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A MAPPING OF DESIGN DECISION-MAKING

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1. Introduction

In the situation where an industrial company develops a new product to the consumer market, based upon more or less new invented solutions the engineering designers' tasks may be articulated as:

- To target the consumers' need and values, and ensure timely market introduction.
- To target the business to create proper profit for the company.
- To find the best design solutions and ensure that the product fits to all life phases.
- To co-ordinate all design and activity elements into a proper totality during the design process.

Thus, the decision-making activities during the design process are complex, and the decisions made have critical impact on the design solution, the business, and the design process.

There exist guidelines for decision-making in design methodology literature, and attempts to contribute to our understanding from researchers proposing methodologies. Hansen & Andreasen [2000] propose a framework of design decision-making consisting of two models; the *decision node* is a generic model of the interrelated decision-making activities, and the *decision map* is a model of the object of decision-making during design. The framework is based upon a study of current state-of-the-art literature and methodologies.

However, a survey carried out in British industry [Wright et al. 1995] indicates that design methods are sparsely adopted and used in industrial practice. An empirical study of engineering designers in industrial practice [Ahmed 2001] has not found support for the generally believed approach: the engineering designer externalises considerations on alternatives and criteria in a structured way. Ahmed's study indicates that engineering designers follow a design strategy dependent on their perception of the current status of the design process rather than applying a decision method.

Thus, the authors see a challenge to deliver contributions to a model-based theory of design decision-making, which can be seen as an efficient mindset, and to deliver methods, which increase the engineering designers' adoption and use of design research results. The objective of our research work is to create a better basis for design decision-making in industrial practice by combining the design methodology's understanding with results of empirical studies. The basis of the research work is the decision node and map, and our first step is to use the results of the empirical study to create a more comprehensive picture of how engineering designers should perceive decision-making, and to propose a new model upon this understanding. The second step is to make a first attempt to verify the model by confronting it with other studies of decision-making.

The structure of the paper is as follows: In section 2 we describe the decision map and node; and we describe Ahmed's observations of design work in industrial practice. In section 3 we propose a new model of design decision-making seen in the engineering designer's perspective of the design process dynamics. In section 4 we make a first attempt to justify the model by logical verification, based upon different research contributions. Finally, we discuss and conclude.

2. Design decision-making in theory and practice

The design methodology literature, not least the textbooks, presents decision-making in a surprisingly uniform way, where the terminology and methods are based on normative approaches. We have added up these contributions into a framework of design decision-making consisting of the decision node and the decision map, which represents a contribution to a model-based theory of decision-making. The authors assume that the framework constitutes a best proposal of a crystallization of what many authors see as best practice of decision-making. In this paper we will confront the framework with empirical findings, and identify differences between theory and practice. The differences lead to a proposal for a model of design decision-making seen in the engineering designer's perspective of the design process dynamics.

2.1 Decision-making in the design methodology literature

We have identified several different descriptions of design decision-making in the literature:

- During the design process the engineering designers are again and again confronted with the problem of selecting a design solution from a number of alternatives, i.e. to answer the question "what is the best design?" Roozenburg & Eekels [1995] describe a number of methods and rules to structure decision-making and to support selection taking several criteria into account.
- Validation is concerned with whether a design is acceptable. The engineering designers are faced with a design proposal and the question: is this design "fit for purpose"? Validation is an important activity in e.g. development of medical devices. Alexander & Clarkson [2000] present a normative design model for validating medical devices. The model is a framework consisting of a process model and a number of design tactics.
- A number of researchers focus on the design process, i.e. "what to do next?" Asimow [1962] discusses the balance between attractiveness of the design solution and tractability of the process. According to Asimow the skilled designer is not only result-oriented; he/she also understands the process for reaching the design result. Pahl & Beitz [1996] treat evaluation of concept variants against technical and economic criteria in detail, and they outline a basic evaluation procedure. The purpose of evaluating concept variants is to provide an objective basis for selecting the concept with which to proceed to embodiment design.
- In the literature we see two different descriptions of the elements of a decision. Roozenburg & Eekels [1995] state that three elements are present in any decision: alternatives, consequences, and goals. The decision-maker's problem is to decide which alternative best meets the required goals. Kunz & Rittel [1970] see decision-making as an argumentative process and propose the Issue-Based Information System (IBIS). The elements of IBIS are: topics, issues, questions of fact, positions, arguments, and model problems.

