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ISSUE DRIVEN ANALYSIS OF AN EXISTING PRODUCT AT DIFFERENT LEVELS OF ABSTRACTION

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1. Introduction

Understanding existing products is a fundamental part of the development of new products. Most designs are created by modification of existing products. In the design of complex products the goal is often to keep successfully working parts and to reduce novelty as much as possible, as it introduces risk into the design process; novelty not only arises from new sub-systems, but also from putting existing components to a slightly different use, e.g. increasing the operating temperature or load [Wyatt et al. 2009]. While some designers work on the same component for many product generations, many designers are new to their tasks, the product or the company. They therefore have to start the design process by generating an understanding of the existing product or product group on which the new design is based. For them design starts with an analysis of an existing product.

On the surface this seems a simple task. The product exists, its uses are known, and therefore the design documentation ought to exist. However, in practice the documentation can be incomplete and consist mainly of the description of the product's geometry. In particular designers are notoriously bad at capturing design rationale. In the absence of an explanation of why a product is designed in a particular way, designers have to deduce this from the existing product. This explanation is closely linked to the way a product functions. How easily, how quickly and how correctly they are able to understand is likely to vary with the designer's prior knowledge of the product and their general skills as engineers.

To investigate in detail how designers analyse an existing product, an experiment was conducted with 20 engineers from a very homogeneous background, who were given the same product to analyse and ask to summarise their findings in a function tree. The resulting function trees varied vastly in terms of accuracy, completeness and depth of analysis between the participants [Alink and Eckert 2010]. This paper concentrates on the analysis of one particular subject, who appeared on the surface to have produced one of the most systematic and complete analyses of the product and generated comprehensive drawings. This designer made very significant progress in his understanding through looking at the product at different levels of abstraction. Starting with a superficial look at the product, he increasingly looked in more detail, but kept coming back to a more abstract view in order to place his newly gained understanding in the wider context of the product. The role of abstraction in the generation of design synthesis is well known and summarised in section 2. After a description of our methodology in section 3, this paper explains the analysis of this designer's behaviour in section 4 and reflects about it in section 5. Section 6 discusses the wider implications of the findings before we draw conclusions in section 7.

2. Abstraction in Design Problem Solving

Abstraction is a universally used, but rarely defined term, which is informed by different traditions. Philosophical distinctions are typically drawn between "abstract" and "concrete" – the class of flowers of a specific kind and a specific flower that needs to be described, appreciated and used. Abstract objects are defined as those that lack certain features possessed by paradigmatic concrete things. This implies that abstraction is a process of selecting certain features as important and thereby discarding other features. Abstraction is often applied over multiple similar objects, some concrete and some idealised memories, so that common features are selected to form the descriptions of the abstraction. Abstraction is driven by a particular purpose rather than being an absolute property of the product. This selection of significant features is biased by what seems to be important at a particular time from a particular viewpoint. Abstraction is not a deterministic process, but includes an element of subjective selection. Frigg (2003) argues abstraction only exists if there is also one or a group of more concrete concepts that could provide a more specific description. A related and often overlapping concept is that of the level of detail of a description or model. A description at a low level of detail also lacks certain features possessed by a concrete or more detailed description. An abstract view of the product is one that does not include details about the form; a concrete view would describe the form of the product at a particular level of detail.

Designers employ a wide range of tools, techniques and methods while designing, which address design problems at different level of abstraction. Any method or formalism requires some kind of abstract representation of a product. According to the classical prescriptive engineering design methodologies, e.g. those of Roth, Hubka, Pahl and Beitz and others [see Cross 1989, for a review], the design process begins with a detailed analysis of the functional requirements, which are broken down as far as possible to inform the design of components. This is seen as an abstract description of the product, as shape information is not included. Prescriptive design methodologies can be contrary to many industrial projects which incorporate existing solutions, either as components and systems that are reused or as concepts and ideas [see Cross 1989]. Designers very quickly work with component geometry as the primary representation of products. In fact many design managers complain that their designers concentrate too quickly on the details of one solution, rather than explore the solution space systematically. As Simon (1969) puts it, designers *satisfice*: they settle for the first solution that fulfils their needs rather then search for the best. Design processes start in reality with a mixture of very detailed and very coarse design descriptions, as well as concrete product details and abstract requirements or functional descriptions.

