ANALYSIS OF CREATED REPRESENTATIONS OF THE DESIGN OBJECT DURING THE PROBLEM SOLVING PROCESS

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ABSTRACT

During the process of developing new solutions, the designer creates different representations of the design object, which have a high variation in their level of abstraction. These representations have great impact on reaching the project targets. Therefore, it is important to understand how the designers create these representations for the problem solving, in order to derive general ways of proceeding. This paper describes the assessment, classification and analysis of designer's proceedings during the process of problem-solving, based on two examples from the industry. The evaluation contains the created representations, as well as the proceedings for the problem solving. The results show, what level of detail and what scope is to be preferred by the designer, for representing the design object during the different stages of the problem solving. Furthermore, it is shown, in what order problems are solved during the design process.

Keywords: Representation of design, abstractions, refinements, problem solving

1 INTRODUCTION

Many ideas for new products arise from searching alternatives for already existing solutions, which more effectively fulfil particular targets or customer needs. More and more complex products consist partly of technologies continuously developed by companies over decades. However shortening product life cycles combined with high financial risk prevent, in many cases, the development of entirely new solutions, which fulfilling similar requirements. Hence, many companies follow the strategy of incremental improvements for existing products. The system's main part remains unchanged and is considered validated [1]. To develop a new solution for a part of the system, the designer mentally detaches himself from an already existing solution, by leaving out irrelevant pieces of information. In this way, he extends his solution space. The result of this abstraction process creates the basis for the ensuing search for solutions.

During the development of a new solution, the designer creates a large number of representations of the design object, which vary in their level of abstraction. These representations support the solving of design problems, focus on particular problem aspects and can be regarded as preliminary result of the problem solving process. The representations' level of abstraction determines the extent of the solution space for the following proceedings. Wrong assumptions or disregarding important pieces of information at this stage, can be reasons for missing the project targets. Thus, the representations of the design object have a high impact on the project's success.

The creation of representations, which are appropriate for the problem solving and the choice of the proper level of abstraction, requires a lot of practice and experience. Often, the designers need more than one attempt to create representations, which are supportive of the search for solutions and address the most important problem aspects. In addition, many designers are neither able to create intermediate steps, nor to expand their solution space systematically, during the period of transforming abstract targets into concrete CAD solutions. As a consequence, they often settle early on the first solution, without searching for a better or even the best one [18]. As a possible reason for this behaviour, the lack of intermediate representations (between abstract functional representations and concrete form representations) is mentioned [19]. To develop a methodical support for this difficulty, the designers' working method has to be explored. Therefore, the central research question in this paper is: how can created representations be assessed, analysed and classified?

In order to find answers, two industrial technology projects, carried out by two different designers, are investigated. Targets of this investigation are:

- to analyse the created representations of the design object,
- to analyse the individual proceedings during the problem solving process,
- to derive rules for the creation of representations of the design object.

Therefore the first step will be to give an overview of abstraction in product development in section 2. After a description of our methodology in section 3, this paper explains the results of the evaluation in section 4. In section 5 the results are discussed and interpreted and finally summed up in conclusions in section 6.

2 BACKGROUND

The distinction between abstract and concrete is used differently in many domains. A very simple, but also controversial definition, equates abstract with non-physical [2]. Other controversial attempts to characterise abstract objects, are based on their non-existence in space and time [3]. Even in our language, we use the distinction between abstract and concrete, by calling lower level concepts of the linguistic pyramid concrete, and the higher level concepts abstract [4]. Apart from these controversial, and for the product designing invalid, definitions, most of the other definitions are based on the 'Aristotelian abstraction'. This approach, known in the empirical sciences, describes abstraction as a process, where we 'strip away', in our imagination, all the irrelevant details of the concrete object. The result is an abstract reflection of reality, with a limited selection of characteristics [5] [6]. Thus, abstract objects only exist, if there is at least one, or a group of more concrete concepts that provide a more specific description of them [2]. The common definitions of abstraction in product design take up the thoughts of the Aristotelian abstraction. Here, abstraction is a result of a considered decision, to ignore parts of the design object [7]. The information reduction is a subjective selection of significant features, which are considered relevant at a certain time, for a certain purpose [8]. How the human brain is working exactly during the process of abstraction transforming concrete objects in abstract ones, is, like retransformation, relatively unclear [9]. Explorations concerning the preferred level of abstraction among experts are contradictory. But there is an agreement that systematic application of abstraction, during the development process, improves the design quality. Nevertheless, it is impossible, in most cases, to compensate expertise entirely through systematic application of abstraction [10].