We observe that in the literature there exist many contributions to design decision-making based on different viewpoints and understandings of the design process and of decision-making. We have the opinion that these results may mainly be seen as normative, mirroring what seems to be productive ways of reasoning and proceeding. Based upon these result Hansen & Andreasen [2000] propose a framework of design decision-making in order to enrich the engineering designer's mindset. The framework consists of two models: the decision node and the decision map.

The *decision node* is a model of a decision episode in a product development project. The node, see figure 1, is an elementary decision-making activity consisting of six sub-activities: *to specify*, *to evaluate* solution alternatives, *to validate* a design solution, *to navigate* through the solution/activity space, *to unify* the current decision into consistent wholes, and *to decide*. The node is generic in the sense that it contains the full set of decision-making sub-activities found in a decision episode.

The *decision map*, see figure 2, is a model of what is synthesised during the design process and therefore is the object of decision-making. In a product development project three artefact objects are designed, namely the *product*, the *life phase systems* (e.g. production system and distribution system)

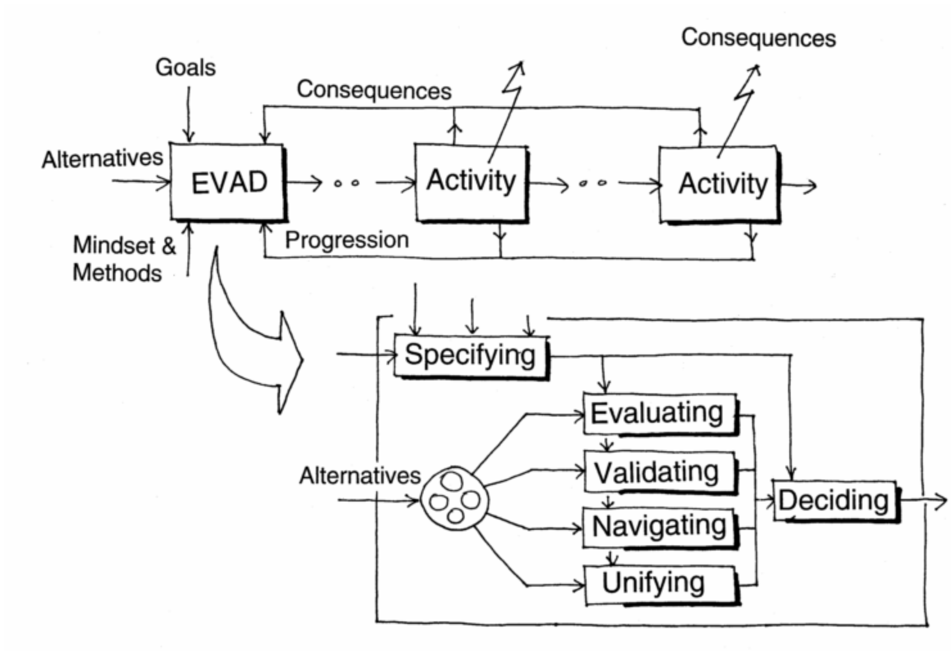

Figure 1. The decision node (EVAD: evaluation and decision-making activity) [Hansen & Andreasen 2000]

and the *meetings* between the product, the operator and the life phase system. However, also the *business* for the company and the *design process* itself are designed. Thus, the engineering designer has to be aware of the fact that decisions have consequences in at least these five dimensions.