One of the reasons why designers settle early on a solution is the lack of intermediate representations of designs (between abstract functional representations and concrete form representations). Design ideas can only be shared and thus evaluated effectively when they can be represented sufficiently unambiguously to be interpreted in the same way [see Stacey and Eckert 2003]. Only when the proposed solution does not satisfy their needs do designers step back and explore abstract problems again. The balance between abstract and concrete descriptions varies with the type of project; an innovative project has a heavy emphasis on abstract descriptions, drawing its concrete ideas from many different sources within and outside the problem domain. Visser (2006) and other authors have carried out empirical studies of designers generating new solutions and discovered that designers follow a systematic approach until they ran into difficulties and need to resolve localised problems.

Research on abstraction has mainly concentrated on the role that abstraction plays in the generation of new designs and has made general comments on the preferred level of abstraction for designers of different expertise. Abstraction is essential in analysing any complex situation, because the ability of humans to considers multiple issues at once is limited, in particular designers' mental representations of designs are limited: they may only include parts of the design, and there is no guarantee that these are consistent or even coherent; people may only recognize the limitations of their mental representations when they encounter questions they cannot answer. Research on mental imagery [see e.g. Logie 1995] shows that people can have a subjective sense that their mental representations are more complete and detailed than they actually are, and that details are only filled in when people focus on parts of their mental images. This makes abstraction a fundamental part of human problem solving in general and design in particular. Abstractions enable designers to simplify problems and concentrate

on particular aspects of a problem. Hoover et al (1991) argue that designs evolve through abstraction and refinement, which occur in the framework of those abstractions.
Closely related to the right level of abstraction is the level of detail that designers choose to represent the aspect of the design they work on. The level of detail that designers work in increases and decreases continuously throughout the design process. The right level of detail is critical to fully explore the relationship between form and function in a design. Abstractions are generated from the mental and physical models that designers have available. The resulting abstraction is only appropriate if the level of detail of these models is suitable. If an aspect of the design or function of product is excluded from the abstraction, the results of the reasoning processes are likely to exclude these aspects, jeopardizing the quality of the solution and the efficiency of the design process.
An abstraction is also a perspective on a problem, and can potentially enable designers to reconceptualise their solution and gain new insights. This indicates that a representation that allows designers to change effortlessly between different levels of abstraction increases their ability to generate effective design solutions. The level of abstraction required varies with the problem, but also with the expertise of the designer. Zeitz (1997) argues that experts prefer a medium level of abstraction, concrete enough to resemble the real problem and to remind them of the tricky details, and abstract enough to provide them with an overview over the problem and its potential solutions. By contrast novices might require much more detailed representations, because they cannot construct the details with abstract representations to see the “big picture”.

3. Methodology

This paper reports on an experiment that has been carried out as part of a systematic evaluation of the Contact and Channel Model (C&CM) approach, developed at the IPEK in Karlsruhe [Albers et al. 2008g. C&CM is an approach to describing, analysing and designing products in terms of their functions, working surface pairs, where the functions act, and channel and support structures through which the functions are transmitted. C&CM has the potential to be employed in design synthesis; its main application has been so far in the analysis of existing system to find problems or improve the design.

