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That which is not form: the practical challenges in using functional concepts in design

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Abstract

Functional modelling is a very significant part of many different well known design methodologies. This paper investigates the questions of what functional modelling approaches people use in industry and how they conceptualize functions. Using interviews and the findings from an experiment where 20 individual designers were asked to generate a functional model of a product, the paper highlights the different notions designers associate with the word *function*. Difficulties associated with functional modelling arise from varied and inconsistent notions of functions as well as wider challenges associated with modelling and the introduction of methods in industry.

Keywords: function, behaviour, design experiment, design methodology

1 Introduction

“Function” is one of those words we use on a daily basis. We talk about the function of the heart being to pump blood around the body, and by analogy about functions in an organisation, referring to a role or activity that something carries out. Mathematics has a clear definition of function in terms of a mapping from inputs to outputs. Vermaas (2010) identifies three archetypal engineering meanings of function: function as *intended behaviour* of

devices (e.g. Stone and Wood, 2000), function as *desired effects of behaviour* of devices (e.g. Lind; 1994); and function as *purposes* for which a device is designed (e.g. Gero and Kannengiesser, 2002). In our ordinary conversation we rarely think about the exact meaning of the word, feeling confident in the use of our own languages. It is those vague everyday meanings of terms that we have to fall back on when we encounter the terms in a professional context.

The connotations of the word *function* are different in different languages. Germans speak of a machine functioning almost synonymously with the machine working. For example the German use the verb “funktionieren” all the time colloquially as a synonym for “working”, as in “der Lift funktioniert nicht” meaning “the lift does not work”, i.e. is broken, whereas the English meaning of “to function” more points to a purpose. For example when an English person might say “the lift does not function” when it is running, but might stop at the wrong place or not have the right capacity. Many native speakers of English intuitively draw a distinction between *function* (relating to purpose) and *behaviour* (describing actions) which is central to the FBS model by Gero and Kannengiesser (2002). By contrast the German industry VDI guideline 2221 on the “Systematic Approach to the Design of Technical Systems and Products” (VDI, 1993) defines a function as a solution neutral description of the relationship between input and output, which is an operation on material, energy and information, and explicitly includes behaviour in the definition of function. Shifting verbal intuitions is difficult for people, and requires considerable training. Reading a definition once at the beginning even if it makes sense - at least in the author’s experience - does not stick and one reverts back to some intuitive meaning.

Function is a key term in engineering design methodology, as this special issue demonstrates with a rich history in German and English speaking methodology. As Goel (2013) shows in this special issue, many meanings of the term can coexist within a single line of research. Vermaas (2010) explains the range of different meanings that the term has in design research methodology. While both these papers and other recent reviews, such as Crilly (2010), provide a systematic account of the relation between different

meanings of the word in different methodologies, the authors of those methodologies themselves show much less awareness of the debates that go on around the concept of function, which the special issue is hoping to elaborate.

This paper brings together experiences from interactions with engineers who are building or using functional models. Their modes of interact with the models differ, as do their organizations, but all point to the conclusion that building and using functional models is not straightforward. Section 2 introduces some functional modelling approaches that are used in industry, while section 3 reports on two series of interviews in companies where designers talk about their use and understanding of function, as well as general issues associated with the introduction of new methods, which constitute a real barrier to bringing new functional modelling approaches to industry. Section 4 reports on an experiment with 20 graduate engineers, who had been provided with the same brief to analyse an existing product and identify its functions. It shows the range of notions of functions the subjects had as well as the range of functional breakdowns that they produced. Section 5 reflects on the challenges around functional modelling as well as building models in general and argues that engineers want programmatic ways to build useful models rather than being caught up in theoretical discussions of the nature of function. Section 6 draws conclusions.

2 Functional methods used in industry

Many academic methods involving functional model have been validated through industrial case studies, but academics generally struggle to introduce their methods successfully into companies. Many methods that are used have been developed by other companies and then publicized through academics, such as Lean Production (Womack et al., 1990) or Total Quality Management (Clark and Fujimoto, 1991), which were both developed in Toyota and described by researchers at leading US universities. This section introduces a selection of methods or approaches which are used in industry without any claim to completeness.

2.1 The challenge of method introduction

Some methods have been hugely influential on industrial practice. For example the classic German product development methodologies, such as Pahl and Beitz (1977/2007) or Ehrlenspiel (1995) have been taught to generations of students and firmly instilled systematic product development thinking in companies. However, it is hard to judge to what extent these methodologies are followed in companies both in terms of the rigour and the completeness with which they are employed. These methodologies prescribe a sequence of steps that the engineers need to follow, producing particular types of models, to guarantee a successful outcome of their projects. How the methods can be applied in a specific context and how models can be developed for complex real life cases rather than smaller teaching examples is left to the engineers' personal experience. This challenge has led to a certain method fatigue in general, which can be explained by the lack of flexibility and adaptability of many methods (Geis et al., 2008). The use of functional modelling has to be seen in this context.

2.2 Functional methods used in industry

Function is also an important concept in well established methods used in industry, even though not necessarily with a crisp definition. For example Quality Function Deployment (QFD) was developed in the 1970s and 1980s originally in the Japanese shipbuilding industry, but then widely published in the US as a means to bring marketing and design closer together (Hauser and Clausing, 1988). When functions are mentioned in Hauser and Clausing's influential paper, they refer to roles or departments in an organisation; however the paper implies that by applying the method a high quality working product will be developed through a systematic translation of customer requirements into engineering characteristics and then part characteristics, which in turn are mapped to key process operations and ultimately production requirements. While very few companies follow the entire four step process, QFD has now become an established part of modern business processes such as Business Process Excellence or Lean Processes.

Many companies now carry out Failure Mode and Effect Analysis (FMEA), which identifies the potential failures and their likelihood and severity based on past projects, or Failure Mode, Effects and Criticality Analysis (FMECA), which includes a rank ordering of the failure risks. A failure is defined as "the loss of an intended function of a device under stated conditions" (Langford, 1995, p. 488). For example a bicycle might fail to move smoothly. The failure modes are the ways in which the failure is observed, for example the bicycle has a flat tire, and effects are the "immediate consequences of a failure on operation, function or functionality, or status of some item", for example the wheel does not turn smoothly. Knowing this is a risk, the designers can take a number of actions, for example having stronger rubber or a solid wheel to mitigate against the risk, or deciding that the risk is acceptable. This is not a narrow or technical definition of function, but what is often interpreted as failure is when a product does not do what it is meant to do and the customer would get annoyed about it. As designers need to mitigate against risk through the entire life cycle of the product, this is closely linked to design for robustness, which emphasises resistance to damage and fit to environment, reliability, which is related to predictability and the ability to function within defined parameters, and resilience, which includes recoverability or adaptability in changing circumstances.