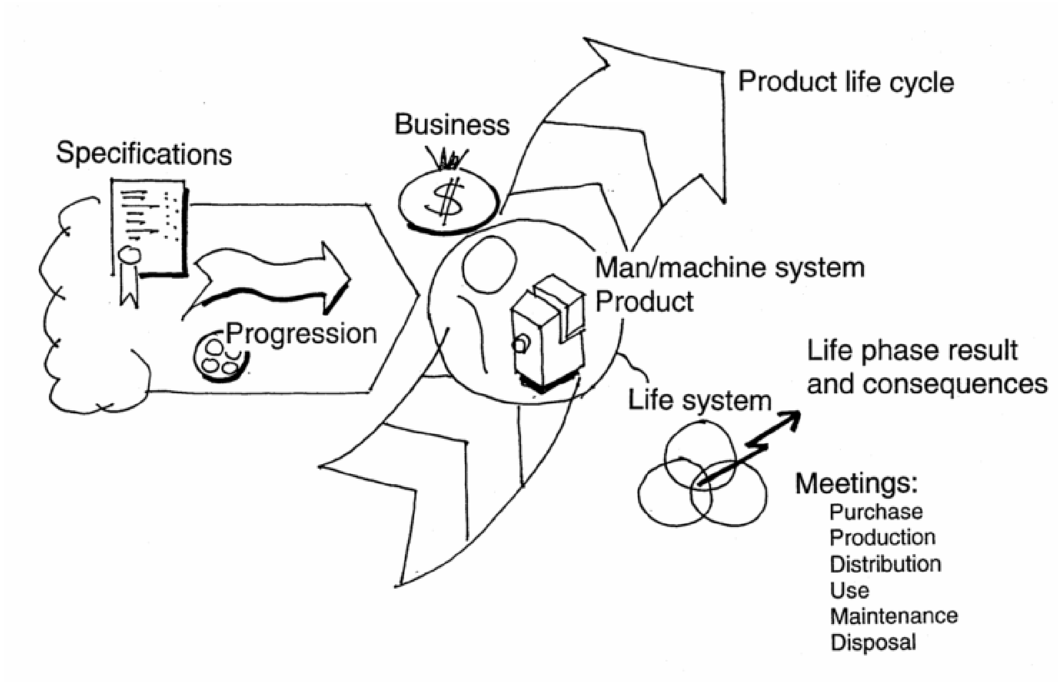

Figure 2. The decision map [Hansen & Andreasen 2000]

Hansen & Andreasen state that an engineering designer with a proper design context understanding makes better decisions, and propose the decision node and decision map as fundamental elements in building a mindset of design decision-making.

2.2 An empirical study of engineering designers

Ahmed [2001] carried out an empirical study of engineering designers working in industrial practice. The purpose of the study was to understand how engineering designers approach their design tasks. Ahmed made twelve observations together with thinking-aloud designers as a means to identify differences in cognitive approach between experienced and novice designers. The participants were working in the aerospace industry and they were observed when working on their real design tasks. The duration of each observation was around one and a half hour. The transcripts were analysed and a classification consisting of twenty-two categories to describe the thoughts and actions of the engineering designers was developed. Eight of these categories can be seen as design strategies, and the strategies were observed as mainly experienced designer behaviour. The design strategies were labelled as [Ahmed 2001]: *consider issues*, *question data, question is it worth pursuing, aware of reason, aware of limitations, aware of trade-offs, refer to past design*, and *keep options open*.

Two of the twelve protocols were analysed by Ahmed & Hansen [2002] from a decision-making perspective. In this analysis Ahmed & Hansen observed that:

- All of the design strategies were observed during the decision-making episodes, but the engineering designers did not use decision methods to structure their decision-making activities.
- In the literature it is stated that when evaluating between alternatives, all the alternatives should be developed to the same level and represented in an external form [Pahl & Beitz 1996; Pugh 1997]. However, the two designers were observed to evaluate designs that had yet to be externalised. The designers did not externalise their design alternative unless their evaluation had been successful, if not they would generate another design alternative. Hence, the evaluation was between alternatives, but was sequential and in a "synthesise and evaluate"-activity.
- The designers did not externalise a set of relevant criteria in a decision episode. The decision-making sub-activity *to specify* seems to be related to the strategy *consider issues*. *To specify* only appears with *consider issues*, however *consider issues* appears many times without the activity *to specify* and hence, suggests that *consider issues* is a strategy that aids the designer *to specify* as well as other activities.

The analysis of the two protocols indicates that an engineering designer follows a design strategy dependent on his/her perception of the current status of the design process rather than applying a decision method.

