of this section, the main concepts of the descriptive model, namely a design situation and a design activity, the property concept, and our definition of designing are compared to the literature and discussed. A *design activity* is described in our model as an activity causing a state transition. This is, however, only one way of describing design activities. In the literature, as mentioned, for example, in Section 3.2.1, many other definitions and models of design activities are given. The concept of a *design situation* is already used in the literature about designing, but we did not find an explicit definition of it. We took the term design situation from Dorst [14]. Dorst points out that a designer is 'thrown' into a design situation. He is inside a design process and is not always in the position to consider it critically and rationally. Hubka and Eder [26, p141] and Badke et al. [4] use the term (design) situation in combination with factors influencing the design process. In our definition, factors influencing the design process and the product being designed are part of a design situation. The classification of important factors made in [26] and [4] also corresponds to the three parts in our definition of a design situation, namely the product being designed, the design process, and the design context. In [55] and [64], the term is used with a similar meaning as in our model. In McDonnell [40], general descriptions of design situations are generated, based on a systematic grammar network. This kind of description differs from our definition of a description of a design situation, due to McDonell's specific perspective on the study of designing, namely an interpretivistic. This perspective is a complementary way of looking at designing. In contrast to our analytical perspective, which focuses on analysis of action as manifested behavior; the interpretivist perspective focuses on understanding action as purposeful, meaningful interaction in a social setting.

Literature about the concept property can be found in general artifact theories like cybernetics [31], systems theory and systems engineering [9, 23]. A core element in these theories is the distinction between structural characteristics and behavioral or functional properties. A systems' structure is designed by determination of its characteristics, whereas the properties of a system determine how it reacts to input and how human beings perceive it. Our concept property (describing a characteristic of the product being designed or the design process) combines the 'structural characteristics' and 'behavioral properties'. We did not make a distinction between both; this refinement can be part of further research. We made only a distinction between properties of the product being designed and properties of the design process, and between current and desired properties. A factor is defined in our model as an external influence on the characteristics of the product being designed or of the design process. It can thus influence both 'structural characteristics' and 'behavioral properties'.

In the literature, many different definitions of designing are given (a brief summary can be found in [15]). It is very difficult to give one general definition of designing. Depending on the importance of certain activities or aspects in the design process, different aspects are emphasized in a definition of designing. A design process is, for example, characterized as an iterative process (in

Evbuomwan et al. [16]), a dynamic process [16], and a dialectical process (Bax [7]). These characteristics can be described in our model as follows: an iterative process can be described as changing and refining properties; a dynamic process as changing states and representations; and a dialectical process as changing between product being designed and design process. We defined designing as the activity of transforming the state of *the product being designed* as well as the state of *the design process*. In almost all definitions of designing, the transformation or creation of the product being designed is included in one way or another. In our definition, also the transformation of the design process is included. Our definition makes explicit that designers also change properties of the design process. Our definition of the goal of a design process includes the concept of *producing representations*. The same idea can be found in Galle [20]. Galle describes designing as the production of design representations. 'Design' in his definition refers to the product; for us, representations can be made of the product (being designed) and of the design process. Note that in the descriptive model, we have chosen to refer to the product during the design process as 'product being designed' and to define a 'representation of the product being designed'. These choices avoid the difficulty of defining a representation of something (a product) without implying the existence of such a non-existent thing (a product does not yet exist during a design process). Galle offers a good discussion on the above mentioned problem and makes an attempt to solve it, but in a different way than we do, namely by defining a design representation in terms of human agents, their actions, and their ideas. More about representations of designed artifacts and of design processes can, for example, be found in Dym [15].

# 4 A prescriptive model for supporting structured reflection

The previous section gives an answer to the question "How to describe design processes in a domain-independent way?". To illustrate the usefulness of the descriptive model for design support, we developed a domain-independent prescriptive model, based on the descriptive model, which offers designers support for reflecting on a design process in a structured way. It partly answers the following question: "How to support structured reflection on a design process in a domain-independent way?". The support, elaborated in a method, is part of an answer since it only supports the first step of the reflection process we propose (see Section 4.1.3).

This section summarizes the prescriptive model briefly. More about the method can be found in [46]. In Section 4.1, we define reflection on a design process, a reflection process, and structured reflection on a design process using the concepts of the descriptive model. The concepts about structured reflection are further explained in Sections 4.2 and 4.3, using the terminology of the descriptive model. Sections 4.4 and 4.5 give an overview of the method and describe its use briefly. In Section 4.6, the prescriptive model is discussed based on the obtained feedback and a comparison with the literature. A more detailed description of the method can be found in [46] and further elaborations in [24], [50], and [52].

## 4.1 Structured reflection on a design process

### *4.1.1 Reflection on a design process*

Main concepts in the descriptive model are design situations and design activities. Designers start from the design situation at a certain moment and perform design activities to meet the design goal at that moment. We define *reflection on a design process* as critically considering the designer's perception of the design situation and of the remembered design activities. Reflection on a design process is thus defined as a combination of *reflection on the perceived design situation* and *reflection on the remembered design activities*. A design situation offers a static perspective on the design process; design activities offer a dynamic perspective on the design process. Reflection on the design situation can, for example, offer information (1) about the difference between current and desired properties of the product being designed, which is useful for checking if all important