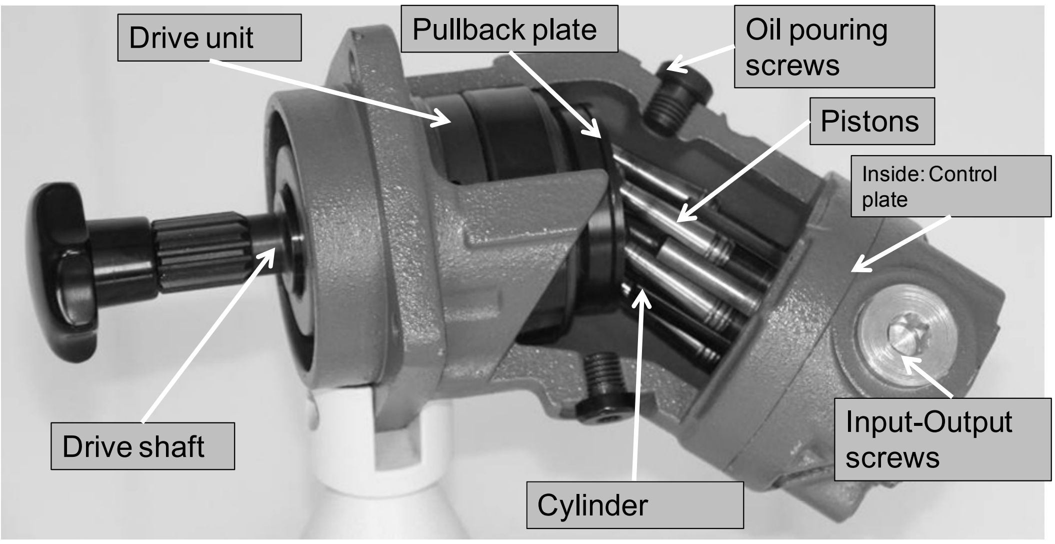

Figure 1. Pump used in the experiment

The experiment was designed to compare the analysis of an existing product by engineers familiar with C&CM with those by engineers less familiar with C&CM. 20 subjects took part over a period of one month in the summer of 2009. The subjects (18 male, 2 female) were all design engineers and graduates of the University of Karlsruhe, thus all have received a very similar design education. All subjects are working as researchers at the IPEK. All but two have between 1 and 5 years post graduate

experience. The other two were experienced engineers who have been teaching C&CM to the other subjects.
The task of the experiment was to analyse a hydraulic pump that is employed in off road vehicles for lifting or moving heavy parts, for example in the shuffle of a digger. The product is highly optimised for robustness and durability. The subjects were divided into two groups. Eleven subjects were given the physical pump, which has been prepared for teaching as shown in Figure 1 by replacing a motor with a manual handle and cutting the top cover to expose the pumping mechanism. The subjects were allowed to manipulate the pump, but could not unscrew its components. The second group of nine subjects were provided with a 2D maintenance drawing, which was obtained from the publicly accessible product maintenance documentation. The subjects were given identical briefing notes, asking them to analyse this pump to assess the potential for improvement and summarise their understanding in a function tree. The experimental brief asked them to imagine that were a new engineer at the pump company and needed to find ways to improve the pump. They were therefore asked to analyse the pump, explain the pump to one of the experimenters and summarise their understanding in a function tree.

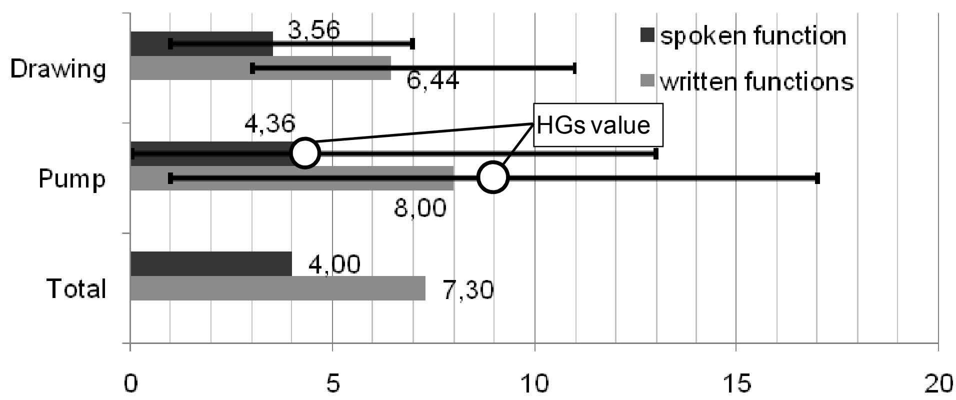

Figure 2. The number of functions identified

To gain as complete a protocol as possible the experimenters asked the subjects what they were thinking or looking at in order to keep them talking and asked them targeted questions to encourage them to fully explore the pump. While the experimenter might have biased the activity compared to a classical concurrent verbalisation approach, the subjects commented that they experienced their explanations as a natural dialogue similar to a student coaching session. All experiments were observed by the first two authors, recorded with two video cameras, and transcribed. The experimenters discussed the experiments after each experiment and provided feedback to the subjects at the end of the experimental period. The experiments were conducted in German. Quotes are translated. The analysis of all the experiments is ongoing and further details can be found in Alink et al. (2010).
This paper concentrates on the protocol of one of the most experienced subjects, based on the experimenters' impressions after the session and an analysis of the completeness of the resulting function trees. He stood out for the completeness of the analysis, the clarity of his representations, and the absence of mistakes in his analysis. The subject (HG) has four years postgraduate experience and is currently in the last year of his doctoral research and employment as a researcher associate on design optimisation. Figure 2 shows the range of the number of functions identified by the subjects, the average number, and the number reported by HG, classified by experimental condition and whether the functions were written down or mentioned verbally.

