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AN ANALYSIS OF DESIGN DECISION-MAKING IN INDUSTRIAL PRACTICE

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1. Introduction

A survey carried out in British industry [Wright et al. 1995] indicates that design methods are sparsely adopted and used in industrial practice. With respect to design decision-making this is an unfortunate situation for at least two reasons. Firstly, because of the importance of making the right decisions during design, and secondly because many methods to support decision-making do exist [e.g. Jones 1970, Pahl & Beitz 1996, Roozenburg & Eekels 1995].

In order to strengthen the engineering designer's mindset for decision-making a framework of design decision-making has been proposed [Hansen & Andreasen 2000]. The framework consists of two models: the decision map and the decision node. The *decision map* is a model showing what is synthesised during the design process and therefore the object of decision-making. The *decision node* is a model of the interrelated decision-making activities. The node is meant to be generic in the sense that it contains all sub-activities in a decision-making activity. However, the node does not explain or prescribe how the engineering designer should carry out the decision-making sub-activities.

Empirical research in the aerospace industry was carried out to understand how engineering designers approach design tasks [Ahmed 2001]. Twelve observations together with thinking-aloud were used to understand the differences between novices and experienced designers. The transcripts were analysed and a classification consisting of twenty-two categories to describe the thoughts and actions of the engineering designers was developed.

This paper describes research that confronts the decision node with the design strategies employed by experienced engineering designers. We focus on two decision-making sub-activities, namely evaluation and validation, and we ask how engineering designers carry out these activities in industrial practice. By combining these two understandings of the design process we are one step closer towards prescribing how engineering designers should carry out design decision-making.

The paper is structured as follows: section 2 a description of related work; section 3 a description of the decision node, strategies employed by experienced designers, and the research approach; section 4 a description of the findings of the research; and section 5 the conclusions.

2. Related work

A widely referenced book on engineering design is [Pahl & Beitz 1996], which describes a design process consisting of four phases: Clarification of the task, conceptual design, embodiment design, and detail design. Each phase comprises a set of activities, and the phases are carried out in a fixed sequence. Pahl & Beitz treat the 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.

Roozenburg & Eekels set up the Basic Design Cycle consisting of the activities: Analysis, synthesis, simulation, evaluation, and decision [Roozenburg & Eekels 1995]. The authors treat evaluation and

decision-making by describing several methods and rules and their theoretical fundament.
According to Ward development of medical devices is a highly regulated area [Ward et al. 1999]. Any new medical device has to be demonstrated as being "fit for purpose" before it can be released to market. Alexander & Clarkson present a normative design process model focusing on such a validation of medical devices [Alexander & Clarkson 2000]. The aim of the model is to provide the engineering designer with a proactive role towards validation during the design process. The design validation model is a framework consisting of a design process model and a number of tactics.
Dwarakanath's goal is to establish a framework for a computer-based system to support design decision-making [Dwarakanath 1996]. Dwarakanath carries out an empirical study of design work in an experimental setting, and he observes among other things that individual designers tend to apply a single-string solution-oriented approach, where alternatives are not considered unless the pursued direction in the solution space is recognised to be infeasible. From his observations Dwarakanath recognises a need for a structured and explicit basis for design decision-making based on identified types of decision-making processes, the use of criteria, and the types of information used.
Galle & Kovacs provided designers with a problem brief and a final design solution [Galle & Kovacs 1996]. The designers were asked to describe the thinking process that they thought would have been used to achieve the final design solution. Galle identified two types of decisions from the analysis: a *that* decision and a *how* decision. A *that* decision specified an end or a goal and a *how* decision identified the means to achieve the end or goal.
From the literature study we observe that there exist many methodologies and guidelines to support decision-making in design, and interesting elements of insight from empirical studies of decision-making are reported. However, the area has few fundamental works, which could serve as a theory base and the majority of empirical studies of design decision-making have been conducted in a laboratory environment.

3. Design decision-making

The aim of this research is to identify how experienced engineering designers carry out the decision-making sub-activities evaluation and validation. In this section we describe firstly the decision node. The node was established based on a study of methodologies and guidelines to support design decision-making found in the literature. Secondly, we describe eight design strategies employed by experienced engineering designers. The strategies were identified by observations of designers carrying out their design tasks in the aerospace industry. Thirdly, we describe the research approach chosen for this work.

3.1 The decision node

During the design process the engineering designer or design team have to make decisions repeatedly. These decision episodes are modelled in the decision node model. The node, see Figure 1, is a generic, 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 decision node is generic in the sense that it contains the full set of sub-activities, which are found in different design decision episodes:

- *To specify* sets the criteria for the decision. It is the engineering designer's task to compile stakeholders' goals and translate these goals into product design specifications.
- *To evaluate* a number of design alternatives is to identify the better ones or establish a ranking of the alternatives with respect to the current criteria.
- *To validate* is to check whether the current design proposal is "fit for purpose" with respect to identified product life concerns, e.g. manufacturing, distribution, or use.