Abstraction reduces information and therefore the complexity of design problems (Figure 1). Hence, abstraction can be seen as a critical process, because models with too high complexity are difficult to handle, whereas low complexity models ignore essential interactions. However, there is the danger, in both cases, that essential design problems are not identified in time, and the duration of development prolongs due to development loops. The complexity of a problem is determined, in the designing process, by its scope and its level of detail [7]. The scope defines the system boundary of the abstraction. It determines which parts of the design object are taken into consideration during the abstraction process. The level of detail defines how realistically form and shape of the elements are represented. When creating an abstract representation, it is important to determine its purpose first. If it is clear, which behaviour of the system shall be investigated by the representation, the scope and the level of detail can be determined. Theoretically, a comparable level of complexity can be realized by different variations of scope and level of detail (Figure 1).

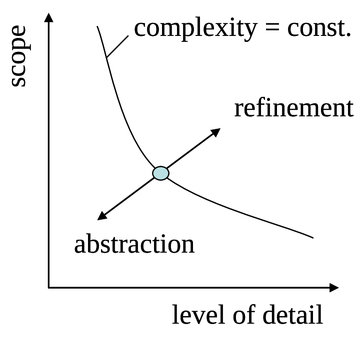

Figure 1: Abstraction in product-designing

Abstraction shows not only a reductive, but also a highly creative character. Hence, it can be taken as a mental operation, serving the discovery of structure and regularity, pattern or order within a large

number of impressions. Therefore, abstraction serves as a basis for the conceptual new design [11]. To transform abstract representations into physical existent design objects, the contrary of an abstraction – a refinement has to be done. During such a refinement, structure and details are added to a design object [7]. Hence, a refinement can be measured, by an increase in level of detail and/or scope, compared to the previous representation of the design object. Refinements constrict the solution-space, won earlier by abstraction. The solution-space, or problem-space, goes back to Newell's and Simon's 'problem-space theory' [12]. It describes the totality of all possible 'solution-states', no matter if they serve the problem-solving or occur during the problem-solving. Thus, it is called solution-space [13].
During the creation of the refinements, the designer is confronted with the choice between different solution-directions. Typical, for such a situation in problem-solving, are a high number of possibilities and a lack of attention, because it is all but impossible for the designer, to think through all possible solutions [14]. In such a situation, the designer, generally, creates representations of different solution alternatives of the solution space, and finally decides for one of them. Thus, decisions reduce the considered solution-space and turn uncertainty into certainty [17]. In order to prevent extensive mistakes, it is important that already during the first strategic decisions, the relevant aspects for the designing are considered. This is supported by approaches, like integrated product-designing, simultaneous engineering and core-teams [15] [16].
Researches concerning mental imagination [20] reveal that human beings experience their mental imagination a lot more completed and detailed than it actually is. The creation of physical existent representations of the mental imagination, confronts the designer with the incompleteness of his imagination. At the same time, he is forced, by representing his thought, to complete the gaps in his imagination. Furthermore, the representations of the design object serve as a basis for discussions, for documentation and for revealing the state of development. The creation of representations of the design object at different stages of product-designing, with different intentions, at different levels of abstraction, is therefore a fundamental part of solving design-problems.

3 METHOD

3.1 Data source

The here presented data was collected in a company, which is mostly known in the sector of fastening technology, and produces high quality electronic tools and accessories. Basis for these data are two technology projects, one managed by a graduate, the other one managed by an experienced designer. Both designers are with degree in mechanical engineering and therefore, according to Günther [24], they are 'M-designers'. Beside this classification by means of education, differences can also be seen in their degree of designing experience and their proceeding during the problem solving (Figure 2).