Another somewhat surprising meaning of the word function or functional is in the context of functional products (Alonso-Rasgado et al., 2004) in the context of a manufacturer selling a functionality rather than a product. For example Rolls-Royce sells flight hours to some of their customers, whereby Rolls-Royce owns the engines, and services and maintains them, and the customer devolves the responsibility for looking after the product to the manufacturer. A very similar concept is expressed as Product Service System (Mont and Tukker, 2006), which emphasises that the product and the process through which it is used need to be designed together.

Many companies use TRIZ (e.g. Altshuller, 1999; see Hua et al. (2006) for a review), which helps designers to identify conflicting constraints at the heart of design problems and uses solution principles elicited from an extensive review of Russian patents to resolve the conflict. The TRIZ vendors Invention Machine Corporation have patented a

tool that allows graphical mapping of useful and harmful actions or effects between artefacts in a specialised form of concept maps, called Functional Analysis Diagrams (FADs), describing artefacts, users and other resources as nouns, and behavioural relationships as verbs. The key difference between FADs and function trees and function structures, is that in FADs functions are intimately linked with the physical elements of a product, rather than aiming for complete independence from physical form. Knott (2001) reports that TRIZ has been applied in Rolls-Royce for many years to resolve specific problems. For a long time they generated FAD diagrams in Microsoft PowerPoint, as illustrated in Figure 1.

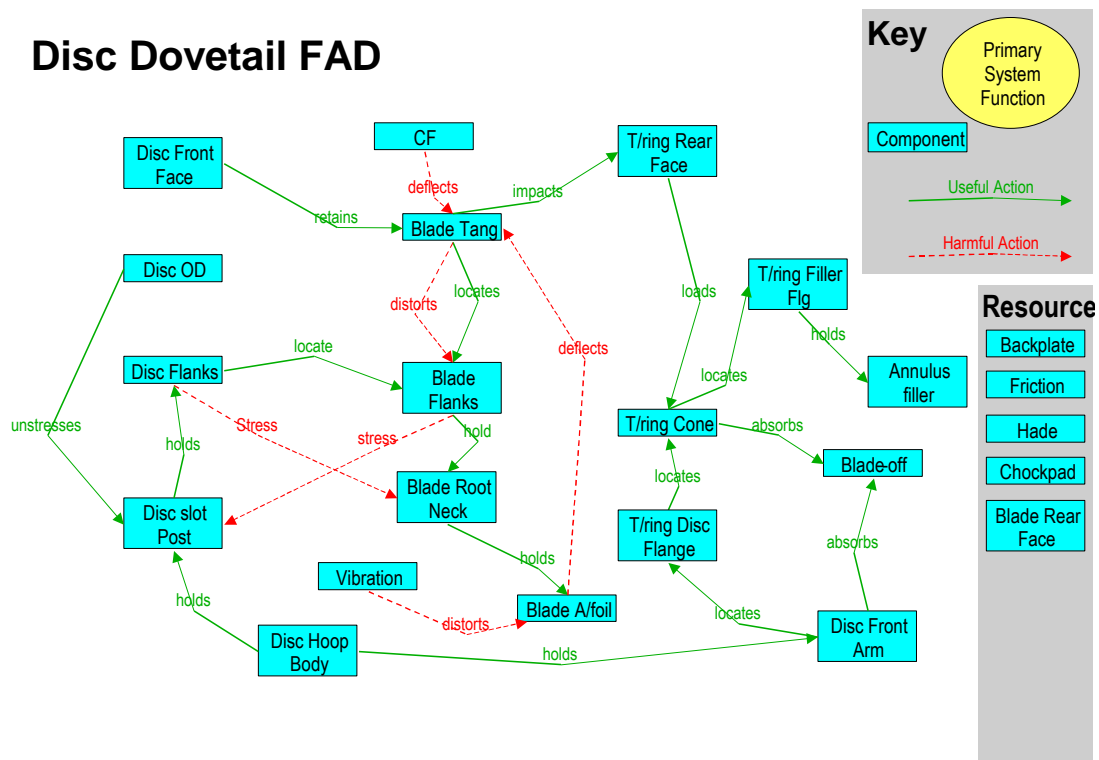


Figure 1. Example of FAD diagram generated in Microsoft PowerPoint, from Bracewell et al. (2009)

The FAD modelling has been taken up much more widely in the organization since a FAD diagram extension (see Figure 2) has been developed for the DReD rationale capture system (see Bracewell et al., 2009, and in this issue, Aurisicchio et al., 2013). The software was developed at Cambridge University in very close collaboration with Rolls-Royce. As the company invested heavily, they embedded the software in their official company processes, offer training internally and have company champions for the

software. This enables a rare link between CAD models and functional models, but important CAD files and superimposing a FAD model over it.