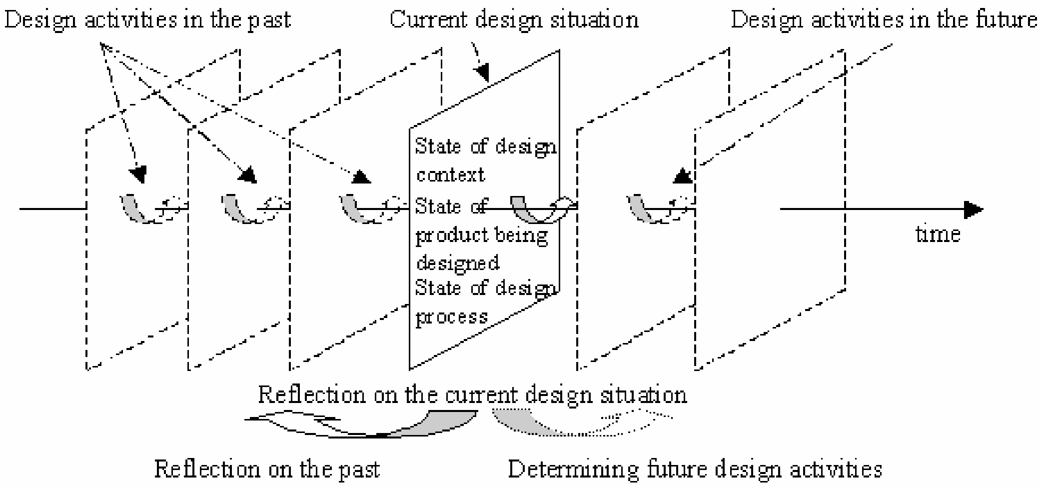

Fig. 8. Reflection on a design process.

aspects are taken into account; (2) about the difference between the current and the desired state in the design process, which is useful for judging its progress; (3) about important factors in the design context, which is useful for determining next interactions with the design context. Reflection on the performed design activities can, for example, learn which activities were not successful for reaching the design goal or how to improve the efficiency and effectiveness of certain activities. Together, these two kinds of reflection can help to reach the goal of reflection on a design process, namely to determine suitable next design activities in the design process. The definition of reflection on a design process is illustrated in Figure 8. In our view, reflection on a design process aims at answering essential questions like “Am I solving the essential problems or am I busy with sub-optimizations?”, “Does the result feel satisfactory or are further iterations necessary?”, “Is my way of designing effective and efficient?”, “Is my design process appropriate for the problem?”.

### 4.1.2 A reflection process

We define *a reflection process* as a process that consists of three main activities that are called preparation, image forming, and conclusion drawing. These steps are related to the steps of the basic design cycle [53], to the mechanism of reflective practice [55], to the major stages in creative problem-solving processes [28], and to the stages of a reflection process as described by Daudelin [13]. The *preparation* step consists of collecting facts, preparing initial questions, and analyzing the facts critically in relation to these questions. The facts in the preparation step are the properties, factors, and relations between properties and factors of the design situation and the design activities performed during the design process. The following evaluation criteria can be important for the critical analysis: coherency, completeness, consistency, reliability, and validity of the facts (based on Schön [55]). The *image-forming step* makes a selection and synthesis of the facts and their analysis. The goal of the image-forming step is to form an image of the design process as a whole, based on the information collected and analyzed during the preparation step. The designer has to lean back for a while and form an image of the design situation and the performed design activities. During the *conclusion-drawing step*, the image is analyzed; the questions “Why is the situation like that?”, “What can I learn?”, and “What must be changed?” should be answered. During the conclusion-drawing step, the image of the design process and the goal of the design process are taken into account to determine the next activities in the design process. What can be learned is relative to the expectations. During the conclusion-drawing step, new expectations can be formulated. The preparation and image-forming step mainly look back in the past. The conclusion-drawing step starts from the results of the first two steps and looks forward to determine the next activities. We introduce the possibility of a break between the preparation and image-forming step to simulate ‘natural’ reflection processes in which some incubation period is necessary before conclusions can be drawn. We assume that during this break, the reflection process continues, but in an unconscious way.

### *4.1.3 Structured reflection*

*Structured reflection* on a design process is defined in this paper as the combination of reflection in a systematic way and reflection regularly during a design process. A systematic approach decreases the chance of overlooking important aspects. Regular reflection increases the chance that reflection is performed during a design process. Structured reflection indicates thus something about how to reflect and when to reflect. Our method, as introduced in the next subsections, supports when to reflect on a design process and partly how to reflect. The method only supports *how* to perform the preparation step of a reflection process, namely by supporting the description of design situations and design activities and the analysis of these descriptions in a systematic way; describing a design process is one way to become aware of it and to get an overview. We used the concepts of the descriptive model to know what to describe, namely the design situation, design activities, and interaction with the design context. Developing support for the image-forming and conclusion-drawing steps of a reflection process must be part of further research. This support will be less rational and analytical than the method developed so far but more intuitive and synthesis-oriented, and will require knowledge of cognitive and social sciences. The method supports *when* to reflect by introducing the idea of design sessions. Design sessions create some structure in the design process that is useful for regular reflection. In the descriptive model, a design situation is defined as the state at a certain moment. A design session is defined as a specific period between two states (see Section 4.3). The two main concepts of our method, namely the description and analysis of design situations and design activities and the idea of design sessions, are briefly explained in the next two sections.

## 4.2 Description and analysis of design situations and design activities

Describing the design situation and design activities is aimed at getting an overview of the important facts; analyzing these descriptions is the basis for determining next design activities. Three checklists and three forms have been developed to help designers with performing the preparation step of a reflection process in a systematic way. The *forms* can be used to describe the properties of the product being designed and the design process, the factors of the design context, relations between properties and factors in the design situation and performed and planned design activities, including interactions with the design context. Our forms are similar to worksheets, design logs, diaries, and design-history systems described in the literature, for example, in Hansen [25] and Wiegeraad [71]. The goal of all these 'things' is to store information about the design process that can be looked up later on in the design process or in research settings. We developed a *checklist* to help designers with inventorying important aspects of the design situation. Two checklists have been developed to help also with the analysis of design situations and design activities. The checklists stimulate to look from different perspectives at the design process. They include questions like "What are desired properties of the product?", "Which part of the project budget has already been used?", "What are important stakeholders and their concerns?", and "What are important processes in the product lifecycle?". Note that the latter question concerns the time dimension of the description structure as explained in Section 3.6. The checklists and forms have, on purpose, been kept simple to avoid that designers see them as a burden. They are first proposals, exploring the possibilities of possible support.  The next two subsections describe support for reflection on a design situation and reflection on design activities.