4. Case study: Analysing a pump for potential improvement

In discussions the subjects often associated the division between abstract – concrete with a function – form division. All subjects were asked to define *function*, and either conceptualised function as a transformation of inputs into outputs or took a goal directed approach. In line with official German

VDI definitions of function, none of the subjects made an explicit distinction between function and behaviour in the sense of FBS [Gero and Kannengiesser 2004]. Nor did they distinguish clearly between wanted and unwanted functions, therefore they struggled to distinguish between the primary design and features of product that were included to suppress undesirable behaviour. An analysis is ongoing of how the conceptualisation of functions affects the detail and quality of the analysis.

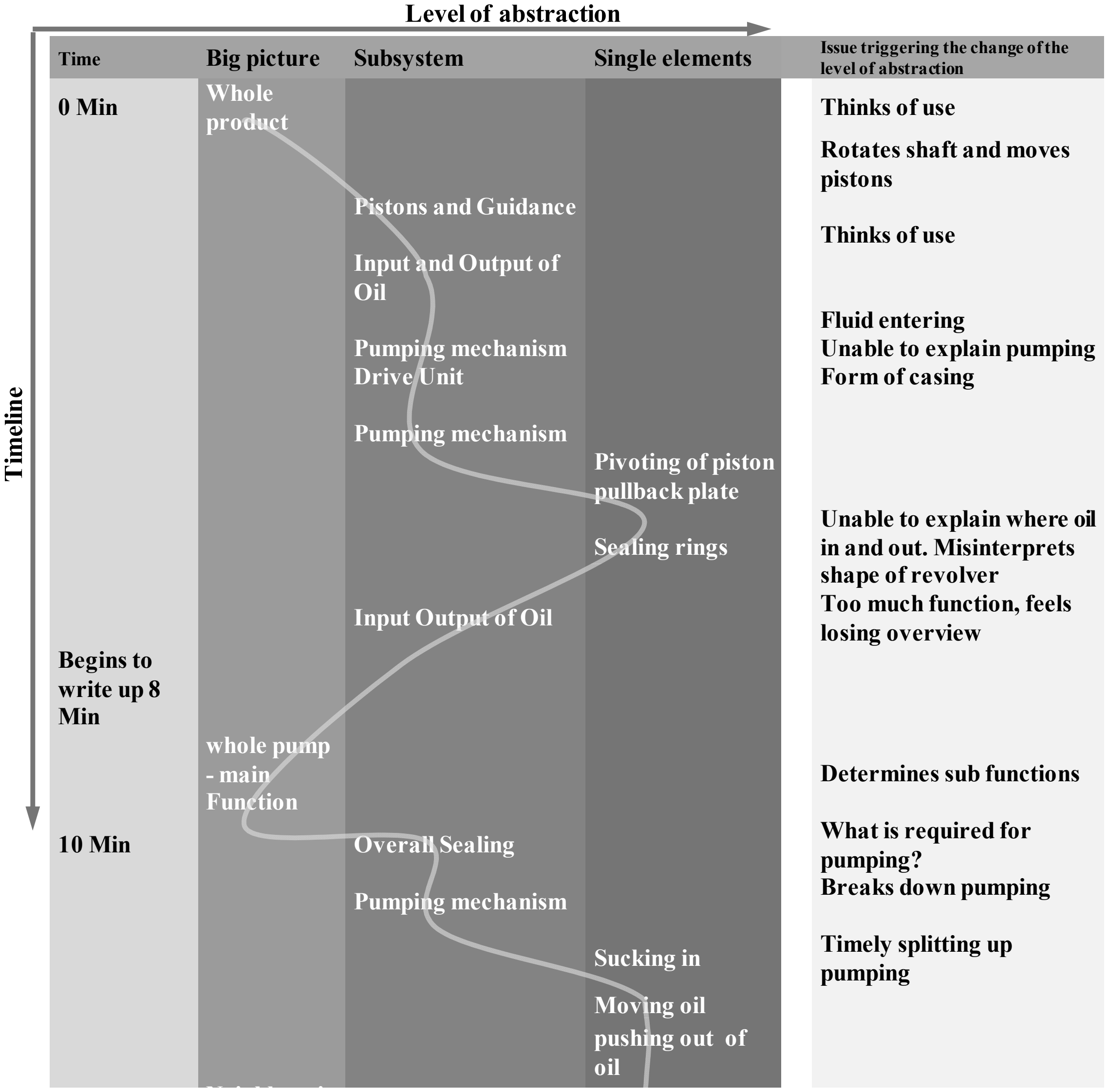

Figure 3. Summary of the focus of attention in the analysis over the first 10 minutes

This section describes the approach taken by the single subject HG in analysing the product. During the experiment the authors perceived his analysis as very systematic and complete, but closer inspection revealed that he was very much driven by curiosity. He conducted the C&CM analysis in three phases. First he tried to understand the functions the product has. Then he looked at the product form with an abstract notation to indentify subsystems and last he looked at details of the forms and tried to interpret their function. To achieve this he drew detailed sketches (Figure 5 and 6). Figure 3 shows the first 10 minutes of the analysis with a timeline and different levels of abstraction. As the figure indicates he was looking at the product essentially at three different levels of abstraction: the whole product, i.e. the entire pump, a sub-system level, e.g. the drive mechanism or the pumping mechanism and a single element level, e.g. sealing rings. He changed the level