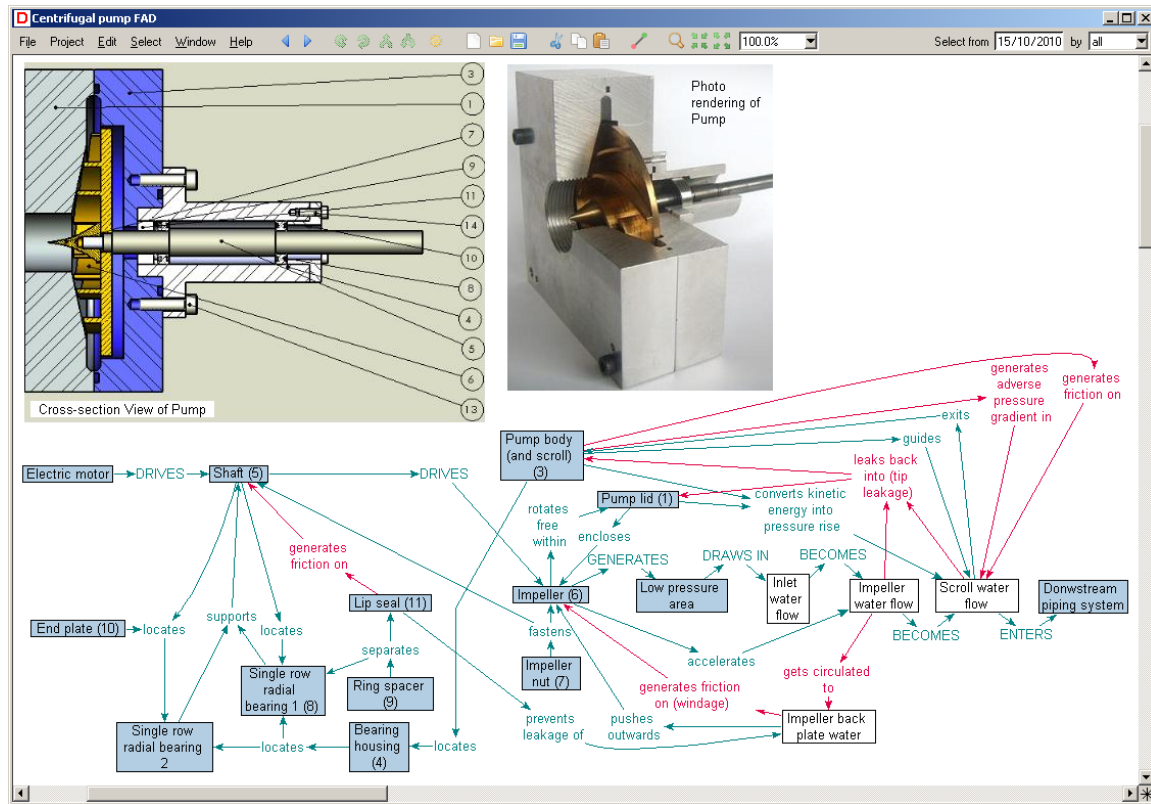


Figure 2. Functional Analysis Diagram (FAD) for a centrifugal pump

Through PhD students entering companies the Contact and Channel (C&C) approach developed at Karlsruhe University (e.g. Albers et al., 2008a,b; Alink, 2010) is increasingly used in German speaking companies. C&C models products through functions and the working surface pairs on which they take place. The core idea of the C&C approach is that function is only fulfilled when two components, systems or products interact, through working surface pairs. The working surface pairs are connected through channel and support structures and are have a physical location on the product. This ties product form and function intrinsically together, but does not assign specific functions to specific components. Rather it looks at functions and the working surface pairs where they take place at whatever level of detail is relevant, from the entire product to detailed features. C&C does not have a firmly defined concept of function, but usually conceptualizes functions as creating, enabling or suppressing behaviour. The approach

therefore lends itself to incremental design, as it supports the analysis of existing products as well as targeted improvements, where the designer can analyse exactly where a function takes place and how it could be modified, or which new working surface pairs would be created by a modification and thus which effects or functions could occur.

3 Observations in industry

Engineers talk about functions in their daily working life. They have to describe that which is not form about a product, but their use of words is surprisingly loose as is in some cases their understanding of exactly how form and function fit together. To illustrate some of these points, this paper draws on two case studies, in which function was discussed in the context of discussing other methodological issues. As the case studies touched on similar issues and deployed a mixture of notions of functions, they will be discussed together. The first case study was carried out in the summer of 2009 at a central European manufacturer of building tools. Interviews were carried out with six engineers at two sites to investigate the use of C&C in the context of general method introduction. The interviews were conducted in German; quotations were translated by the author. The second was carried out in 2011 in a UK diesel engine company on the role of virtual and physical testing. Again six engineers were interviewed. The author has worked with this company for years and is familiar with their overall processes and ways of working.

3.1 Introducing methods in companies

The UK diesel engine company is part of an American multinational, which tends to decide on methods used across the organization. They work with consultants on introducing methods in across all their companies. As they are part of the automotive industry they can draw on methods used in the sector. The products are certified so that certain methods are part of the certification process.

The building tool company is independent and does not operate in such a tightly regulated sector. The company has hired method specialists with PhDs in product

development, who are responsible for bringing new methods into the organization and supporting people in carrying out the methods. One of the method specialists commented on the general resistance to using methods in the organization:

There is always a spread, 30% of the people don't care, 30% are anyway against it, 30% are enthusiastic and simple accept such solutions The remaining 10% promote such things

The challenge in method introduction for him lies in getting people to distinguish between the suitability of the methods and how well people have used it. Methods need champions who help with a successful introduction at the beginning.

A method depends strongly on the people who carry it out. People who... don't know about development methods say the method does not work. This is simple, if I have somebody who tries to hammer a nail in a wall and hits his finger five times, he says the hammer does not work, but everybody would laugh and say you are too stupid to use a hammer. Applying methods is largely a matter of discipline. I have to discipline myself to use the approach and conventions of the method. This can particularly be a problem in creative areas, because people are worried that they lose flexibility through a method.

One of the engineers commented that learning a new method takes time and therefore can put a burden on the project on which the new method is first used.

3.2 Modelling and understanding functions.

When the engineers in the tool manufacturer were asked about which methods they used in the company, they claimed that they would carry out functional modelling, building abstract top-down functional models in the Pahl & Beitz tradition. However, when they were asked for an example the engineers were unwilling to volunteer an example. After some discussion it emerged that they had several times attempted to build functional models but got stuck and abandoned the endeavour; and they did not show us an example.

During the development of an innovative screw, they ran into problems, which they struggled to solve until they carried out a very systematic analysis of exactly how and where the functions of a screw were carried out. While they understood their product

very well, they had not fully understood where and how vital functions, such as “cutting or displacing material” were carried out. As explained in more detail by Matthiesen (2011) they built detailed C&C models of parts of the screw, such as the tip or the thread of the screw, to see exactly which working surface carried out which function.

3.3 Incremental product development with known functions

It is not surprising that the screw development engineers did not know exactly how functions are carried out in their product in detail. They did not have to ask themselves this question previously, because at a high level both the purpose and the behaviour of a screw are clear. More importantly any new screw inherits some or all of its function from a previous generation of screws. Most engineering products are developed by modification from existing products, usually past designs created by the same company. Engineers are also well aware of competitor products and study related products to some extent.