### *4.2.1 Reflection on a design situation*

Making a description implies modeling the reality from a particular point of view, i.e., neglecting certain irrelevant characteristics. To make a description, the questions "What to describe?" and "How to describe it?" must be answered. The method helps designers to answer these questions, by means of checklists and forms.

*What to describe?* Making a description of a design situation is similar to explaining the state of a design task to an outsider to the project: The problem, the requirements, and the obtained solutions are explained; the state of the design process and other related processes are given; and factors in the context that influence the design task are mentioned. According to our descriptive model, for making a description of a design situation, the state of the product being designed, the design process, and the design context must be described.

*How to describe a design situation?* We propose to make a textual description of a design situation with references to other types of representations (graphs, sketches, drawings, or prototypes). The description can be a combination of quantitative and qualitative information and can be at any level of detail.

Table 5: An example of a filled out FORM Properties&Factors.

| FORM Properties&Factors: Description of a design situation: properties and factors | | | |
|---|---|---|---|
| Design task: Design of a photo-voltaic/thermal hybrid panel | | | |
| Designer/team: Douwe De Vries | | Date: March 14 | Time: 11h50 |
| **Subject** | **Properties/factors** | **Values of properties/factors** | |
| The product being designed | dimensions of a hybrid solar energy panel | 0.25m high, 1.2m wide, and 1.5m long | |
| | type of a hybrid solar energy panel | photo-voltaic/thermal combi panel | |
| | yearly electrical yield | ‚x’ | |
| | yearly thermal yield | ‚y’ | |
| The design process | max. duration | 1 year | |
| | time spent | 9 months | |
| | budget spent | 20.000 euro | |
| The design context | stakeholders | company of sun collectors, Shell Solar energy B.V., The Energy Center of the Netherlands, Technnische Universiteit Eindhoven | |

FORM Properties&Factors has been developed to help designers in making a description of a design situation. An example of a filled out form is given in Table 5. This form is a table that consists of one column for the subject of the properties and factors (being the product being designed, the design process, or the design context), one for labeling the properties and factors and one for describing the values of the properties and factors. Every row of the table describes one property or factor. Only important properties and factors must be described; designers themselves have to decide what is relevant in a particular situation. For that reason, it is necessary to realize that the main goal of the description is reflection and not making a complete documentation of the situation. The developed checklist (as discussed below) can help designers deciding what to describe. We do not prescribe in detail which aspects are important because they differ for each discipline, design task, and designer. A list of issues that designers tend to overlook and that need to be brought to their attention, specific for a certain group of designers, might, however, be useful. The form also includes cells for the name of the design task, the name of the designer, and the date at which the description is made.

FORM Relations has been developed for describing relations between properties and factors. This form is a table that consists of one column for labeling the relations, one column for describing the first part of the relation (from a certain property or factor), one column to describe the second part of the relation (to a certain property or factor), one column to describe the kind of relation, and one column to describe the rationale behind the relation. Every row of the table describes one relation. An example of a filled out form is given in Table 6.

Table 6: An example of a filled out FORM Relations.

| FORM Relations: Description of a design situation: relations | | | | |
|---|---|---|---|---|
| Design task: Design of a photo-voltaic/thermal hybrid panel | | | | |
| Designer/team: Douwe De Vries | | | Date: March 14 | Time: 11h50 |
| **Relations** | FROM | TO | KIND | RATIONALE |
| Thermal yield (1) | Yield | Degree of insulation of collector | Is influenced by | A high insulation degree offers a good yield |
| Thermal yield (2) | Yield | Temperature of photovoltaic cells | Is influenced by | Cold photovoltaic cells offer a good yield. |
| Produce ability | Dimensions of production machines | Dimension of combi panel | Limit | The production machines limit the dimension of the combi panel. |
| Capacity | Staff | Duration | Influences | With more capacity, the duration of the design process can be shorter. |

Table 7: Basic CHECKLIST Description Design Situation.

| CHECKLIST FOR INVENTORYING PROPERTIES AND FACTORS |
|---|
| **Design task (properties)**<br>– Product being designed<br>    – What is the desired state of the product being designed?<br>    – What is the current state of the product being designed?<br>– Design process<br>    – What is the desired state of the design process?<br>    – What is the current state of the design process?<br>**Context of the design task (factors)**<br>– What is the current state of the design context?<br>– What are possible trends in the design context? |

CHECKLIST Description Design Situation has been developed to help designers with inventorying important properties and factors. The structure of the checklist consists of two main parts, namely one part for the design task and one part for the design context. This distinction separates questions about properties and questions about factors. Questions about the design task are subdivided into questions about the product being designed and questions about the design process. Together, these parts cover the three parts of a design situation, namely the product being designed, the design process, and the design context. For the product being designed and for the design process, questions about the current and the desired state are being asked. The distinction between current and desired state is important because future design activities must be determined based on differences between the current and the desired state. For the design context, questions about the current state and possible trends are asked. The described checklist, shown in Table 7, is a basic checklist that is domain independent, but that can be tailored to the needs of a specific design discipline, design task, or user by adding questions about specific topics. An example of a checklist including questions about specific topics is shown in Table 8. These specific topics are based on our case studies and literature study. Among others, the following literature has been consulted: [4], [26], and [22]. Further research is necessary to define a good set of topics.

The goal of *analyzing* a design situation is to look critically at the current and desired state. A critical analysis can be performed by asking and answering a number of questions. Our method supports a designer in asking relevant questions about individual properties, factors, and relations and about a set of properties, factors, and relations.