of abstraction as he came across particular issues or problems in his understanding, which are shown at the right of Figure 3. He went to a greater level of detail when he did not understand a particular issue and zoomed back out when he needed to look at what he had learned in the wider context of the sub-system or product.

Overall as time progressed he tended to look at more and more detail and asked more and more specific questions.

4.1 Functional breakdown of the product

As shown in Figure 3 HG began his analysis with looking superficially at the complete product for about one minute. He realised that it was not immediately obvious where the pumping fluid comes in; therefore he looked in more detail at the oil flow. He returned to the entire product to identify and name major subsystems and define a system boundary for the entire system. Still struggling to see the fluid flows he concentrated on where the oil comes in and studied the basic pumping mechanism in more detail. He recognised the importance of the sealing rings around the pistons to the main pumping operation. Once he understood the pumping mechanisms of the pistons he drew his attention to the bottom sealing disk.

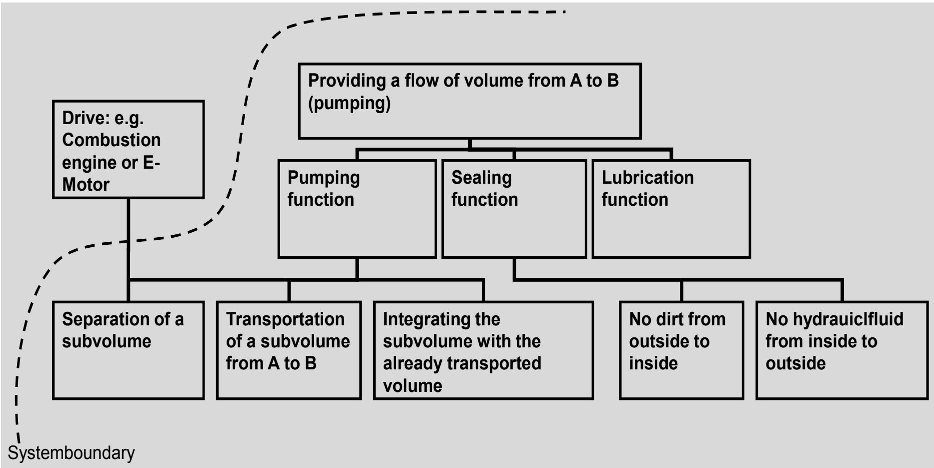

Figure 4. Translation of HG's Function Tree

Only at this point he began to write down the functions (see Figure 4). Motivated by thinking about lubrication he limited his analysis to pumping oil. Lubrication was very important to him as it affects the entire system. Note that he placed it next to the sealing function box. Lubrication is an emergent property of the details of the form. Understanding exactly how the lubrication worked drove much of his later analysis. He returned to the basic pumping mechanism. He understood the fundamental principle behind the pumping functions and decided to limit top level functions to pumping, sealing and lubrication, because he sees all other functions as dependent on the form.