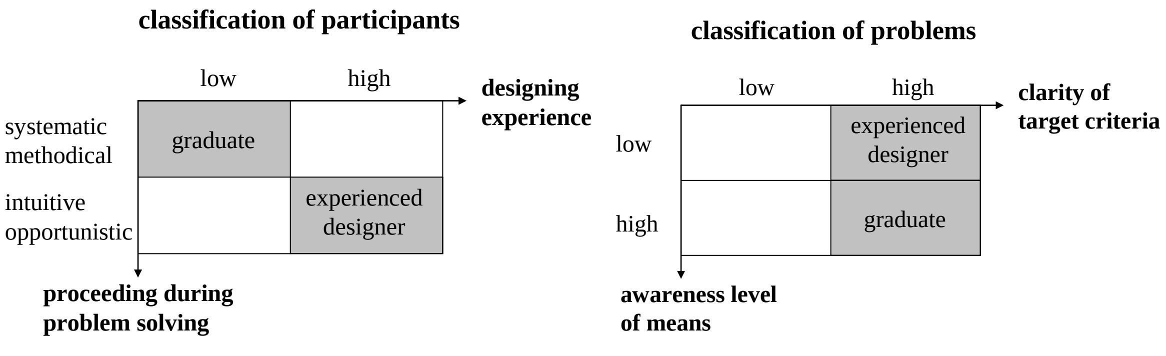

Figure 2: Classification of participants (left hand side) and problems [25] (right hand side)

Additionally, both projects differed significantly from each other, in their classification of problems [25], which had to be solved (Figure 2). The graduate's project contained the development of two subsystems of an electronic devise. The focus of the technology project lied on the development of the interface, which connected both systems. Therefore, the awareness level of the means for problem solving was quite high. The complexity of this project consisted in finding an optimum design, to reach a high number of project targets. The project of the experienced designer contained the new development of a subsystem, without changing the bordering interfaces. In contrast to the graduate's

project, the awareness level of the means for problem solving was quite low. In this case, the project's complexity emerges from finding a completely new design, which fulfils an additional target.
During the project of the experienced designer, about 65 relevant representations of the system or parts of it were created, 40 of them during a brainstorming for the solution of a particular problem. The project was successfully finished within approx. 400 working days. In comparison to this, the graduate created 75, for the development relevant, representations within approx. 600 working days. For this investigation, all representations were assessed, based on particular criteria.

3.2 Evaluation of representations

The first step of the evaluation process was to collect the representations, created during the project, and reconstruct their creation date. Afterwards, these representations were assessed, based on particular aspects: level of detail, scope, problem focus and solution-space.
The level of detail refers to the stage of design. Four different levels with increasing complexity have been distinguished (Figure 3):

1. text/symbol: lowest level of detail and stage of design. Functional connections are represented schematically by texts and/or symbols (e.g. Black box).
2. sketch: second lowest level of detail and stage of design. Functional connections are represented by sketches (e.g. sketching of the shape or the functional principle).
3. rough design: second highest level of detail and stage of design. Functional connections are represented by illustrations of the qualitative rough design (e.g. not true to scale, but already high developed hand drawings).
4. smooth design: highest level of detail with completed shape of design. Functional connections are represented true to scale (e.g. cross section created via CAD-systems).

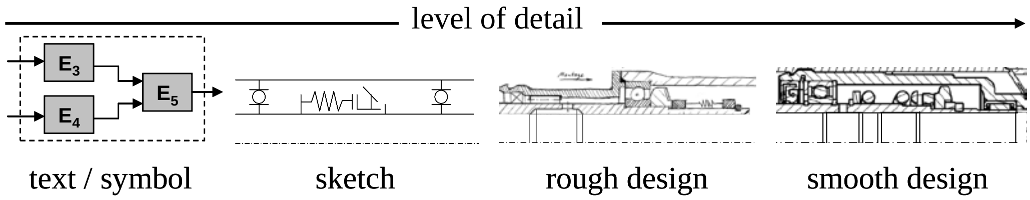

Figure 3: distinguished levels of detail

The scope refers to the represented system sections. Four different levels of increasing complexity have been distinguished:

1. single element: One single element is in the focus.
2. part of subsystem: Only one particular part of the subsystem is represented. The rest is not.
3. subsystem: Only one subsystem is represented. Other bordering subsystems are not.
4. complete system: All elements and subsystems are represented. It is regarded as a product, which fulfils the user's needs (e.g. the entire car).