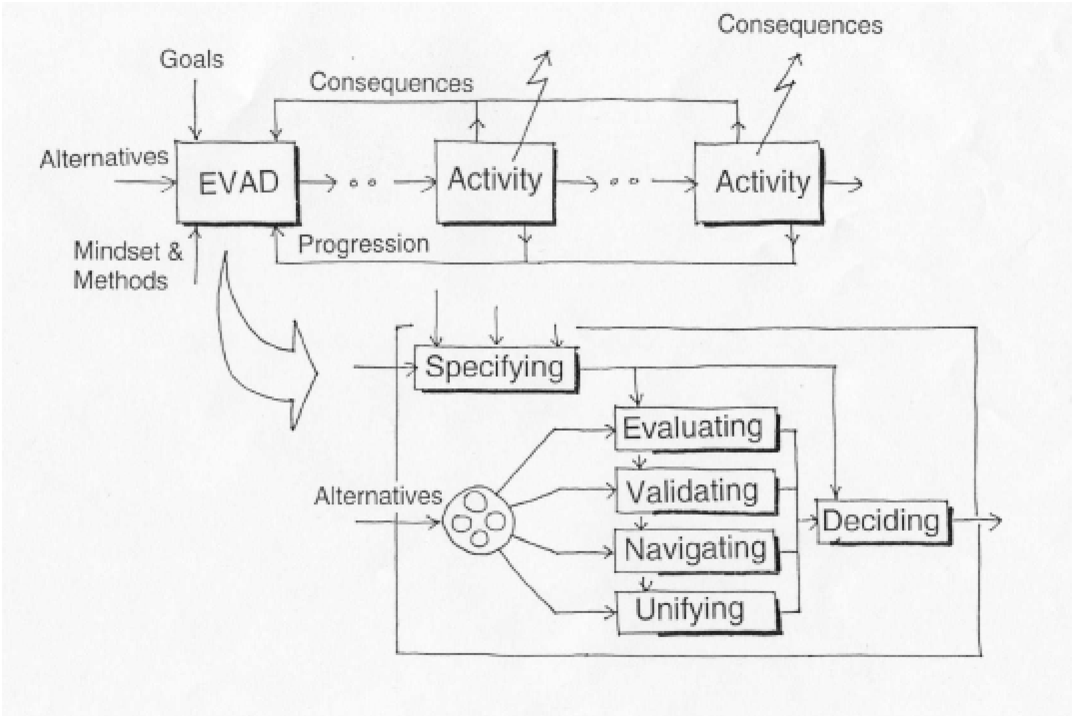

Figure 1. The decision node

- The skilled engineering designer is not only goal-oriented; he/she also understands the process for reaching the goal. *To navigate* is to consider not only the current solution alternatives, but also these alternatives' influence upon the progression in the design project.
- During the design process a solution is synthesised through a sequence of complex decisions. The engineering designer has *to unify* the current decision into the totality of process and solution in order to obtain a satisfactory result.
- To evaluate, to validate, to navigate, and to unify are sub-activities, which result in a basis for making a decision. In a decision episode each of the sub-activities carried out provides a signal, and the engineering designer or design team has *to decide* based upon the signals obtained.

3.2 Strategies employed by experienced designers

Twelve observations together with thinking-aloud were used to understand the differences between how novices and experienced designers approached their design tasks [Ahmed, 2001]. The transcripts were analysed and a total of twenty-two categories describing the thoughts and actions of the designers were generated. Eight of these categories have been identified as design strategies, these were observed to be predominantly experienced designer behaviour. The strategies were:

- **Consider issues:** the experienced designers tended to consider several relevant issues, and decided which were the most important. They were also aware when issues were not relevant.
- **Question data:** the experienced designers questioned data they obtained from any source. They questioned the accuracy of the data; how components were modelled or tested; how much accuracy was required; customer specifications; and the applicability of standards.
- **Question is it worth pursuing:** the experienced designers asked themselves how much they could expect to achieve if they continued a particular approach and if it was worthwhile.
- **Aware of reason:** the experienced designers were often aware of the reasons behind the use of a particular design solution or manufacturing process. The reasons why a component or process was used may be due to a specific function or the capability of a particular supplier or manufacturing process. The experienced designers assessed the reasons and their applicability in the current situation.

- **Aware of limitations:** the experienced designers were aware of the limitations of the current design task and hence of the amount of time to spend on it. The following reasons were identified to limit the task: the expected achievement of the current task versus further design tasks, and incompleteness of information.
- **Aware of trade-offs:** the experienced designers were aware of the relationships between issues. They were aware that many decisions were based on compromises and once aware of the trade-off, they would question whether it was worthwhile continuing to pursue the task or implementing a decision.
- **Refer to past designs:** the experienced designers referred to past projects to find similar designs; designs in similar environmental and functional conditions; and where similar problems had been encountered and how they were resolved.
- **Keep options open:** the experienced designers rejected an option or delayed a decision on an option if it limited later options in the design task. They were aware of what needs had to be considered further down the design process.