> *"I just find it difficult to add something new beneath the sealing function and the pumping function, which I wrote down on the top, because I would directly get into the designing. A soon as I write something new I am getting fixed on a solution*".

When questioned he commented that he tried to avoid looking at form, because he wanted to keep an open mind for different solution principles. He was the only experimental subject, who focused on the request in the brief to improve the component, which he interpreted as the component having a fault that he needed to find.

Next he tried to understand the power source of the pump, which he identified as some form of rotational power, therefore he reformulated the core function of the pump as abstractly as possible "*rotational drive is being converted into a translation*". He tried to narrow the potential power sources, but looked at the side effects of different types of engine, which would have to be mediated against (see Figure 3 outside the system boundary). Note that he drew a system boundary within the function tree and connected the drive function of a potential combustion engine or e-motor to a function on the lowest level of the function hierarchy. Again he scanned the whole product and wondered about screws for pouring in lubrication oil at the side of the casing. He thought again about the relationship between sealing, lubricating and pumping and realized that they are very closely connected in the pump. At this point he declared that he understood the main functions of the product and finished his function tree and started the work on the analysis of the product form to conduct a full C&CM analysis.

4.2 Analysis of the product form

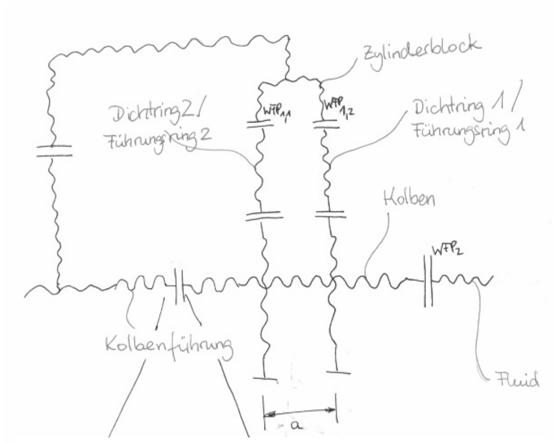

Figure 5. Sketch of the C&CM structure of the product

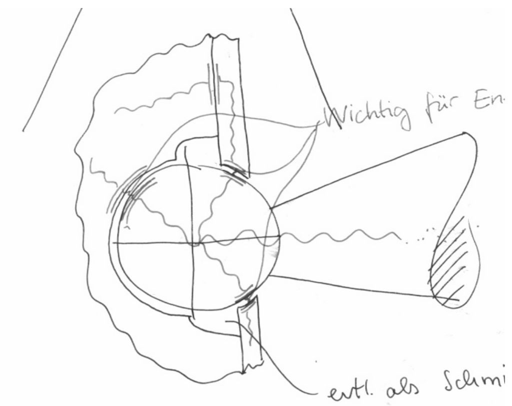

Figure 6. Detailed sketch of the piston heads

His aim was to describe the form of the product as abstractly as possible using a stylized C&CM sketch representation (see Figure 5), which draws components as wavy lines which are connected to adjacent components through double lines (Working Surface Pairs). However before he could start to write anything down, he needed to name the components. He struggled, and defined names by analogy, for example he named the cylinder block (“*Zylinderblock”* in Figure 1) by analogy to a car engine. He commented on a conscious decision to name the rings around the piston “*seal and guidance ring*” to avoid just thinking of them as one of the two possible functions. To understand how the pistons are moved and guided he tried to think abstractly about the general physics behind the mechanism and recognizes lubrication as an issue. While he claimed to discard lubrication as an issue at this point, he turned his attention to the disk where the piston heads are located, and recognized this as a very critical part.

Now he began to combine his abstract sketch (Figure 5) of the components with his function tree and realises that he does have components that have no function assigned to them. He scanned the components and focussed on the bottom sealing disk. As he could not see the component in detail he again hypothesised about what the component needed to looks like. To verify his hypotheses he looked at the implications of the required design decisions and asked the experimenters for confirmation. He never fully assigned functions to components and also did not revise the function tree to reflect the previously undiscovered functions that some components have. At this point he stalled and was prompted to look at the central guiding rod. He realised that he had not looked at this part before and concluded that he should probably be looking at this component in the context of his analysis of the guidance of the piston, when he had previously only looked at the pistons themselves and their position in the cylinder block.