Table 8: An example of CHECKLIST Description Design Situation.

| CHECKLIST FOR INVENTORYING PROPERTIES AND FACTORS |
| --- |
| **Design task (properties)** |
| – Product being designed |
|   – Which main problem must be solved? |
|   – What are desired properties of the product? |
|   – Which representation of the product being designed is desired? (medium, level of detail) |
|   – What are properties of the product being designed at this moment? |
|   – What are the important problems to be solved at this moment? |
|   – Which representations of the current state of the product being designed have been made? |
| – Design process |
|   – What is the deadline of the design process? |
|   – What is the budget for the design process? |
|   – What is the capacity of the design team? |
|   – Which other properties of the design process are desired? |
|   – Can the deadline of the design process be met? |
|   – Who are the members of the design team? |
|   – Which part of the budget has already been used? |
|   – How is the design process supported (machines, software, tools, secretary, room, methods, procedures, environment, etc.)? |
|   – What are problems in the design process at this moment? |
|   – Which representations of the current state of the design process have been made? |
| **Context of the design task (factors)** |
| – What are the important stakeholders and their concerns? |
| – What are important processes in the product lifecycle? |
| – What are important factors in these processes? |
| – Which related design tasks have been defined? |
| – What are important factors in those related design tasks? |
| – What are the current and the desired state of the overall design task? |
| – What is the company strategy regarding product planning? |
| – How does the company's vision influence the design task? |
| – What are important competitors? |
| – Which norms and laws are related to the design task? |
| – What is the state-of-the art knowledge related to the design task? |
| – Which representations of the current state of the design context have been made? |
| – What are possible changes in related design tasks? |
| – What are possible changes in the processes of the product lifecycle? |

CHECKLIST Analysis Design Situation consists of questions about specific topics ordered in some kind of structure. The structure of the checklist consists of four parts, namely an analysis of the state of the product being designed, of the design process, of the design context, and of the complete design situation. An example of CHECKLIST Analysis Design Situation, including questions about specific topics, is presented in Table 9. More empirical research is necessary to improve the list of questions. The checklist should also be tailored to the needs of a specific design discipline, design task, or user. The questions mentioned in Table 9 are based on the following evaluation criteria: coherency, completeness, consistency, reliability, and validity of the facts (as mentioned in Section 4.1.2). Questions about completeness and consistency can be answered by comparing the current and the desired state. Validity of the desired properties can take place together with the stakeholders. No special form for describing the answers to the questions of the analysis has been developed, because answers to these questions are supposed to be used for the completion of FORMS Properties&Factors and Relations.

Table 9: An example of CHECKLIST Analysis Design Situation.

| |
|---|
| CHECKLIST FOR ANALYSING DESIGN SITUATIONS |
| **Analysis of the state of the product being designed** |
| – Is the list of important desired properties about the product being designed complete? |
| – Is the list of important desired properties about the product being designed consistent? |
| – What is the core problem to be solved? Is this the real problem to be solved? Are similar problems known? |
| – Is the list of important current properties about the product being designed complete? |
| – Is the list of important current properties about the product being designed consistent? |
| – Which desired properties are met up to now? |
| – Are all factors taken into account in the design of the product being designed? |
| – Which representations of the product being designed are missing? |
| – What are consequences of the current state of the product being designed for processes in the product lifecycle? |
| – What are alternative properties and values? Why? |
| – Does the product being designed fits its purpose? To what degree is the design challenge met and are the design conflicts resolved? What are the chances on the market? Is the product being designed future oriented with respect to the future development of the market and the technology? |
| – Which current properties can be improved? Why? |
| – Which concepts of the product being designed can be re-used? |
| |
| **Analysis of the state of the design process** |
| – Is the list of important desired properties about the design process complete? |
| – Is the list of important desired properties about the design process consistent? |
| – Which desired properties are not met? |
| – Are all important factors taken into account in the design of the design process? |
| – Which representations of the design process are missing? |
| – What are consequences of the current state of the design process (duration, budget, capacity, etc.) for other processes in the product lifecycle? |
| – What are alternative possibilities for the organization of the design process? |
| – How was the management support? How was the collaboration with the design team? |
| – How can the current state of the design process be improved? |
| – Which concepts of the design process can be re-used? |
| |
| **Analysis of the state of the design context** |
| – Is the list of relevant factors complete? |
| – Are other representations of the design context desirable? |
| |
| **Analysis of the complete design situation** |
| – What is the challenge of the design task? |
| – Is the list of important relations complete? |
| – Are all relations consistent? |
| – Are properties about the product being designed and properties about the design process mutually consistent? |

### *4.2.2 Reflection on design activities*

Support for the preparation step of reflection on a sequence of design activities, or, in other words, reflection on the flow of the design process, is discussed in this section. Based on the descriptive model, the following types of design activities are distinguished:

- activities that change properties of the product being designed; for example, solving conflicts, looking up production techniques, trying out alternative solutions, and testing results;
- activities that change properties of the design process; for example, contacting a new design-team member, discussing support for the design process, and arranging a meeting with stakeholders for getting acquainted;
- activities that consist of interactions with the design context; for example, asking and receiving information from stakeholders, and giving information to stakeholders.

To reflect on the design activities in the design process, also an overview of important transitions (changes) in the design context is needed. We propose to make a description of both design activities and transitions in the design context. The level of detail of this description must depend on the design task and the preferences of a specific user.

Table 10: An example of a filled out FORM Design Activities&Transitions.

| FORM Design Activities&Transitions: Description of design activities and transitions | | | | |
|---|---|---|---|---|
| Design task: Design of a photo-voltaic/thermal hybrid panel | | | | |
| Designer/team: Douwe De Vries | | | Date: March 14 | Time: 11h50 |
| | **Design activities** | | | **Transitions in the design context** |
| | ACTIVITIES ABOUT THE PRODUCT BEING DESIGNED | ACTIVITIES ABOUT THE DESIGN PROCESS | INTERACTIONS WITH THE DESIGN CONTEXT | CHANGES IN THE DESIGN CONTEXT |
| **Past** | Generate design concepts | Discussion with other junior designers | Contact company of solar cell for information about production of prototype | Company of solar cells wants more focus on electrical modeling |
| | Model design concepts to estimate yearly electrical and thermal yield | | | |
| **Future** | Evaluate the design concepts economically | Solve software problem | Talk with company of solar cells | Changes in production technology |
| | Define requirements of a prototype | Hire expert on production process? | Analyze related patents (rationale: to find which components cannot be used without permission) | |
| | Design, realize and test the prototype | | | |

FORM Design Activities&Transitions supports the description of design activities and transitions in the design context. This form consists of four main parts defined by two main columns and two main rows. The two columns are labeled 'design activities' and 'transitions in the design context'. The two rows are labeled 'past' and 'future'. The two columns distinguish important design activities executed in the design task and transitions in the design context. The rows distinguish design activities and transitions performed in the past and to be performed in the future. The first column is subdivided into three other columns: one column for describing activities about the product being designed, one column for describing activities about the design process, and one column for describing interactions with the design context. The activities, interactions, and transitions and their rationale can be given in the cells. An example of a filled out form can be found in Table 10.