The focus refers to different problems within the development project. Generally, problem-specific and unspecific representations are distinguished. Within these problem-specific representations, there is a distinction between the different problems of the projects. There were two main problems in both projects. The notation 1.problem and 2.problem just refers to the order of treatment, and not their complexity. Dots in the middle of the problem sector are used for the problem in general. Different aspects of the problem are represented by dots deviating from the middle of the problem sector up or down the y-axis. Thus, it is possible to recognize the change of the focus, caused by representations created for different aspects of one problem.
In order to explore the development of the solution space size, every representation of the design object was analysed and the number of the created alternative partial solutions were counted as well as the number of the excluded ones. Phases, where the designer explores and develops the solution space, can be identified by high growth of created partial solutions. Accordingly, designers constrict the solution space during phases of excluding a high number of partial solutions.

3.3 Analysis of the problem solving

The analysis of the problem solving focused on different aspects. The aim was to represent, which different phases the process went through. At the same time, it should be represented which category these operations belong to. For representing the problem solving, all documented operations were assigned to the different activities of Albers' SPALTEN-approach [21]. The SPALTEN-approach serves the purposeful search for solutions [21]. The acronym SPALTEN stands for:

- situation analysis (SA),
- problem containment (PE),
- search for alternative solutions (AL),
- selection of solutions (LA),
- analysis of the level of fulfilment (TA),
- make decision/implement (EU) and
- recapitulate/learn (NL).

In the course of the problem solving process, these steps can be worked on either sequentially or dynamically (event-oriented) [23].

The operations, carried out during the development process, can be assigned to four main categories: design, theoretic validation, prototyping and practical validation.

3.4 Targets of Analysis

- Identification of phases during the problem solving, in which representations are created with high level of abstraction (in figure 4 marked with a). The investigations concern creation, kind and purpose of the relevant representations.
- Identification of phases during the problem solving, in which a high number of created partial solutions (in figure 4 marked with b), and therefore a high development in the size of solution space, can be registered. The investigations concern the designer's preferred level of detail and scope at this stage.
- Analysis of proceeding during the problem solving. It shall be clarified, if problems are worked on parallel or sequentially. In case of sequential problem solving, the order of treated problems shall be analyzed.

4. RESULTS

In this paper, the two development projects are compared in six different categories (Figure 4). The first four categories show the development of the representation, created in the course of the project. The different aspect, looked at closely, are the course of the level of detail, scope, problem-focus and the number of generated/excluded partial solutions during the project.

The two remaining categories show the proceedings during the problem solving. In the first chart it is documented, how the operations, worked on during the project, have been assigned to the phases of Albers' SPALTEN-approach. The second chart shows the different kinds of operations.

4.1 Development of representations

At the beginning of the project, the graduate analysed the complete system. For this analysis, he chose the highest level of detail and scope (Figure 4). By means of force conduction analysis, an understanding for the completed system was built up, which was used for an abstract description of the system. During this step of abstraction, he, initially, decreased the level of detail to its lowest level, and shortly afterwards also the scope. In doing so, the focus, which had been problem-unspecific at the beginning, was directed to the two essential problem areas of the project. In the following time, he stayed focused on the first problem, until a solution was found, which can be seen in the chart for 'problem focus', where no changes to other problems can be noticed. Around day 300, the project had a very creative phase, where most of the representations of the design object were created. At this stage, representations with a varying level of detail, for different aspects of the first problem, were created. The scope was mostly on the level 'part of subsystem'. Towards the end of this creative phase, the level of detail was reduced to its lowest level, in order to decrease the complexity of a decision, concerning different solution directions. Afterwards, the solution of the first problem was represented in 'smooth design'. During the short period of working on the second problem, again, an abstract representation was created. The level of detail was lowered to the level of 'sketch' and later to the level of 'text/symbol' (Figure 4). At the same time, the scope was reduced to the level 'part of subsystem'. Only two aspects were looked at, within the problem, until a solution was found, which can be recognized the in chart, because no further representations had been created (Figure 4).