Many engineering products have changed little in their basic functions over many decades and the assignment of functions to systems is so stable that it is reflected in the organizational structure of the company. For example the engine company has a piston group, a rotary component group, a gear group, etc. The core expertise of the organization is tied up with designing components that provide known functions. While modern engine development is highly innovative (see Eckert et al., in press) the pressure is towards achieving new requirements with minimal changes. Occasionally it is necessary to design a component from scratch. For example the company designed a new configuration of a bracket for a generator where they systematically evaluated different configurations (see Wyatt, 2011); however the function was clear from the beginning.

One of the interviewees summarized this in the following way.

This comes back to what are our goals. We are an engine manufacturer. We are not going to produce a totally different power solution that is not an engine. That is not our goal. We start with this starting assumption. There are many different ways you can design an engine in a product and there are many

different technologies you can add to this. Part of this is an engine. The abstract nature is kind of taken away.

3.4 Functions versus requirements

When the engine engineers were asked about an exact meaning of the term function, one of them provided the following answers.

We use ... function in many different guises. When I use the word function I think of how we are organised, which is the functions of the business, which is totally different to the requirements, the functional requirements.

The company produces off-highway diesel engines, which are employed in a very large range of products from construction equipment to agricultural vehicles operating in most countries and climates in the world. The robustness and reliability of the products are key to their commercial success. Most of the design effort is directed to making sure that the engine will operate as required in all the situations. Therefore there are a very large number of requirements regarding what the engines needs to do. The following dialogue from the interview exemplified the casual use of terminology in industry:

Interviewer: You talk about functional deployment and QFD also talks about function, but when one talks to [your] people, they never talk about function

Eng1: [Nervous laughter] ... I suppose it depends on how you want to define it in the letter of the theory. But I suppose we are all interested in function. Different functions of the engine, different functions of systems of the engine, different function of each component. It means something slightly different to all of the engineering community

Interviewer: What actually is a function for you?

Eng2: A functional requirement can be anything. It can be an overall engine performance, fuel economy. Do we actually meet the requirements that the customer is looking for or it can be. If we go into the FMEA world, we can have functional requirements for every single component. The piston must withstand this environment; the engine must use ... fuel. Those functional requirements get listed out in all our FMEA

Interviewer: But these are just requirements, why are these functional requirements?

Eng1: Because they are requirements for the engine to meet this function. It is just nomenclature.

Eng2: We class it as a product function.

Rather than making a distinction between behaviour, function or performance, the engineers at the engine company lumped them all into the term functional requirement. The distinction is between functional requirements, i.e. what the engine does, and other requirements, mainly business requirements, such as costs or resource use requirements. Theoretically functional requirements are concerned with what a product does and needs to enable the user to do, and the rest are non-functional requirements. However, the boundaries are blurred, because the non-functional requirements affect the functions, e.g. buying a cheaper material to meet a cost target would impede the robustness of the product and thus the functions. The diesel engine engineers are pragmatic. They use FMEA as a formal process of managing process risk and listing a requirement as a functional requirement in the FMEA assures that it will be handled systematically.

Following the logic of FMEA, unwanted behaviour of the engine is picked out as a potential failure mode against a specific functional requirement, for example vibration would be a failure mode against several requirements, such as robustness. The tool designers thought of unwanted behaviour as a type of disturbance (*Störgröße*). For them function was “something positive”. Whether unwanted behaviours are seen as functions is closely related to the notion of function. In a behaviour view of function, unwanted functions and desired functions are both functions. In a purpose view of function, an unwanted function cannot exist and becomes a disturbance. Designers are not necessarily consistent about this. The tool designers had no problem with the behaviour view of function embodied in the C&C method and still did not use a concept of unwanted function.

The same broad meaning of function appeared again when the diesel engine engineers explained how they had developed a functional model for a QFD for the last generation of engine, which they have begun to reuse for other engines. Here the terminology points to the engineers assuming that performance arises from function, which is provided by the embodiment of the engine.

Interviewer: In the theory you would break down the function quite abstractly into what parts of the engine would do and from that get to an embodiment of the parts. From how you are talking about it you have an architecture in mind and then characteristics of what these

parts need to do... interesting that this slightly more abstract view of QFD does not seem to be necessary for you

Eng1: You say that, but for [last generation] we tried to follow this. Saying we have an engine that has a set of functions to perform, deliver torque etc. and then we break that down into functional systems. So within that you have a combustion system, a fuel system, a rotation system etc. to map out the interactions between these systems. For example in the combustion system you have influx, as well as pressure and temperatures. In the [last generation] we did a complete piece of work for these product characteristics how would you break down the engine into functional systems, and how these systems need to deliver, such that it all adds up into an overall engine performance. Then for those systems, what components exist in those systems and therefore what these components need to do to deliver this system function.

The engineers used the abstract function decomposition as a targeted exercise to force themselves to think abstractly about the product and how components and systems contribute to the delivery of the overall system function.

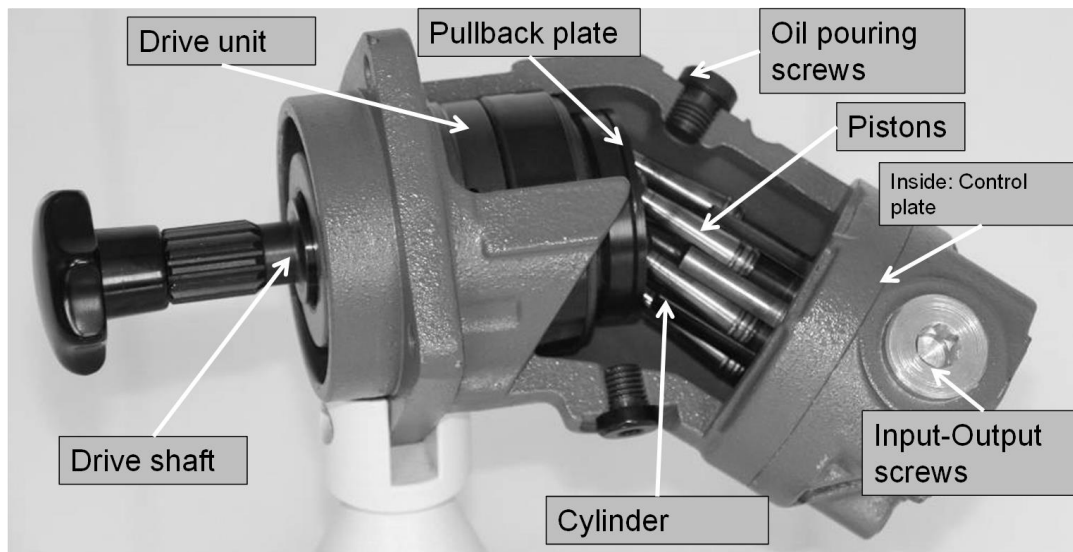
4 Findings of the experiment

The findings from industry show that the understanding of functions in companies is loose and divergent without a clear definition of function or a consistent use of functional methods. This section reports on the findings from an experiment in which engineers were asked to analyse the same product individually, which showed that the notions of function used by individuals was as diverse as the functional breakdowns they generated to describe this product.