To support the analysis of past and future design activities and transitions in the design context, CHECKLIST Analysis Design Activities&Transitions has been developed. The structure of the checklist consists of five main parts, namely an analysis of the activities about the product being designed, of the activities about the design process, of the interactions with the design context, of the complete design process, and of transitions in the design context. An example of CHECKLIST Analysis Design Activities&Transitions, including a first proposal of questions that can be asked, is presented in Table 11. Again, more empirical research is necessary to improve this list of questions.

Table 11: An example of CHECKLIST Analysis Design Activities&Transitions.

| |
|---|
| CHECKLIST FOR ANALYSING DESIGN ACTIVITIES AND TRANSITIONS IN THE DESIGN CONTEXT |
| **Analysis of activities about the product being designed** |
| – How did the desired state of the product being designed evolve? |
| – How did the current state of the product being designed evolve? |
| – What were problems in executing the activities about the product being designed? |
| – How can the activities about the product being designed be improved? |
| **Analysis of activities about the design process** |
| – How did the desired state of the design process evolve? |
| – How did the current state of the design process evolve? |
| – What were problems in executing the activities about the design process? |
| – How can the activities about the design process be improved? |
| **Analysis of interactions with the design context** |
| – What were problems in executing the interactions with the design context? |
| – How can the interactions with the design context be improved? |
| **Analysis of the complete design process** |
| – What is the cause of problems in the design process? Could these problems be solved in a different way? What can be learned from these problems for future processes? |
| – Which design activities did not result in a change towards the design goal? Why? |
| – Which mistakes were made in the design process? Had it been possible to anticipate these mistakes? |
| – Is enough progress made in the design process? |
| – Which design activities can be performed more efficiently? How? |
| – Which concepts of the design process can be re-used for a similar design task? |
| – What were critical situations? |
| – What can be learned from the evolution of the different states? |
| – Which design activities must be performed in future subtasks? |
| Analysis of transitions in the design context |
| – How did the design context evolve? |
| – How can transitions and future transitions in the design context better be taken into account? |
| – How can laws be influenced? |

## 4.3 Design sessions

The second concept of our method, namely the idea of design sessions*,* aims at supporting regular reflection. In Dorst [14], it is described that a designer, when designing, is inside a design process (thrown into a situation) and not always in the position to consider the process critically and rationally. A designer that wants to be in control of the design process [by means of regular reflection on the design process] must step out of the 'designerly way of thinking' (Cross [10]) every now and then. Based on these observations, it seems important to reserve certain moments during the design process for reflection. Reflection only at the beginning and end of a whole design process is often too superficial; reflection must take place at many more moments during a design process. Currently, a design process is usually structured as a series of design phases (defined by milestones). Depending on the project, these phases take weeks or even several months. In our opinion (and as indicated in the empirical basis in Section 3.1), the period of a design phase is often too long to support designers accurately in their daily activities, i.e., to support regular reflection. On the other hand, the period between two reflections may not be too short, because then, the reflections interrupt the creative process and are not efficient. The period of time of a design session is a good and flexible compromise.

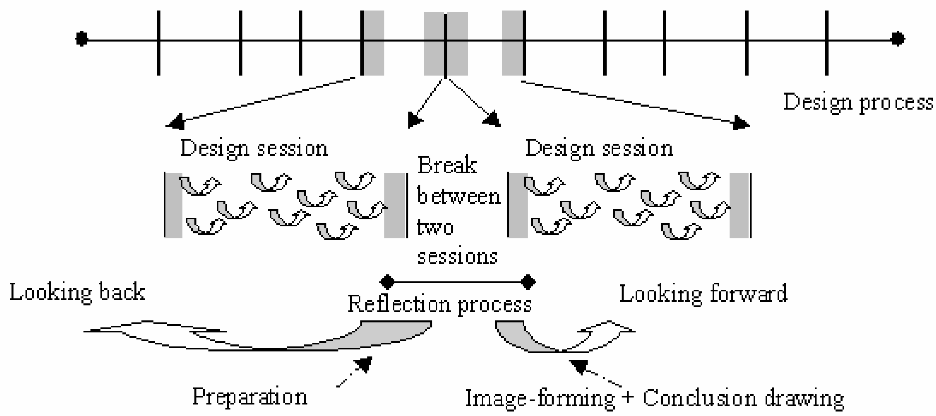


Fig. 9. The structure of a design session.

A *design session* is defined as a period of time during which one or more designers are working on a subtask of a certain design task. A design session can take a period of time like one afternoon, a whole day, some days, or a week; it is often shorter than a design phase. Breaks between design sessions can be coffee or lunch, interactions with stakeholders in the design context, other meetings, periods spent working on other projects, weekends, holidays, or others. A design process can be seen as a sequence of design sessions; a design task is being executed during a series of design sessions. Designers can themselves determine the duration of a design session. We propose to reflect at the beginning and end of the design session and to design during the core of the session. As illustrated in Figure 9, we propose to devise a reflection process over two design sessions. At the end of a session, the preparation step should be performed. When the preparation step is finished, the session ends and a break is made. A new session starts with the continuation of the reflection process, namely the image-forming and conclusion-drawing steps. These steps should determine the focus and direction of the next design session and generate ideas for design activities to be performed.

## 4.4 Overview of the method

Our method for supporting structured reflection consists of the following four steps that can be repeated for each design session.