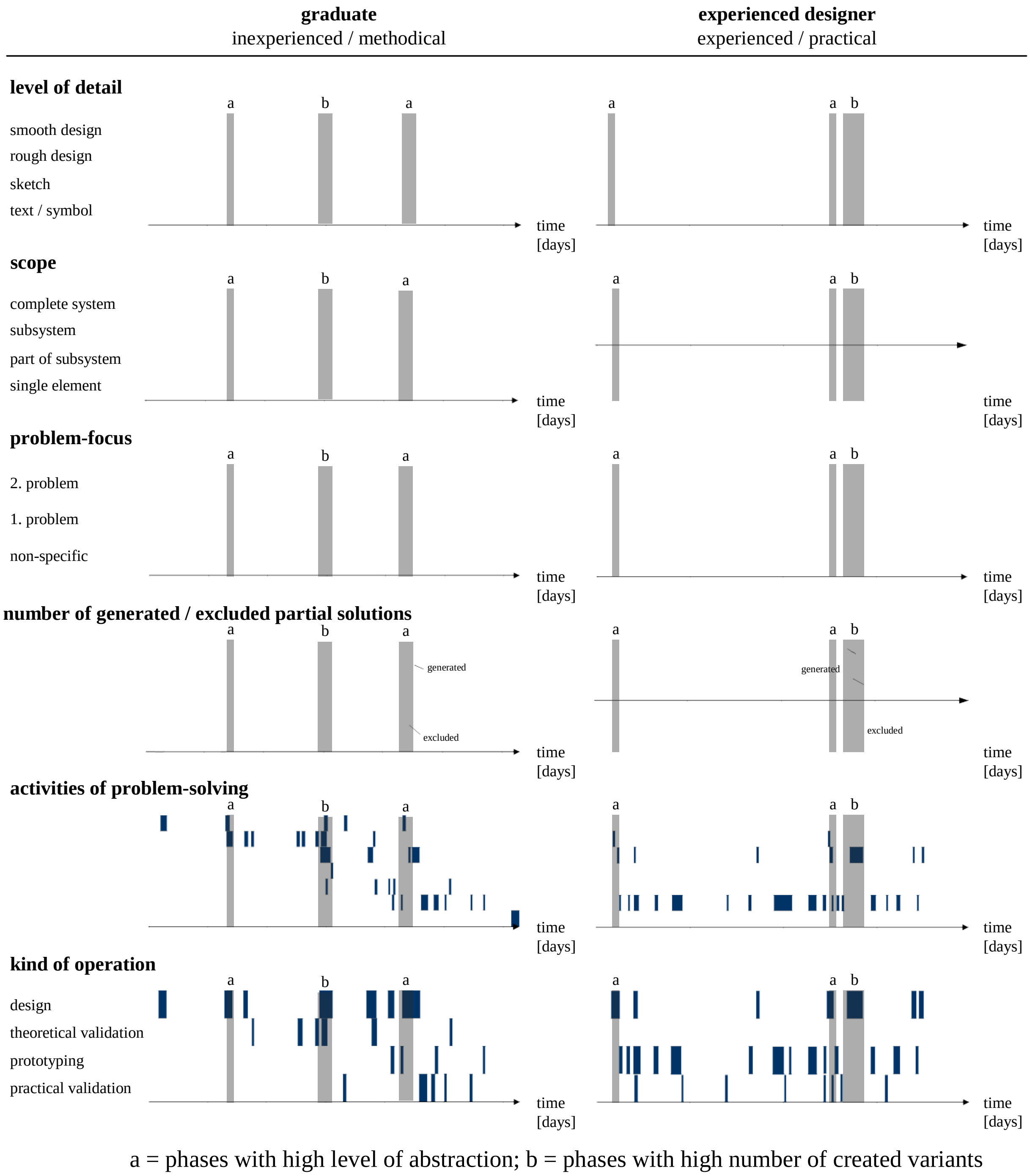

Figure 4: Investigation results of two industrial projects undertaken by a graduate (left hand side) and a experienced designer (right hand side)