3.3 Research approach

Two of the protocols used to identify the design strategies described above were reanalysed to understand how the engineering designers made decisions. Both participants were experienced engineering designers: designer A had 19 years of experience, and B 8 years. The participants were working on real design tasks: Design of a shaft respectively design of O-ring and squeeze film. Both design tasks observed were detail design.

The analysis of the two protocols was carried out in two phases: encoding phase and analysis phase.

During the *encoding phase* the decision-making episodes were identified. As protocols with thinking-aloud were used, the decisions identified were limited to those the designer verbalised. Each of decision-making episodes was encoded into an encoding scheme. The encoding scheme used to identify the decision-making sub-activities were:

- *Specify*: a statement concerning compilation of design criteria.
- *Evaluate*: a statement concerning either the value of a design alternative, on a design alternative being better/worse.
- *Validate*: a statement whether a design proposal is "fit for purpose", e.g. "not problematic", *purpose* includes consideration of the product lifecycle, e.g. consider the manufacture or use.
- *Navigate*: a statement regarding the progression and feasibility of the design work, i.e. which activity to do next or in which direction to go next.
- *Unify*: a statement concerning the current design solution or design activity in relation to the totality of the product or process.
- *Decide*: a verbally expressed decision.
- *Other*: statements which do not belong to any of the first six categories

During the *analysis phase* the encoding schemes were analysed. For each decision episode statements regarding the decision-making sub-activities were recorded. Thereafter, the encoding schemes were compared with a previous analysis to identify the occurrence of the eight design strategies. The encoded scheme used was: consider issues, question data, question is it worth pursuing, aware of reason, aware of limitations, aware of trade-offs, refer to past designs and keep options open. During this phase the protocols were analysed to identify any relationships between the design strategies and the decision-making sub-activities. Observations of any patterns in the order of which the strategies were used during the decision-making sub-activities were formulated.

4. Findings

In total, six decision episodes were observed, two of these were encoded as *to evaluate* and four as *to validate*. Each of the evaluating and validating episodes are described together with the decision-making activities and design strategies employed in Table 1. All eight design strategies were observed during these episodes.

Table 1. Decision-making activities and design strategies

Designer	Overall decision-making activity	Description of episode	Decision-making activities observed during episode	Design Strategies
A	validating	Is this design drawing fit for purpose?		refer to past designs
			Specifying	consider issues
				refer to past designs
A	validating	Is specification of shaft suitable for manufacturers?		refer to past designs
A	evaluating	Should the design have a cold-expansion process on the holes? Evaluating between a design with process and without		consider issues-aware of reason-refer to past designs
				aware of limitations-aware of reason-question is it worth pursuing -refer to past designs
				consider issues-refer to past designs
B	validating	Is this O-ring fit for purpose?		consider issues-question data
				consider issues
			Navigate	question is it worth pursuing
B	validating	Does the length of squeeze film need to be extended or is it good enough?		aware of reason
				aware of limitations-question data-aware of reason
				consider issues
			Navigate	consider issues-question is it worth pursuing-keep options open
				question data
B	evaluating	What are the alternative ways to improve the film?		consider issues
				consider issues-aware of reason
			Unify	aware of trade-offs
				aware of reason
				question data
			Specify	consider issues-refer to past designs
				consider issues-aware of reason -question is it worth pursuing

All of the design strategies were observed during the decision-making activities *to evaluate* and *to validate*. The strategy *question is it worth pursuing* was used by the designer before making a decision in all but two episodes. Both these episodes were validating a design drawing and hence, the decision to pursue the design has already been made. Therefore, *question is it worth pursuing* seems to be used by the designers just before validating or evaluating a design.

The sub-activity *to specify* seems to be related to the design 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 activity *to navigate* always appears together with *question is it worth pursuing.* This strategy is related to the design process, as is *keep options open* and hence, it was expected that these strategies are related to the activity *to navigate.*

The activity *to unify* was observed only once, in this instance, the activity was used together with *aware of trade-offs* to consider the effects of choosing a particular alternative.

5. Conclusion

The findings reported in this paper are based upon the analysis of only two protocols and within a particular company and therefore conclusions that can be drawn are limited. However, the analysis of the protocols has led to a deeper understanding of the decision-making activities undertaken by engineering designers in industrial practice. The decision-making episodes undertaken by individual designers were supported by design strategies, not by formal decision-making methods. This implies that designers in practice do not rely solely on methods to support their decision-making process, but also on the use of relevant design strategies.

This understanding has implications to teaching design decision-making to engineering students and designers working in industrial practice: in addition to teaching methods and techniques found in literature, we must also include a description of decision-making activities together with a set of relevant strategies based upon empirical research.

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