1. Ending a design session with *reflection* on the design situation and design activities, using the forms and checklists. First, properties of the product being designed, properties of the design process, important factors in the design context, and relations between properties and factors can be described and analyzed. Second, the most important design activities and interactions with and transitions in the design context can be described and analyzed. The activities performed during the preparation step stimulate designers to look from different perspectives at the current design situation and the performed design activities. This broad view can be very helpful during the image-forming and conclusion-drawing steps, performed at the beginning of the next session. When the filled out forms are kept for the next session(s), these can be used as some kind of documentation of the previous design situations, of design activities performed in the previous design session(s), and of possible design activities for the next design session(s).
2. Starting a new design session with *reflection* on the design situation and design activities, based on the use of the checklists and based on information written down on the forms at the end of the previous session. At this moment, the image-forming and conclusion-drawing step of the reflection process must take place. No support is yet provided for these steps, but any kind of support can straight forwardly be plugged in.
3. *Planning the duration of the current design session* by planning the end of the design session and thus also the moment for the start of the next reflection process. The duration of a design session and the planning of a sequence of design sessions may depend on the planning of the

design task and on the agenda of the designers and other persons involved in the design process. When planning a design session, a designer automatically plans moments for reflection, namely at the beginning and end of each session.
4. *Designing* during the core of the design session. No specific support for performing design activities during a design session (what to do in a particular design situation) has been developed. Many disciplines have their own design methods that can be used at this stage. During the core of a design session, designers also have to realize that they will need some time for reflection at the end of the design session. For example, when they go to lunch at twelve o'clock, they have to stop their design activities ten minutes before, to have some time for reflection.

## 4.5 Using the method

The method has been developed to help designers with structured reflection on a design process. The method is intended for individual designers in every type of design project. An individual designer can perform the four steps of the method described in the previous section. We believe both novice and expert designers may benefit from using this kind of reflection support, but for different reasons: Novice designers may profit from the overview they can get by describing and analyzing the design situation and design activities regularly during a design process. Expert designers are often involved in much more complex projects, in which reflection is useful for determining further actions to be taken. Because the method is domain independent, it may be useful in different design disciplines and in multidisciplinary projects. The use of the method can be tailored to the needs of a specific discipline and designer by defining domain-specific questions and structures for the checklists and forms and designers can plan the moments for reflection according to their preferences. Some learning time is needed to get experienced with the method and to use it efficiently.

The concrete use of the method can be realized in several ways: The forms can be filled out on paper or a computer can assist the user. We developed a *prototype of a software system*, called Echo, to explore the benefits of using a software system to facilitate the use of the method. In the prototype, so far, only the description and analysis of design situations is yet supported. Echo consists of a database for storing properties, factors, and relations, a database-management system, and a user interface. Echo is domain independent, but the concept of a template makes it possible to tailor the use of the method to the terminology and concepts of a specific discipline. The prototype can be used during the first step of the method for describing and analyzing a design situation. To *describe a design situation*, a user can add properties and factors in a tree, describe properties, factors, and relations more precisely by using electronic forms, and change values for the various attributes in the electronic forms. To *analyze a design situation*, a designer can query information and check design relations. A detailed description of the prototype, including recommendations for further development, can be found in [46] and [47].

Below, the use of the method is illustrated for an hypothetical example, based on the obtained data of the case Douwe De Vries. In the example, Douwe uses the method in the ninth month of his project. To perform step 1 of the method, he ends his design session (A) on Wednesday morning March 14th with describing the design situation and design activities, using the forms and checklists as described in Section 4.2. The filled out forms are (partly) given in Tables 5, 6, and 10. When finishing the description and analysis, he takes a break and goes out for lunch. He starts his afternoon design session (B) with performing steps two and three of the method. For performing step two of the method, he makes a selection and synthesis of the facts described in the forms. He is triggered by his lack of expertise on production processes, as suggested in Table 10 During the conclusion-drawing step, he looks up what was again the goal of his design process. He decides that he will not finish the design of the production of the hybrid panels, but leave it to other designers. During the rest of his design process, he will concentrate on the other aspects of the design of the panel. He plans to evaluate, in the current design session B, the design concepts during two and a half days. The end of the design session B will thus be Friday evening, when the start of a new reflection process will thus take place (again step 1). Performing the planned activities for design session B corresponds to performing step 4 of the method.

## 4.6 Discussion

This section summarizes the feedback of junior and expert designers on (a preliminary version of) the prescriptive model and compares the model with the literature. Feedback was given to judge the generality, the relevance, and the potential usefulness of the results for design practice. More about the received feedback can be found in [49].

### *4.6.1 Feedback*

*Expert designers* from the three studied design disciplines understood the concepts of the method, which indicates the domain independency of the concepts. To indicate the relevance of our support, the experts made clear that different kinds of reflection and critical analyses are already performed in the current design practice of the experts. We could make a distinction with respect to different moments in time when the reflection is performed, with respect to reflection by an individual and a group, with respect to formalized and non-formalized reflection, and with respect to the fact that results of the reflection are used as documentation or not. For the expert designers, the term 'session' refers to meetings (group sessions). The implementation of the method must thus take into account the specific processes/procedures related to reflecting already existing in a certain company. Our combination of systematic reflection with design sessions seemed relevant to the experts.

The experts gave us some warnings concerning the usefulness of the developed support: Non-trivial analyses (reflection) consume very much time. When these analyses are performed too often, they may become a ritual, problems are being avoided, and nothing is learned anymore. Awareness of the whole design situation may also become routine when reflection on the design situation is performed too often. The method must also only be used as a guideline in a flexible way, i.e., not forcing designers to follow the steps exactly. The need for reflection also differs for the phase in the design process. Reflection may be less meaningful when minor decisions are taken during elaboration of a certain concept. Several expert designers (mainly in architecture) mentioned that the need for reflection on a design process early in the process is high: Certain aspects, like production methods, are usually taken into account only too late in a design process. This results in many problems, like redesigning the product during the production process, which consumes a lot of time and money.