The experiment was carried out as part of an evaluation of the C&C approach. As the C&C teaching at Karlsruhe explains the notion of function mainly through examples, the research aimed to contribute to a suitable definition for C&C as well as pragmatic ways of handling the concept of function. The following research hypothesis was investigated in the experiment: **The way designers analyse a product is strongly influenced by their notion of function.** This type of analysis requires rich data sets, and therefore the number of subjects that can be studied effectively is limited. A statistical analysis was never intended.

4.1 Methodology

The task given to participants was to analyse a hydraulic pump used in off-road vehicles for lifting or moving heavy parts (for example the bucket of an excavator). This product was selected as an example of a design that is highly optimized for robustness and durability, and has sufficient complexity to reflect components that are designed by teams in industry. A more detailed explanation of the experiment can be found in Eckert et al. (in press). Figure 3 shows the physical pump prepared for teaching, where the motor was replaced by a handle and part of the casing cut off, and a maintenance drawing of it.



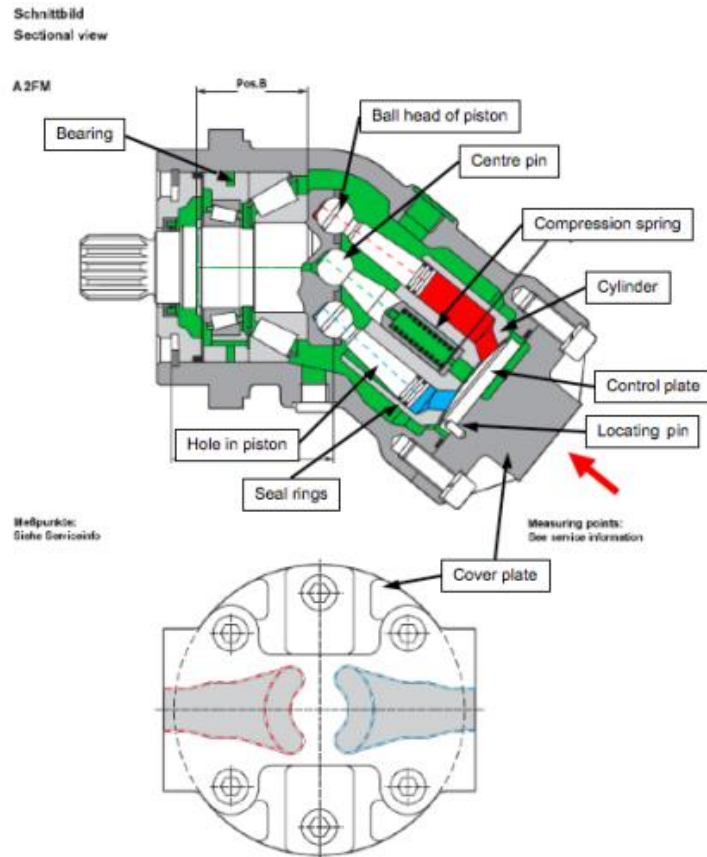


Figure 3. Physical pump, prepared for teaching, and a maintenance drawing

The subjects (18 male, 2 female) were all graduate mechanical engineers with between one and thirty years of professional experience. They had a similar academic background, being either trained at Karlsruhe in the last eight years or else involved in teaching there. All but one (a Tunisian) were native speakers of German.

The first 11 subjects were given a physical example of the pump, shown in Figure 3. The subjects were permitted to manipulate the pump, but not to dismantle it. Since certain aspects of how the pump works were hard to see on the physical object, it was decided to give the next 9 subjects a maintenance drawing of the pump instead of the physical pump to avoid biasing the results through the use of one particular representation of the design, in terms of what subjects could see easily. It is well recognized that how designs are represented strongly influences in design activities (e.g. Goldschmidt and Porter, 2004).

The subjects were asked to explain the pump to one of the experimenters. To acquire a protocol that was as complete as possible, the experimenters asked the subjects what they were thinking or looking at in order to keep them talking, and asked targeted questions to encourage them to fully explore the pump. While the experimenters might have biased the activity compared to a classical concurrent verbalization approach (see Ericsson and Simon, 1993), the experiments yielded rich protocols, and the subjects commented that they experienced their explanations as a natural dialogue similar to a student coaching session.

The duration of the experiment was limited to one hour. However, many subjects declared that they had concluded the task earlier, and were therefore released. The experimenters discussed the outcomes after each experiment, and provided feedback to the subjects at the end of the experimental period. The experiment was video recorded and a transcript was generated. The experiment was conducted in German. All functions and other results of the experiments have been translated to English by the author as literally as possible.

4.2 Analysis of the data

The audio recordings were transcribed. The transcriptions of the 20 experimental protocols consisted of between 3000 and 5000 words each. All sketches were transformed into a standardized tree format (see Figure 5) to express the written functions. The verbal protocols were used to identify when the subjects talked about functions, but did not write them down. These verbally described functions were then added to the function trees based on the context in which they were expressed. The analysis of the function trees concentrated on the following issues:

- Written versus spoken functions
- Level of abstraction of the expression of the function
- Level of detail in the analysis

This was related to the notion of function that the subjects had provided in the prior interviews or at the end of the experiment.

A statistical analysis of this data would not be appropriate due to the small total number of subjects, and lack of even distribution between the different groups. With a sample size of 20, the margin of error would be 21.9% for a confidence level of 95%.