We conclude that there seems to exist a remarkable gap between the understanding and model proposals of decision-making in design methodology literature and the findings from empirical investigations of engineering design practice in industry. Thus, the authors see a challenge to increase the engineering designers' adoption and use of design research results by combining results from theory and practice.

3. A new model of design decision-making

In this section we develop a new model of design decision-making taking empirical findings into account. Thereby, the model will be more adaptable to a pragmatic design approach. In order to develop this model we formulate three clarifying questions about decision-making seen from the engineering designers' viewpoint:

- How do engineering designers see decisions during the design process?
- What is the scope of the decision object during the design process?
- Who are the decision-makers during the design process?

The answers to these questions will help us to develop a model, which provides a proposal for filling the gap between theory and practice of design decision-making.

How do engineering designers see decisions during the design process?

Whereas the design methodology literature focuses on how to make a decision by providing a terminology and proposing a number of decision methods to structure the decision-making activities,

the situation and problem for the engineering designers working in industrial practice is quite different:
An engineering designer does not stop a current design activity and externalise a set of solution alternatives unless he/she perceives the situation as being decisive. Doubt about the value of the current solution, uncertainty about consequences, or a gut feeling that the design work has to change direction due to important clarifications could constitute a decisive situation. As design methodology researchers the authors have to believe that at least the concept selection is a situation, which is seen as being decisive for the outcome of a product development project, and therefore requires externalised concept alternatives.
The engineering designer does not see a neat string of explicitly made decisions. The engineering designer sees a complex totality of interwoven decisions regarding different aspects, which are not distinct in time, but emerge and merge gradually as other decisions are made and clarifications obtained. In practice the engineering designer often works on the basis of a relatively well-known model of the product's totality, in which new and improved solutions have to fit. Thus, the engineering designer does not work in unknown territories, but designs on a "dirty blackboard" [Andreasen & Wognum 2000], where relevant bits and pieces of the previous version of the product are more or less visible.
Often a design decision is made over a period of time. The engineering designers use the available criteria and considerations on consequences in order to make a tentative decision. Based on the tentative decision they continue their work, and the decision remains dwelling or untouched until new criteria emerge and clarifications with respect to consequences reaches a satisfactory level or threshold value. Then the tentative decision is believed verified, and the "decision made", i.e.:

- The engineering designers dare to discard alternatives.
- The engineering designers dare to believe that damaging aspects will not emerge and force a change of the decision.
- There is no "ritual" linked to the decision; the decision grows out of the situation.

Thus, in retrospect the design decision does not appear in a documented form carrying a notation of time or an articulation of the engineering designers' intent.
Now, we could ask what the design methodology approach on decision-making offers to the engineering designers in industrial practice. On the positive side helps terminology and decision methods to structure decision-making activities emphasising the importance of all criteria, all alternatives to the same level of detail, and consequences. Thus, a decision becomes visible and can be object to a deliberation between the engineering designers, and a correct decision-making process emerges. On the negative side such a clear-cut, structured approach forces to simplification, not to the overview of the complex totality of interwoven decisions. Thus, the decisions might become isolated from their totality and timeliness leading to a loss of the engineering designers' gut feeling and insight into the complex situation.
What is the scope of the decision object during the design process?
In section 2.1 it was stated that the object synthesised during a product development project consists of three artefact elements, viz. the product, the life phase systems, and the meetings. But also the established business and its result for the company and the design process itself are designed. Thus, the object of any decision made during the design process encompasses – at least in principle – characteristics with respect to the three artefact elements, and has consequences in the five dimensions. Seen from the engineering designers' viewpoint the task is to synthesise a product, which meets the need and values of the costumers, creates proper profit for the company, and fits to all life phases. This is a complex task, and during the design process the engineering designers gradually determine artefact characteristics and the consequences emerge. When a decision is made, it carries a complex pattern of consequences:

- A design solution determines the quality of the product but also the tractability of the remaining design process. A product concept might be very promising with respect to product quality and user perceived value, but difficult and time-consuming to detail because of unknown sub-solutions.

- Several important properties, e.g. quality, cost, risk, and safety, are relational properties. Therefore, the engineering designers have to both synthesise product characteristics and clarify product context for the relevant product life phases in order to predict property values.
- The product and the business for the company are developed simultaneously during the design process, and both product and business characteristics have to be taken into account.
- The product and the company's assets have to be considered as a totality by the engineering designers for maximum utilisation and enhancement. The awareness, capability, and capacity of the company have to be exploited.