His last stage was a more detailed sketch (Figure 5), to understand in detail a part that he could not see clearly. This brought him back to the positioning of the piston heads and the lubrication of the piston head location disk. To reason about how this worked in detail, he began the detailed drawing. He stated that the detailed drawing made it much easier to understand the function of the product, although he did not write down these functions. However, the detailed sketch of the *“critical component”* allowed him to draw the *“important working surface pairs* .Sketching to gain a deeper understanding stands in contrast to his previous strategy of abstracting away from the specific form.

He reflected about his entire analysis and revised insights in terms of geometrical tolerances. But now he conceptualized these issues in the context of the efficiency of the pump. At the very end he was prompted to think about the casing of the pump. After some stalling he attributed its thickness to the need of the product to be robust.

5. Reflection about his behaviour

The subject had been selected because his approached appeared structured during the experiment. He spoke confidently about his analysis and was aware of what he did and did not understand during the analysis process. He was systematic on a high level. He first scanned the product to gain a basic understanding of the product and then he named the basic components or component groups. As the next step he investigated the function. Once he was satisfied with his function tree, he built a C&CM in an abstract notation. Only at the end, he drew a detailed sketch of a component he could not immediately understand. He had a stated strategy to stay as abstract as possible. This was reflected in the way he represented his analysis. He drew a high level function tree and tried to phrase the functions as abstractly as possible, e.g. writing about "providing a volume flow" as opposed to saying "pumping oil" or "pumping hydraulic fluid". In the second step he drew an abstract C&CM diagram (Figure 4) which indicated the functional relationships of the main components, but not maintaining the geometric relationships of the components. In generating this representation he referred to the concrete object. Only when this was not possible, he generated a sketch of the product form. This representation is abstract in the sense that he made a very deliberate choice of which aspects to select. Very revealingly HG has frequently requested a C&CM computer tool, which would allow the user to draw an abstracted C&CM model over a schematic representation or CAD model of the product.

However in carrying out each of these steps he was very opportunistic and driven by issues he was concerned about and did not understand. On a high level his approach was systematic, in that he started with an abstract function breakdown, as is advocated in many systematic design methodologies. He forced himself to consider the form of the product as little as possible in understanding the functions of the pump. However, he was only able to do that by looking at what the components or systems of the product actually did. The rationale he gave during the experiment for working as abstractly as possible was that he wanted to keep an open mind to using other solution principles to carry out the same function in order to identify areas of improvement in the pump. He had to look at the details when he had a problem understanding what was going on. This is in line with Visser's (1996) observation that designers break off from a systematic approach in generating designs, when they have to resolve problems.

HG did not understand exactly how the piston heads were mounted. He identified the piston pullback disk as a critical component. In particular he could not see how the lubrication of the piston head would work. Clearly reliable and smooth running of the piston heads was critical to the operation of the pump, particularly as he had realised that the piston cylinder was rotated by the force on the piston heads. In the 3D model (Figure 1) this part was obscured. He drew a large scale detailed drawing as a way to think through the functionality of the part. More as an accident of the sketching than by intention he drew an empty space at the side of the pistons (Figure 6). When looking at it, he realised that this could be interpreted as a chamber for lubrication liquid. He pursued the idea and concluded that the piston head disk needed a lubrication chamber. He is correct; the actual lubrication chamber is at the top of the piston head. In this case he needed to look at the concrete form to understand how an abstract function (lubrication) would work. He did not generate a detailed drawing for the other parts of the pump he was not sure about, such as the sealing disk, which several other subjects tried to draw.

While other subjects followed a distinct strategy, such as top-down or along the energy flow, he was opportunistic in his exploration, driven by issues that he did not understand or were unclear to him. He started with the core pumping mechanism, but investigated areas more deeply that he did not understand or was concerned that they would be important. He partly did this by hypothesizing potential effects of his current hypothesis. In particular he was concerned about lubrication and sealing at different points of the analysis process. For example, when he studied the piston, he became aware of the piston rings, which seal the pressure chamber. He thought about their function and looked at the implication for the way force was transferred from the pistons to the cylinder. He contemplated whether the piston rings transfer the power on their own by preventing the side of the cylinder from touching the piston. To decide this he looked for abrasion marks on the piston, which again raised the concern for lubrication. As Figure 2 illustrates, his entire analysis is driven by these issues that he discovered during his analysis.