The experienced designer started with an abstract description of the first problem. He chose a low level of detail, ‘text/symbol’, to describe a part of a subsystem. Thus, he extended his solution space by creating a high number of alternative partial solutions, but excluded nearly half of them at the same time. In the following, he created representations on the level of ‘smooth design’, showing alternative partial solutions for one problem aspect (Figure 4).

The second problem was caused by the solution of the first problem and arose during its validation. At the beginning of solving the second problem, an abstract representation of the design object had been created on the level of detail ‘sketch’. Afterwards, in a brainstorming, about 50 representations for different aspects of the second problems were created by several designers, who clearly preferred the lower three levels of detail. After the brainstorming, a second aspect had been looked at separately, before a final solution was found. This solution was represented in ‘smooth design’ on the level of ‘Subsystem’ (Figure 4).

4.2 Proceedings during the problem solving process

The course of the problem solving was sequential in the graduate’s project (Figure 4). For the solving of both problems, he went through the activities of the SPALTEN-approach in chronological order twice. There is a high concentration of operations in the sectors situation analysis (SA), problem containment (PE) and search for alternative solutions (AL). At the beginning of the project, mainly operations in the sector of design can be observed. Calculations about estimation and dimensioning of the design are made occasionally (sector ‘theoretical validation’ figure 4). Only after the solution of the first problem, operations in the sectors of ‘prototyping’ and ‘practical validation’ were carried out. The solution of the second problem was implemented in following prototypes.
The experienced designer created, after a short period of problem containment (PE), exclusively alternative solutions (AL), which had been realised in prototypes and practical validated afterwards. Thus, four to five loops of design have been run through, throughout the whole project. Operations, which could be assigned to situation analysis (SA), selection of solutions (LA), analysis of the level of fulfilment (TA) or recapitulate/learn (NL), could not be identified. Likewise, no operations in the sector of ‘theoretical validation’ were registered (Figure 4). Therefore, the proceeding of the experienced designer is comparable to the proceeding of the 'P-designers' (without education in mechanical engineering), who spend little time on analyzing the problem by means of creating representations with low level of detail [24].

4.3 Project results

The results of both projects differ in their quality concerning the validation and function of the design object. Within both projects, the general functions are proved. Furthermore, the new principle, which is developed by the experienced designer, has passed a life time test. However, negative impacts on the rest of the system, caused by this principle, are only solved partly.
In comparison to the experienced designer, the graduate has developed a solution without any known dysfunctions, but he could not confirm the required life time.

5 DISCUSSION

5.1 Problem solving starting at a high level of abstraction

The analysis of both projects shows that the basis for each search for alternative solutions for a design problem, is an abstract representation of the design object. When designing new products, the representation can be based on targets and requirements. If there is, however, an already existing solution which shall be changed, like it is in these two cases, an abstract description of the existing solution has to be created first. Hence, at the beginning of the problem solving, in both projects, the designers create representations with a high level of abstraction. By this initial abstraction, a particular problem is focused on. With the intention to solve this problem, the designer reduces the level of detail and the scope of the representation. Both reductions occur at the same time, or within a short time frame (sections a, Figure 4).
In the projects, shown here, the level ‘text/symbol’ or ‘sketch’, as well as the scope on the level ‘part of subsystem’, as a basis for the search for alternative solutions, is preferred.
The analysed representations, with a high level of abstractions, are functional diagrams, sketches and mind maps. Functional diagrams are used by the designer, to clarify the required functions, which must be fulfilled by the design, created via refinements. Sketches represent the principle, which can be used to realize the required function. Abstract representations on the level ‘sketch’ are used in cases of already clarified functions. In the project of the experienced designer, mind maps had been used to explore the solution space on the level ‘text/symbol’. Thus, mind maps are helpful to collect and classify several aspects or solution directions, during the exploration of the solution space.