Due to the complex nature of design decisions the engineering designers have to consider the dependencies between the decisions, the sequence in which the various aspects should have attention and what result or result dimension should be finalised. So, the decision object follows what is the current concern, being the product, a sub-system, a user interface, a quality aspect, assembly method or cost concern; it follows the different ranges and delimitations of this concern during the design process.

Whereas the design methodology literature proposes requirements, criteria and definition of value scales to determine the best design alternative, the industrial situation asks for the engineering designers' insight into complex chain phenomena and interrelations, which demands complex mapping, where the current decision has consequences in several aspects, and dispositional thinking regarding product life phases, see e.g. [Duffy et al. 1999] and [Olesen 1992].

Who are the decision-makers during the design process?

Our answers to the two previous questions show that the decisions made have consequences for many different stakeholders, e.g. the costumers, the company, the engineering designers, and the stakeholders of the different product life phases, such as assembly, sales, maintenance, and disposal. All these stakeholders have different goals and wishes; e.g. the costumers want a good product satisfying their need and values, the company wants a profitable business, the production wants easy assembly, and the engineering designers wants a tractable design process. Thus, the decisions made during the design process can in the widest sense lie in the hands of several decision-makers, some actively working within the design process, and others situated outside the process.

It is an important task for the engineering designers to take the different stakeholders with their goals and wished into account. This can be done in at least two ways:

- The engineering designers can invite or involve relevant stakeholders in decision-making activities. By making the design work visible stakeholders can comment and propose better alternatives seen from their specific viewpoint. According to Horgen et al. [1999] this is a situated, user involved design approach, where relevant stakeholders are considered as domain experts.
- The goals and wishes of the different stakeholders can be modelled as sets of requirements and criteria, which can be taken into account. This is a traditional design approach proposed by e.g. Pahl & Beitz [1996] based upon the underlying assumption that the engineering designers upfront can formulate all relevant requirements and criteria.

It is a common characteristic of the two ways described that in order to ensure coherent and coordinated decision-making the decision-makers have to develop decision models which link or relate the design object to the complex sets of goals and wishes of the stakeholders. The two ways outlined can be seen as extremes, and in a modern product development context [Andreasen & Hein 1987] the engineering designers probably work somewhere in between these extremes.

Two important roles in design decision-making should be mentioned:

- The project leader, who on a daily or weekly basis judges the results obtained so far compared to the resources spend, and determines what to do next. This is a complex decision: the project leader has to act as a conductor or director in order to determine what to do next, how to do it, and who has to do it.
- The company management, which at project milestones judges the results obtained compared to the expected business opportunity, and determines the future of design project in a go/no-go decision.

Also in these decision situations are decision models needed, which relate the design object to the complex sets of goals and wishes of the stakeholders.
Whereas the design methodology literature sees the design decision-maker as an engineering designer of a team of designers having a rational conversation on design alternatives about consequences, the situation is much more complex in industrial practice. There are decision-makers within the design project, but also outside the project stakeholders act as decision-makers influencing the design process and its result.
The answers to the clarifying questions have shown several differences between theory and practice of design decision-making. Thus, we have to expand the framework, which consists of the decision node and the decision map, in order to create a comprehensive picture of how engineering designers should perceive decision-making. We see the following important elements:

- The engineering designers do not see a neat string of distinct and explicitly made decisions, but a complex totality of interwoven decisions and clarifications.
- There are several decision-makers within the design process, and there are many stakeholders, which act as decision-makers influencing the design process and its outcome.
- A design decision is not made at a distinct moment in time. The engineering designers make a tentative decision based on the available information. As new criteria and clarifications emerge, which to a satisfactory level support the tentative decision, it will be considered verified, and the "decision is made".
- The decision object is not static and constant. It develops due to clarifications and possibilities, and it is complex encompassing the product, the business, the product life cycle and the design process, and it follows different ranges and delimitations during the design process.