4.3 Outputs generated in the experiment

This section provides a picture of the outputs of the experiment. All but one subject wrote down at least one function. The most obvious difference between the two groups was that the subjects who were given the 2D schematic drawing did not sketch aspects of the product, whereas ten out of eleven subjects in the other group drew sketches to understand or illustrate parts of the pump. The subjects using the maintenance drawing pointed out and marked the subsystems that carried out the functions they were speaking about, whereas all but one of the subjects using the pump made sketches to point out the subsystems whose functions they were discussing. Figure 4 shows a typical output from a subject given the maintenance drawing. On the left-hand side, the function tree, drawn as a box representation, can be seen, with sub-functions arranged inside the box of the main function. The right shows accompanying annotations to the maintenance drawing.

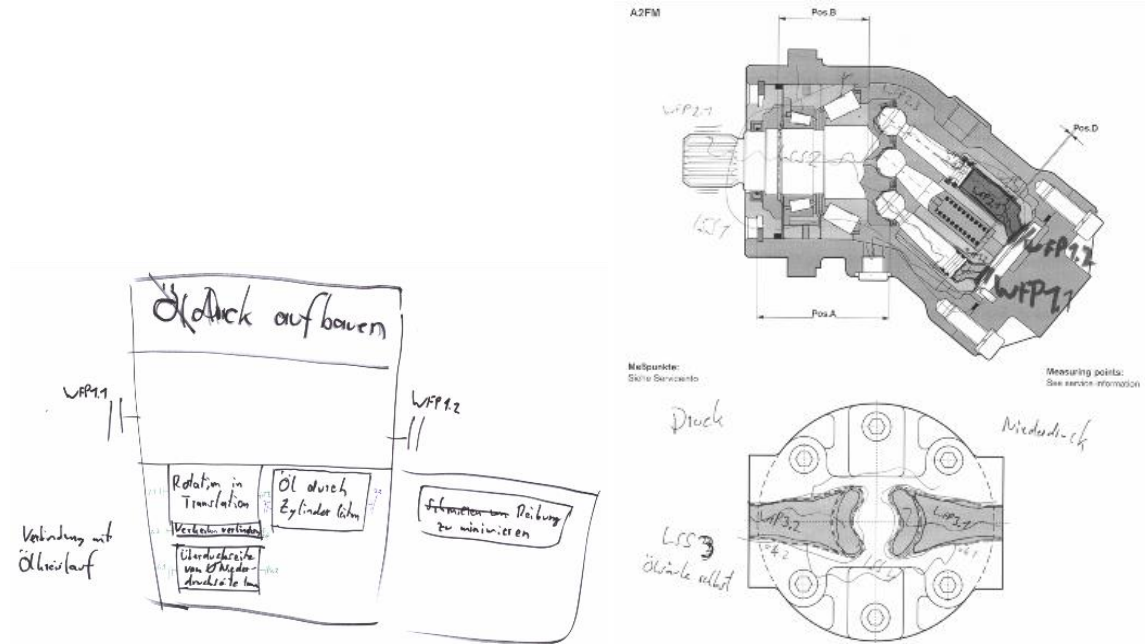


Figure 4. Typical representation of a maintenance drawing subject

Figure 5 shows a typical sketch produced by a subject who was given the pump. He created additional drawings to clarify aspects of the pump. On the top left-hand side of the figure, the main function of the system (HF = Hauptfunktion, i.e. main function) is broken down into three sub functions. These functions correspond to the sequence of the pumping operation: (a) “draw in oil”, (b) “convey oil”, and (c) “dispense oil/create pressure”. To understand the piston movement, he created a sketch of one piston in different positions (a, b, c). As soon as the sketch was created, he identified further functions at a lower level of detail, for which he did not produce more sketches but instead wrote down the functions (g = “position drive unit”, h = “lubrication”). In (f), he shows the arrangement of the pistons that “draw in oil” and “dispense oil”, two functions that occur sequentially, which makes him aware of the need to position the piston cylinder. (j) refers to the function of “support the revolver”. (i) refers to lubrication, which is a function on a lower level in the function hierarchy, since it supports all other functions of the pump. The arrow from the upper drawing (see f to j in Figure 5) indicated a detailing of the analysis.

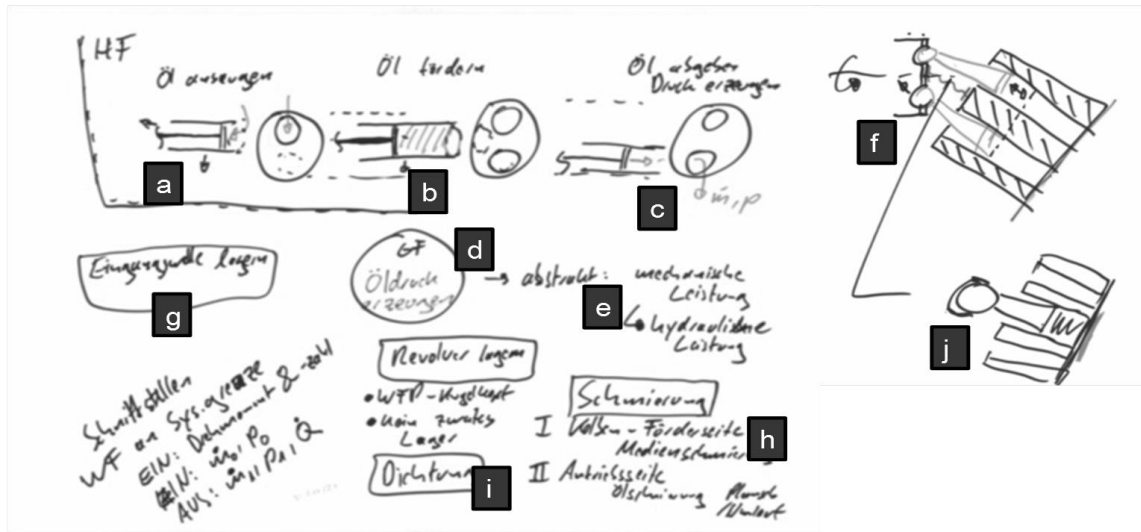


Figure 5. Example of an analysis by a subject provided with the physical pump

4.4 Variation in the functional breakdowns

On average, each subject identified 11.3 functions (written plus verbalized), ranging from 1 to 17 (see Eckert et al., 2010). Figure 6 shows three function trees with very different number of functions, levels of detail and ratio of spoken to written functions. (The spoken functions are shown in italics on a grey background, and connected with dotted lines.)