Several key components of the pump were hidden in the model. He could not see the details of the piston head disk or the sealing disk. To understand what these components did and how they might look like, he hypothesized based on the visible components of the pump. To investigate the sealing rings, he first wished he could unscrew the pump, but then contended himself with looking carefully as the product. He went back to the physical principles of how the pump worked and thought about how a smooth flow of fluid could be achieved. He thought about how the pressure is built up and how the liquid is pushed out to understand the geometry of the sealing disk. Once it became clear that the disk needed to have kidney shaped slits as openings, he did not produce a specific drawing.

At the beginning of his analysis process he tried to name the main components. He tried to separate the pump into the drive and pumping mechanism; however he struggled to draw a boundary between them, because the pistons both carried out the suction and translated the rotation to the cylinder. In mapping components to functions this ambiguity caused him problems and he had to revisit his earlier analysis about halfway through the session to revise the relationship between the pumping mechanism and the drive. As a result of this, the function tree (Figure 3) does not include an element that describes the function of the drive unit. After revisiting his early analysis he verbally made the distinction between the "driving the pump" and the "pumping mechanism". As a boundary between those, he decided on the connection between the piston heads and the pull-back plate. This in fact drew his attention to the piston heads as the critical parts in the system. From the beginning of the process he was very selective in his analysis. He ignores several subsystems completely. After he separated the drive unit from the pumping unit he had decided that the drive unit is "unproblematic" and did not study it in detail. He also ignored the casing and the way it can be mounted, both essential components for the pump to carry out its function, but not to understand how the pump might work. Some, but by no means all, subjects included these elements in their analysis.

6. Implication

This paper presents an early analysis of one out of twenty subjects, all of whom produced different function trees and provided different explanation for how the same product would work. Few subjects produced as rich descriptions or function trees as HG. The experiment shows that analysing an existing product is a difficult task in its own right. It is rarely looked at in the discussion of design processes and design cognition, which has mainly focussed on design synthesis.

While HG's analysis was more detailed than most and did not have errors in the function tree, it still contained mistakes in his interpretation of the product, and he ignored parts of the product, as did the analysis of most of the participants. An hour might not be sufficient to fully understand such a complex product, and therefore time could account for the mistakes in the analysis. However, most participants had a sense of having understood the product much earlier, even though they later discovered that they had been wrong. Most assumed that because they knew how pumps work in general, they understood how this pump worked in detail, i.e. they confused understanding a solution principle with understanding a product. This would indicate that people think prematurely that they have understood how a product works and underestimate the challenges of analysing a design. Future research will look in more detail at the approaches other subjects took and develop guidance on how a product might be analysed efficiently.

HG, like other subjects, got sidetracked in his analysis of particular issues and never quite resolved some issues, e.g. he did not fully assign functions to all components. This partly accounts for why he returned frequently to the same issues, like lubrication or sealing. Again he reached the point of believing he had understood the product, when he still had many open questions.

Some of his difficulties arose from the difficult relationship between form and function. As the example of the pistons illustrates, components can play an important part in carrying out more then one function and therefore need to be considered in more than one context. German research culture often does not draw a distinction between function and behaviour, as defined in the VDI Guidelines. This contributed to the conceptual challenges of analysing a product.

7. Conclusion

Analysing an existing product stands at the beginning of most design processes. This is a challenging activity for which no standard approaches are taught. This paper has described the results of the preliminary analysis of an experiment that illustrates that analysis of a product is error prone and often incomplete. The challenge in analysing products lies in finding the right level of detail. A too high level look and important details are missed. Too many details and the big picture is lost. This subject very deliberately tried to free himself from the specific pump he had in front of him to understand the solution principles and to potentially transfer other ways of achieving the same functionality.

The subject looked at the product at different levels of abstraction in several ways:

- To understand the context of a component or system to understand how it worked;
- To look at the functions of the product independent from the physical form of the product;
- To stop himself from getting fixated on the current proposal for improvement.

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