5.2 Exploration of solution space via representations with intermediate level of detail

Within the search for alternative solutions (AL), several refinements are carried out and for different aspects of the problem, representations, with several variations, are created (Figure 4). These refinements, which occur mutually with abstractions, cause only little changes in the level of

abstraction. The scope is almost on constant level, whereas the level of detail is increased or decreased respectively. Depending on the complexity of the problem, more or less aspects are being looked at.
In this phase, differences between both projects can be registered in the number of created alternative partial solutions. While creating abstract representations, from which he developed solutions via refinement (Figure 4, section b), the graduate worked out alternative partial solutions, with nearly every representation of the design object. In many cases, different solution directions are demonstrated within one representation. Thus, he explores and develops the possible solution space. At the same time, he chose an intermediate level of detail. Many possible patial solutions are created with a level of detail 'sketch' or 'rough design'. The decision between the possible partial solutions is, in many cases, made by means of exclusion. This exclusion was based on an estimation of the feasibility and the reaching of the targets (Figure 5).

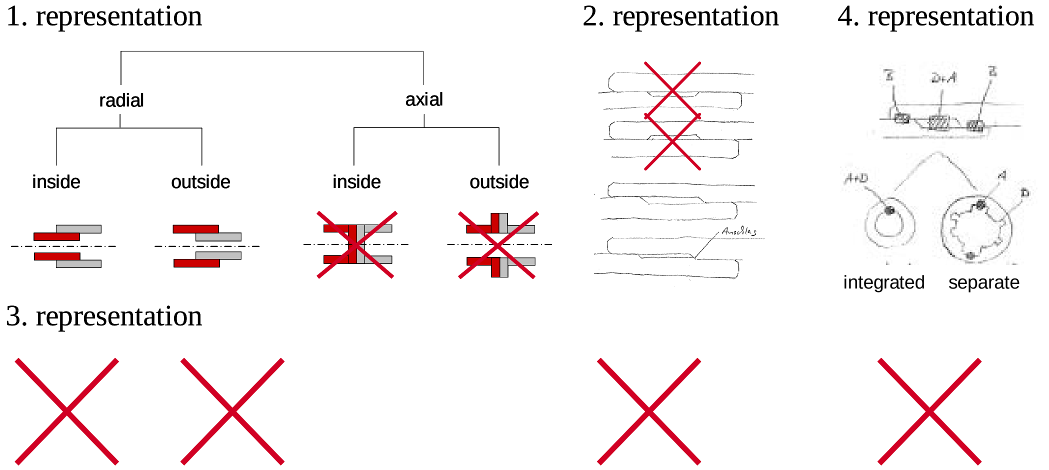

Figure 5: Examples for exploration of the solution space via representations with intermediate level of detail (sketch) made by the graduate

In comparison to the proceeding of the graduate, the experienced designer tends to solve all the problems, after just one immediate step of abstraction, in CAD programs, on a high level of detail. The alternative partial solutions for the problem solving are developed in cooperation with other designers (Figure 4, section b) at the beginning of the project as well as during the brainstorming
A course of project, like the one of the experienced designer, involves the danger of solving the wrong problems, due to insufficient 'situation analysis' (SA) and 'problem containment' (PE). The non-existing development of representations, with an intermediate level of detail during the solving of the first problem, causes an ignorance of the existing solution-space. In spite of the development of a well working solution, it cannot be said, at the end of the project, if there are other solutions, which are perhaps even better. Moreover, without documented immediate steps, the process of problem solving is no longer comprehensible, and the recapitulation for other designers is more difficult.