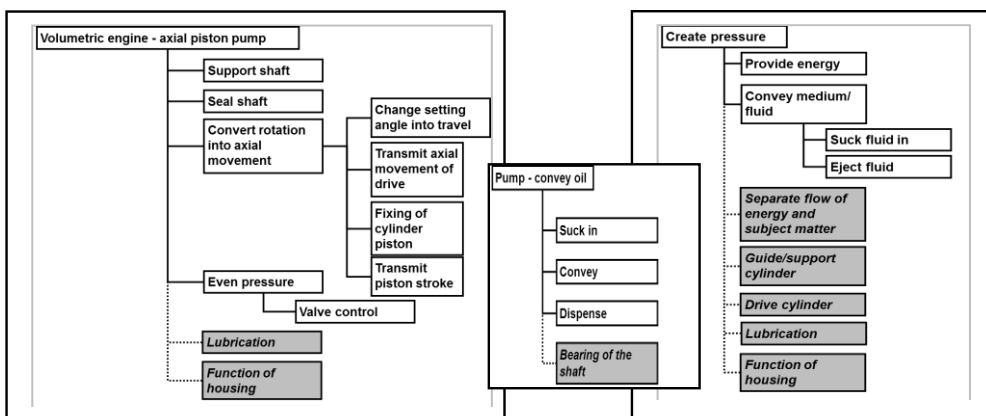


Figure 6. Three function trees of different depth and detail

The greatest agreement was around functions generic to all pumps. However, many subjects missed generic sub-functions, such as lubrication and sealing. A number of additional functions are required to suppress the undesired behaviour of some components. For example, the shape of the sealing plate and the pin that holds the cylinder in place both exist to stop the cylinder from misaligning and thus generating leakage. However, to identify these functions, the subjects needed to understand in detail how the pumping mechanism works, and several of them were not able to do so.

At the end of the experiment, most subjects claimed that they had now understood how the pump worked. Most subjects stopped before the allocated time of one hour was over, yet some subjects indicated that they would have concentrated on the casing or the drive mechanism if more time had been available.

4.5 Different Notions and Expressions of Function

Fourteen subjects had been interviewed prior to the experiment about their experience with C&C and asked about how they would define function; the remaining subjects were asked after the experiment.

Table 1 gives an impression of the range of answers. The middle column lists the key concepts, and the right columns elaborate the flavour of the answer. The partial nature of the answers reflects the subjects' statements.

Table 1. Range of notions of function provided by the subjects

Class of Functions description	Concept	Typical statements
Intentional	Functions as Goals	Purpose of the system; must fulfil purpose; functions often are also requirements; allows fulfilment of the goal of the design process
Physical	Transformation	Transformations of an input into an output; change in state
	Flow	Functions as flow of material, energy and information
Extensional	Verb-noun pairs	Verb noun pairs; needs a noun, then a verb;

		needs a verb
	Property of the function	Must be quantifiable; must be related to form
	Other	Functions exist on the level of principle solutions; functions are solution neutral description of what the system does

To a certain extent the answers mirrored the distinction of Vermaas (2010) into ‘intentional definitions’, which are typically expressed as “what the product does” (akin to an action description), or “what the product is meant to do” (implying a particular goal); and ‘physical descriptions’, covering transformations and flows. However many subjects responded with a syntactic definition saying how a function should be phrased rather than what a function was. The subjects who used syntactic notions expressed their understanding of a product through the convention they attempted to adhere to. For example, one participant, when thinking about lubrication, could not figure out whether this was matter (something physical), information (concerned with the relationship between parts) or energy, since they were not sure whether the pump was self-lubricated, and therefore whether the lubrication fluid could also transmit energy.

All subjects agreed that the main function of the pump was pumping the oil. Two subjects additionally mentioned that the pump could also be a motor that “*transforms the flow of oil into a rotation*”. Table 2 illustrates the range of phrasing and the level of abstraction for the main function of the product.

Table 2. Different expressions of the main function of the pump

Level of abstraction	Nr. of subjects	Outcomes
Concrete expression	12	Convey fluid/oil (6); Provide pressure/oil pressure (4); Provide oil pressure for the brake system of a lorry (1); Acceleration of fluid, providing pressure (1)

Abstract expression	6	Convert mechanical into hydraulic energy (2); Convert mechanical rotation into hydraulic pressure and flow (2); Convert power (1); Provide a volume flow from A to B (1)
Mixed	1	Providing oil pressure/flow → convert mechanical into hydraulic energy (1)

Many subjects indicated that they were unsure whether to name the main function as “pumping oil” or “pumping fluid”. Some changed oil to fluid and vice versa. Other referred to the oil or medium or liquid in the course of the sessions. Ten subjects used a verb-noun pair when writing down a function. Others subjects even used verb-noun pairs to describe functions verbally. The two most experienced subjects had no problems with expressing functions as verb-noun pairs.

4.6 Different approaches to functional decomposition

Subjects adopted different strategies to analyze the product. The following classification is based on the analysis of the protocols and in some cases a discussion with the subjects. The following strategies have been identified:

- **Top-down (4 subjects):** Subjects analyzed the overall system and proceed to further levels of detail. The focus became more detailed step by step.
- **Important things first (2 subjects):** Subjects focused immediately on what they perceived as the main function of the most relevant subsystem. The criteria for the decision were not explicit. The focus was chosen arbitrarily or based on experience.
- **Issue driven (7 subjects):** First the subjects created an overview and then detailed specific issues, which seemed important to understand or which they found problematic. They tended to write functions down as they went along.
- **Power flow throughout the system (7 subjects):** Subjects followed the power flow from the source of the power to interfaces with other parts of the system. The flow starts where torque and rotational motion come into the system through the

drive shaft. The rotation is then used to move the pistons in order to draw in and dispense the hydraulic oil.

The study revealed a very personal and fluid notation of function and a number of strategies which did not appear to be related to the notion of functions. The subjects were genuinely surprised to find that their way of doing a function analysis was not universal. The experiment did not prove or disprove the hypothesis it started out with, nor did it reveal a predominant way to carry out a C&C analysis, rather it pointed to the need for clearly and repeatedly practise function analysis approaches.