*Junior designers* used the method and prototype software tool during two design sessions. The general goal of the method was clear to all of them. They judged the concepts of the method as relevant and useful; the form and elaboration of the method, however, were seen as not yet good enough to be useful in design practice. A negative aspect of the method mentioned very often by the designers was that the method was presented in a very general way and that it was not focused on a specific discipline. Making the translation of the general terminology of the method to the designer's discipline-specific terminology was experienced as difficult because, for example, no domain-specific questions were included in the checklists. The method also forced designers to write down very specific information and left them little freedom. The method also required too much administration from the designers. The junior designers suggested that reflection might not necessary require the documentation of a lot of information.

Almost all participants mentioned the same advantage of the method, namely that it offers help to get an overview (of the design situation and of the design activities). Other characteristics of the method mentioned by the designers are the following: The method helps to increase awareness about the design situation, the steps taken, and the working method; asks relevant questions to think about; helps to identify problems that might otherwise have been forgotten; helps to work in a more focused way; helps to bring order in a chaotic design process; offers opportunities to define and improve the design process; supports learning from shortcomings; is directed towards a continuous improvement of the design quality and a comparison with other stadia of the process; helps to make good documentation of the project state; and offers help to describe the design process.

The designers suggested the following improvements of the method: give an explanation based on an example in a specific discipline; make translations of the terminology to specific disciplines (domain-specific forms and checklists); make the checklists and forms adaptable in time (for example, differences for specific design phases) and adaptable to a specific designer; make the method more compact (decrease the number of forms in order to decrease administration); and test the method in a design process taking more than one month. Note that the changes proposed by the junior designers to overcome the difficulties with the abstract terminology are not very hard to incorporate, but care has to be taken to maintain the domain-independent nature of the method.

### *4.6.2 Comparison with the literature*

Our method can be positioned in the literature as follows. It can be seen as a 'systematic' method. Related methods are methods for exploring design situations and methods of evaluation, as described in [30]. A systematic method that is developed to support a complete reflection process is described in [5] and [70]. The latter authors try to provide designers with support for reflecting on adequate and inadequate design processes and to teach designers to identify critical situations (situations that have an important influence on the further direction of the design process or the product being designed). For this purpose, a training concept that asks involvement of external observers and teachers is developed. For supporting a complete reflection process, our method might also be extended with a training concept. The core of our model is, however, reflection performed by the individual designer himself, without the help of external observers. In some sense, our approach can be compared to the concept of concentric development, described in [53]. Concentric development essentially means taking into consideration all important aspects (of a product-development process) in 'each round'. In practice, a round corresponds to a phase of a product-development process. In our method, concentric development can be seen as taking into account all aspects of a design situation, namely the product being designed, the design process, and the design context, in each design session.

Our forms are developed to help designers making a description of a design situation and of design activities in a systematic way. These forms are similar to worksheets, design logs, diaries, and design-history systems described in the literature, for example, in Hansen [25] and Wiegeraad [71]. The goal of all these 'things' is to store information about the design process that can be looked up later on in the design process or in research settings. Our idea of design sessions, developed to let designers reflect regularly during a design process, is, as far as we know, not yet used for stimulating regular reflection. Schön [56] proposes designers to reflect when a 'surprise' occurs during a design process. However, when a designer does not recognize this 'surprise', no explicit reflection will take place. Our method stimulates designers to reflect on the design process at the beginning and end of a design session. This means that the creative processes in the design process are not disturbed and that each kind of designer is stimulated to reflect many times during each design process. Our viewpoint on reflection is similar to Schön's 'reflection-on-action', which can be defined as thinking about doing after doing, in such a way as to influence further doing.

The development of our method is based on the assumption that explicit reflection can improve design processes. In the managerial context, a similar assumption is already proved: In [13], it is stated that providing managers with a one-hour reflection session, using structured questions and guidelines, significantly increases the learning from their experience. Because our method is only tested during two design sessions, empirical research during a longer period of time and in many different design processes is necessary to check our assumption.

The contribution of our method to design research can be seen as a first proposal of a method that supports (structured) reflection on a design process. We add to design processes a reflection process that includes a conscious preparation step and a conclusion-drawing step that stimulates to look forward in the design process. The method includes concepts for the systematic support of the preparation step of a reflection process and for regular reflection during a design process. Mainly the reflection process of individual designers is supported. In contrast to many other methods, our method pays attention to the product being designed, the design process, and the design context. The method also introduces the idea that designers can be supported on the level of design sessions instead of only on the level of design phases (design sessions are often shorter than design phases). In this way, the idea of design sessions offers also a new approach for organizing a design process.

# 5 Conclusions

In this paper, we presented the results of a broad exploratory study into design processes, based on an empirical study performed in the disciplines architecture, mechanical engineering, and software engineering. The main result is a descriptive model that is developed to describe design processes in a domain-independent way. To judge if the model is really domain independent, we have to check whether or not it fulfils the three criteria of domain independence we stated in the introduction. The first criterion is met in the sense that our model abstracts from domain-specific aspects. The concepts of our model are understood in each discipline we investigated and are compatible with the concepts in general design theories, as mentioned in Section 3.2.1. The structure of the model seems also to be domain independent. Some designers giving us feedback on the model had, however, difficulties with the domain-independent terminology (see Section 4.6). This difficulty can be overcome by providing examples from several disciplines and tailoring the domain-independent terminology to the specific terminology of designers in a specific discipline, for each specific application of our model. Also, experience with the use of the model will facilitate the use of the terminology. We met the second criterion in the sense that we performed research in the disciplines of architecture, mechanical engineering, and software engineering. The third criterion concerns the usefulness for several disciplines and multidisciplinary teams. We found that already only studying similarities and differences in several disciplines is useful for these disciplines, because they have to make explicit their concepts. The comparison of concepts and approaches between disciplines can also offer new points of view for the separate disciplines; a well-known example is software engineering that learns from architecture a way of thinking in design patterns [19]. Our model may be used as a basic representation of a design process both in design practice and design education. It can stimulate and improve communication between designers (in multidisciplinary projects) and between designers and stakeholders in the design context. The model can offer designers and design students a vocabulary for talking and thinking about design situations and design activities and can offer more insight into their design processes. A precise and consistent vocabulary is a necessary condition for improving communication in practice; communication may result in an improved product being designed and a more efficient and effective design process. The domain-independent terminology can also help design researchers from different disciplines to learn from each other. The description structure of the model may help designers as indicated in Section 3.6 and has already been used for developing domain-independent support for reflection on a design process, as illustrated in Section 4.