5.3 Order of problem solving influencing the reaching of targets

Having a closer look at the problem focus, it can be realized in both projects that changes in the problem focus between different problems only occur at the beginning or at the end of the solving process of a particular problem (Figure 4). In both projects, during the creative phases (Figure 4, section b) many different aspects of one problem have been looked at simultaneously. Therefore it can be concluded that problems are worked on sequentially, but different aspects of the same problem are worked on parallel.
The investigation of sequential solved problems identifies two possible reasons for the order of solving problems, which are conscious decision and issue driven reaction. An example for conscious decision is the proceeding of the graduate, who is aware of the existence of both problems at the beginning of project. This can be seen in the representations he created at the beginning of the problem solving (Figure 4, right after section a). Within these representations, he tried to focus on the core of each problem. At this stage, a decision is documented concerning the order of solving the two problems. The documented criteria for the chosen order, is the size of the solution space, which is higher in the first problem. Another possible reason for this decision is that the problem, which has a higher impact

on the reaching of the target, is intuitively worked on first, whereas problems with a low impact on the reaching of the project targets, are only worked on in the following problem solving processes. Aim of this proceeding is, to prevent the necessity of a compromise, which would be the result of working on the problems in a different order. In the case of the graduate it can be noticed that, instead of dealing with the fairly easy second problem, he concentrated on the solution of the more complex first problem, which enabled him to control the reaching of his project targets.

The proceeding of the experienced designer is an example for an issue driven reaction. He starts the problem solving process with the, at this stage only known, first problem. The second problem arises right after the solving of the first problem, due to the negative impacts on the complete system, caused by the found solution. The example of the experienced designer shows that some problems only arise during the course of a project. Therefore, a planed treatment of these problems is impossible. Generally, there must be a decision, if the further proceeding shall concentrate on the found solution or on the arisen problems, which are caused by the solution. In case of the experienced designer, there was a conscious decision to solve the arisen problems, because a higher fulfilment of the project targets has been estimated.

5.4 Reservations and limitations

Within the evaluation of both projects, only documented representations and operations are considered. It is generally agreed that designers create a high number of representations only mentally. These representations can have high impact on problem solving, but until now, no appropriate possibility is discovered, to make them visible for evaluation.

Additionally, the evaluation contains only two projects. Further researches, concerning other projects with different types of participants (Figure 3), should validate the first statements of this paper and improve the proceeding of evaluation.

6. CONCLUSIONS

This paper provides a methodology for evaluating development processes, which enables the analysis of completed development projects, by means of created representations and operations. The methodology focuses on the different levels of abstraction, which are used in the relevant representations, and their role in the context of problem solving. First results from the analysis of two industrial projects showed that, at the beginning of the solving process of a design problem, a representation with high level of abstraction is created. This abstraction includes the reduction of the level of detail and scope, and serves as basis for the following search for solutions. The actual development of the design object occurs, in cases of complex problems, in several small refinements and abstractions. In this period, representations for different aspects of the problem are created, with almost constant scope and a varying level of detail. The investigation showed that those representations, created with intermediate level of detail, are important for the development of the solution-space. If this phase is left out, during the searching for solutions, it is not possible to make a statement concerning other solution, which could work as well or even work better. Furthermore, the process of problem solving is not comprehensible and it is hard to transmit the knowledge to other projects.

Problem solving is worked on sequentially, in which the problems with the highest impact on reaching the targets, are worked on first. This proceeding prevents the necessity of a compromise, which would be the result of working on the problems in a different order.

Overall, this paper can be seen as a first step in the evaluation of abstract representations in industrial development projects. It gives a description of the used methodology and presents first findings concerning the proceeding of designers during the problem solving. In order to validate the statements and to derivate methodical support, further projects with different participants should be evaluated.

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Albert Albers is head of the IPEK - Institute of Product Engineering at the Karlsruhe Institute of Technology (KIT), Germany. After working as head of development of driveline systems and torsion vibration dampers at LuK GmbH & Co. KG, he moved on to the University of Karlsruhe – today's KIT – in 1996. His research focuses on product development processes as well as the support of product development by methods for computer-aided engineering, innovation and knowledge management in mechanical and automotive engineering.