Based on this understanding of design decision-making we have developed the graphical models shown in figure 3 and 4. The model shown in figure 3 illustrates the decision-making aspect of the design process, where a decision has multiple objects and where it is based on earlier decisions, the clarifications obtained so far, and a prediction of consequences and design process progression. We name the model shown in figure 3 the decision score using the parallel to a conductor's score, for creating a mental model of the "multi-instrumental" task of design decision-making.

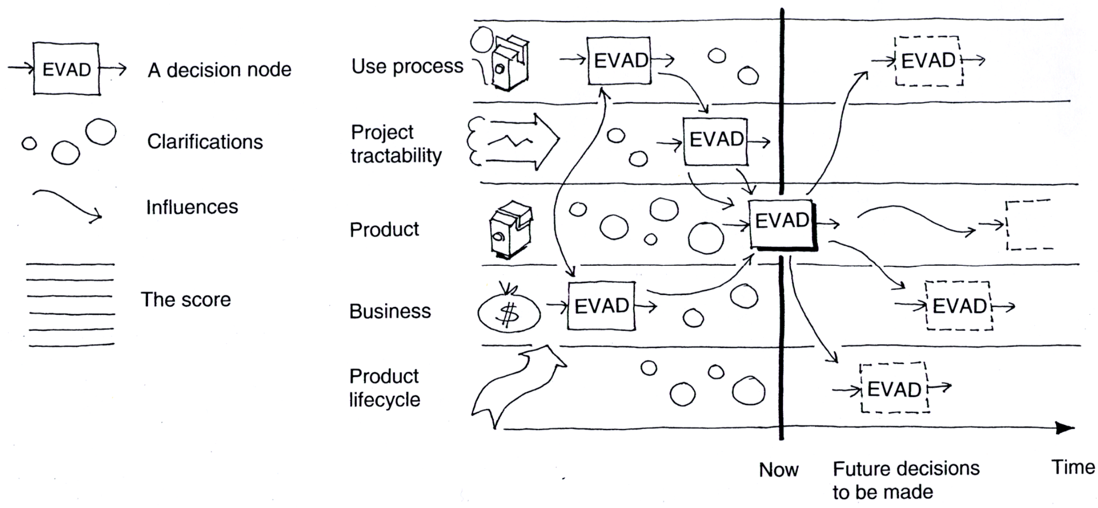

Figure 3. The decision score

Figure 4 shows our understanding that a design decision is not made at an instant in time, but based upon gradually clarification of the design and its consequences in several dimensions until satisfaction. Then the tentative decision is believed verified, and the "decision is made".

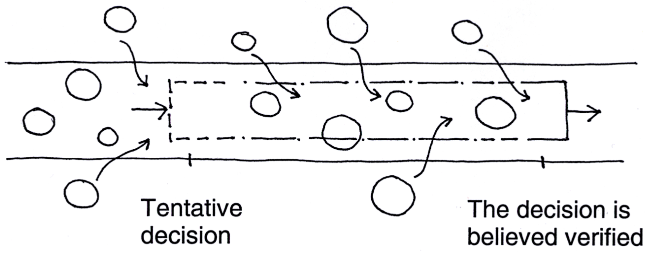

Figure 4. From tentative to verified decision

4. Towards a verification of the new model

In order to make a first attempt to justify the decision score we will confront the important aspects of the model with other studies of decision-making.

In order to identify what decisions do look like in design departments Badke-Schaub & Gehrlicher [2003] have carried out an empirical investigation in a medium-sized enterprise, which supplies automobile devices and system solutions to the automobile industry. The enterprise's design department consisted of 11 employees, divided into two functional units, designing and testing. The empirical study focused on detailed observation and analysis over two weeks of a reengineering project. Badke-Schaub & Gehrlicher used a laptop-based 'online' protocol system to document the observations in real time. The protocol was analysed, and in total 40 decisions were identified and analysed. According to Badke-Schaub & Gehrlicher the analysis showed among other things:

- Decision-making in design is a collaborative process with several departments and organisational hierarchies involved. In the 40 decision situations the organisational unit designing participated in 21, company management participated in 19, testing participated in 28, other company departments participated in 13, and external persons participated in 11 decisions.
- Only 45 % of the decisions were planned in advance, which means most of the important decisions were settled without any forward planning or agenda.