As a result, we may conclude that the three criteria for domain independence are met and that the model is domain independent. The design processes in the three disciplines we studied can thus be described fruitfully in a domain-independent way with the developed concepts, vocabulary, and structure. We assume, however, that it is also possible to describe design processes in other disciplines with the same model; our concepts correspond, for example, to general concepts used in the domain of computer and electrical engineering, for example, described in Van der Putten et al. [68] and Voeten et al. [69]. As already stated above, we presented in this paper also a prescriptive model for supporting structured reflection on a design process, in which we applied the descriptive model. It illustrates the usefulness of the concepts and structure of the descriptive model for design support. We can now conclude that we answered, at least partially, the two main research questions mentioned in Section 2. Some further comments on our results are given below.

The descriptive model describes a design process from the viewpoint of state-transition systems, which is one of many different points of view to describe a design process. In the model, a tension between the general concepts of state-transition systems and the specific aspects of design processes in practice can be recognized. We made the general theory of state-transition systems suitable for describing design processes by instantiating it with important characteristics of design processes in practice like the concept of a design situation and that of a design activity and by adding the distinction between current and desired properties and between properties and factors, the concept of alternatives, the concept of co-evolution of desired and current properties, the concept of a design goal at a certain moment (not 'the' design goal fixed during the whole process), the concept of a design task, and a specific definition of designing. We also explicitly modeled the role of the design context in the design process to make designers aware of the importance of factors in the design context and of interaction between designers and stakeholders in order to improve the quality of both the product being designed and the design process. Many aspects of design processes in practice are, however, not explicitly modeled in our model, like designers and design teams (with their personality, intuition, creativity, and other skills), and aspects like design decisions and design phases. The latter two concepts can, however, easily be modeled using the theory of state-transition systems: A design decision can be modeled as an elementary transition, taking a short period of time; a design phase can be modeled as a transition taking a long period of time. The theory of state-transition systems is however not appropriate to model a designer and his characteristics; theories based on the social sciences are more appropriate to do so.

To further increase the usefulness of our model for supporting communication between designers (from several disciplines) and for supporting interaction between designers and stakeholders in the design context, the descriptive model must be refined and extended. A major extension is the explicit modeling of the designers and the stakeholders and their characteristics as individuals and as groups. To add these concepts, as already mentioned, the model should be extended with concepts from social sciences in which humans (designers) get a central role. For the extension of the design model, further research can also be based on multidisciplinary teams instead of only on individual designers in a number of disciplines as we did. For supporting communication between designers of a multidisciplinary team, support to make a common (domain-independent) representation of a design situation would be useful. For supporting interaction between designers and stakeholders, types of interaction and communication between designers and several types of stakeholders in the design context can be studied.

The descriptive model can also be refined with the concepts hierarchy and parallelism. Hierarchy (of properties, factors, relations, design tasks, and representations) can, for example, make explicit the relation between subtasks of design tasks and these design tasks, and make explicit the relation between representations that cover part of other representations and these latter representations. Parallelism makes it possible to describe the execution of several subtasks in parallel. The proposed structure of the description structure is not the only one possible; testing several alternatives for this structure may result in a better structure and in new applications. Further research should also concentrate on a better theoretical and empirical foundation of the set of dimensions and its combination with subjects of a design situation. Empirical research can also investigate if there exist other dimensions that can help to structure and position properties, factors, design tasks, and representations.

To be really useful for supporting structured reflection on a design process, the prescriptive model of Section 4 should be extended and tested more extensively. We propose to start further research with refining and extending the method, based on an extended literature study and an investigation of the current practice of (individual and team) reflection on a design process. Afterwards, individual designers from several disciplines can test the whole method in practice, in the disciplines we studied, but also in other disciplines in design practice and education. Before the tests can be performed, the general terminology used in the method must be translated to specific terminology of each discipline. After the method is improved based on the feedback resulting from these tests, we advice to make the method useful for design teams.

Systematic methods that include checklists and classification systems may offer inspiration for improving the structure and the questions of our checklists and forms. One of the goals of the forms and checklists we developed is helping designers to get an overview of the design process. The current checklists and forms, however, mainly help to make lists (which are not yet overviews). Supporting designers to create a real overview of the design situation and design activities may help to increase the effectiveness and efficiency of the method. An overview may be generated by using different kind of forms or by using a more interactive software system. For teams, the prototype software tool can be improved by offering insight into the overview of other team members and by indicating similarities and differences between perspectives of different team members. Further research can also look for possibilities to reduce the amount of information that must be written down during a design process. Distinguishing different focuses of reflection for the different phases of a design process may also refine the method; reflection on the main planning of a design process should, for example, only take place at the end of a design phase. A software tool can, for example, offer different kinds of lists of questions and different kinds of overviews depending on the design phase.

Further research is also necessary to extend the results with support for the image-forming and conclusion-drawing steps of a reflection process because only the preparation step of a reflection process is supported so far. This kind of support would probably require knowledge of cognitive and social sciences and will be less rational and analytical than the method developed so far, but more intuitive and synthesis-oriented. Support can, for example, consist of a training session with external coaches in which designers can learn the necessary skills for the image-building and conclusion-drawing steps, like being critical and daring to question implicit assumptions.

As a final conclusion, we like to encourage other design researchers to base their research on several design disciplines and to make their results useful for many design disciplines. We learned very much from this approach and we believe it can help researchers from different disciplines learning from each other and it can accelerate the improvement of design processes in several disciplines.

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