We observe that the analysis of Badke-Shaub & Gerlicher supports two important elements of our understanding of design decision-making. Firstly, there are several decision-makers within the design process, and there are process external stakeholders, which act as decision-makers. Secondly, the engineering designers do not see a neat string of distinct and explicitly made decisions, but in an unplanned pattern decisions pop up or emerge as a result of other decisions being made and clarifications obtained.

In order to investigate concurrency in the design process Mortensen & Tichem [1994] carried out a case study concerning the development of the loading unit of a CD player by Bang & Olufsen. The information about the development of this sub-system was obtained by interviewing the designer, who was responsible for the development of the CD player. An analysis of the interview gained some insight into main designer's perception of decision-making during the design process. Mortensen & Tichem [1994] write "*Most critical for development of the tray system was to obtain a sufficient mirroring and homogeneous surface. Three solution candidates were synthesized ... The aluminium-milling solution candidate seemed to be most promising for obtaining a homogeneous surface. For verifying this assumption it was decided (tentative decision) to detail this solution further, i.e. product and production method. By means of experiments the surface quality were verified. After verification the tray system decision changes from tentative to verified and purchase of milling machine, tools and material started parallel with development of remaining subsystems.*"

We observe that the case study of Mortensen & Tichem supports one element of our model of decision-making, viz. a design decision is not made at an instant in time. The engineering designers make a tentative decision, and as clarifications emerge the tentative decision will be considered verified.

As a means to study real-world design thinking Galle & Kovacs [1996] present the Replication Protocol Analysis. The idea is to provide a designer with a problem brief and a final design solution, and ask the designer to describe the thinking process that he/she believes would have been used to achieve the final design solution. Thus, the designer replicates a line of reasoning that might have led from brief to solution, and the designer's description constitutes the replication protocol. As a case study Galle (being trained as an architect) is given the brief of an architectural competition on site planning, and the design awarded the first prize. Galle, acting as a replicator, produces a line of reasoning from brief to design. The replication protocol was analysed and Galle & Kovacs identify two types of decision: a *that* decision and a *how* decision. A *that* decision specifies an end or a goal and a *how* decision identifies the means to achieve the end or goal. Further, Galle & Kovacs observe that a given decision can be seen as specifying the means in relation to an earlier decision, and as specifying an end in relation to a later decision.
The analysis of Gale & Kovacs supports one element of our understanding of design decision-making, namely that the decision object is developing and changing nature during the design process.
We observe that the important aspects of our model of decision-making seen in the perspective of the engineering designers are in accordance with the empirical studies of engineering designers' decision-making behaviour. We interpret the observed accordance as an important and fundamental element in the verification of our model.

5. Discussion and conclusion

The authors see a challenge to explore the schism between the content of guidelines and decision methods proposed in the design methodology literature and the very different picture of design decision-making, which appears when industrial practice is studied empirically.
Our first contribution was a framework of design decision-making consisting of two models: the decision node and the decision map. These models link the normative recommendations found in the design methodology literature into a contribution to a model-based theory of design decision-making. We believe that the decision node and map are well suited as a linkage between design methodology and the area of mathematical based decision-making and optimisation. However, we have seen that the models are very idealized and over-simplified compared to design decision-making in industrial practice.
In this paper we have developed a model, the decision score, which mirrors the pragmatics of decision-making in industrial practice, and it should be seen as an attempt to include the engineering designer's approach and behaviour in the complex and dynamic pattern of decision-making, which seldom allows or make it appropriate to turn decisions into ritualised events.
When we confront the decision score with empirical studies, we observe an agreement with respect to the pattern, context, and behaviour. There is good reason to believe that the decision score model represents a new model-based theory element, which constitutes an enhancement to the framework of design decision-making. Thus, the enhanced framework makes up a mapping of design decision-making, which can serve partly as a basis for development of more realistic mindsets and teaching material and partly as a basis for further empirical studies of design decision-making.
The authors believe that the enhanced framework of design decision-making is a contribution to the Design Society's goal of consolidating terminology and knowledge within engineering design, and we hope that the mapping will be useful in future discussions within the SIG Decision-making.

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