4.7 Subjective understanding of the pump

As soon as the subjects saw the pump several commented that they knew how it worked. As they began analyzing it, they realized that while they might have known in general how pumps worked they did not understand the details of this pump. However when at the end of the experiment the subjects were asked whether they understood the pump now, all responded that they did. However the function trees show that the understanding is partial and in many cases the subjects had made actual mistakes. Several of the subjects also commented through the experiment that they had now understood how the pump worked; however when they were subsequently asked what a particular component or feature did, they realized that they had not fully understood it. While they all claimed that they had understood the pump, their understanding was partial and different judging from the different function trees that they produced. None of the subjects drew a distinction between function and behaviour in discussing the functions of the pump. Even those subjects who had a goal or purpose view of function did not consider behaviour as a separate category. Some of them had particular problems with conceptualizing unwanted behaviour, and in consequence knowing how to handle in functional terms the features of the pump that were targeted at suppressing unwanted behaviour. This showed that the participant notion of function influenced the way they analysed functions. However, the experiment did not show whether a particular notation of function lead to better or more in-depth analyses of functions.

Creating a functional breakdown was not easy or comfortable for many of the subjects, as they realized that they could not find the location where function they had hypothesized would be carried out, or could not see the role a particular feature played. For example, several had difficulties in seeing where the oil comes into the pump and the product subsequently did not make sense to them. Even when they were guided to an answer, their sense of frustration lingered. Even the subjects who had not made mistakes sometimes had difficulties in

- understanding the role of features and components in the overall function;
- phrasing of functions;
- assigning functions to places in the function tree;
- describing aspects of the products, such as sealing or lubrication, which applied to several high level functions or components;
- recovering from mistaken assumptions about how the product worked.

It also became clear that the confusion around the concept of function was detrimental to a consistent application of C&C. Alink (2010) concluded that designers need to be guided through a set of pragmatic questions, such as “what does the component do?”, “what is happening at this working surface pair?”, “where is the second working surface pair to fulfil a function?”, etc.

5 Challenges of using functional models

The interviews and the experiments have revealed that designers use different notions of functions as required by the context in which they are working with specific models like QFD, Pahl&Beitz or C&C models being deployed for a specific purpose. This section explores some of challenges associated with functional modelling regardless of a specific modelling approach. Challenges in functional modelling arise both from the concept of function and from the nature of models.

Both the industrial interviews and the experiments point to the fact that designers in industry do not have a clear concept of function, and mix many issues, such as behaviour, purpose, performance and met requirement under the one term *function*. Building models

without clear concepts is very problematic. Modelling can be problematic for designers and managers in many situations where the mapping between the model and the target of the model is not entirely clear or habitually defined. This is especially the case with modelling design processes (Eckert and Stacey, 2010).

The participants in both the interviews and the experiments were graduate engineers. They had been trained in product development methods during their degrees and will have had a certain exposure to academic methods involving functions. The participants did not comment on why they did not pick up a clear understanding of function during their design education. However, during another interview series a young engineer once commented to the author, how much he regretted not having paid more attention to methodology training at university. At the time he was just interested in the technology and had not gathered experience with projects. Now that he has to manage things, he really would like to know.

5.1 The trouble with models

Designers build many models and interact frequently with models, but they rarely think about what a model is or can give them. They frequently use CAD models, which describe the form of a component with the underlying assumption that a component will be built according to the geometry defined in the model. With the CAD model it is clear to the designers what aspects of the product are or are not included in the model. They describe geometry and have properties associated with this geometry. CAD models can be simulated to reveal the behaviour of the product or component under certain circumstances. However at present the link between the geometry and the intended function cannot easily be represented. Performance models are mathematical and have a very clear range of relationships incorporated in them.

However, assessing how closely a model describes its target (the object or process that it models) is in general far from simple. The relationship between a model and its target is fundamentally analogical, requiring the construction of a mapping between dissimilar

things that have similar combinations of relationships between their parts (see Holyoak and Thagard, 1996). Grier (2005) points out referring to work by Sua'rez (2003), that it is not the model that represents reality, but the scientist using the model by exploiting similarities between the model and reality and making selections about what they include. Teller (2001) puts this as "WE make something into a model by determining to use it to represent". Models both isolate aspects of reality and idealise reality (Mäki, 2011). The philosopher Roman Frigg (2003) explains representations in terms of three relations: denotation, display and designation: 'A model denotes its target system in roughly the same way in which a name denotes its bearer. At the same time it displays certain aspects, that is, it possesses these aspects and a user of the model thematises them. Finally, an aspect of the model designates an aspect of the target if the former stands for the latter and a specification of how exactly the two relate is provided'.

From a practical perspective this relates to challenges designers generally face with models:

Selection: Models are produced from a particular viewpoint for a particular purpose. Without these being explicit, the user of a model does not understand the rationale of the person who built the model. This is clearly an issue with functional models, both around the scope of the model and the notion of function. For example whether unwanted functions (e.g. vibration) are included in a functional model depends on the view of function. In the experiment many subjects were unsure how to handle issues such as lubrication or sealing. Clearly the system needed to be sealed and lubricated. Some ignored these in their functional decompositions, even though they had thought about them during the product analysis; others mentioned lubrication as a function, but did not connect it to other functions, and some added lubrication as a top level function.

Abstraction: Models can be generated at different levels of abstraction, which influence the range of objects they denote. As many design methodologies, such as Pahl and Beitz (1977/2007), request abstract functional models independent of the embodiment, many of the subjects in the experiment aspired to abstract models, without being quite aware what

this meant. For many this expressed itself in the struggle to find the right phrasing. This is linked to the purpose of a model. If a model serves for a particular analysis, as in the case of the screw, this problem might not arise, but often the ambitions behind functional modelling go beyond an individual product to a whole product family, leaving the designers with the challenge of knowing what specific characteristics to include or not to include. Therefore designers don't have a real sense of how "true" or accurate the model is. In the case of the engine the basic functionality has changed very little and the designers know the functions of components and systems and can draw on this knowledge to build a model. They created an abstract model built using their generic experience of engines. The engine company has experts who have a very deep, but also broad understanding of their products (Flanagan et al., 2007). Most products are based on existing products; building a functional model for such an incrementally developed product requires understanding the starting product very well, really knowing the roles of specific features in the product, which as the experiment showed is not easy, but also defining the function of the new parts.

Utility: Designers in industry need to see a merit in both creating and using functional models. In the case of the diesel engine designers, they build functional models because they understand the benefits of QFD and are strongly incentivized by their organization to apply QFD successfully. The tool designers built a partial functional model when they had run into a problem and needed to understand exactly how and where a function was carried out in a product. Designers need an incentive to build functional models, and this needs to be clear to them before they begin to build a model. The benefit of model building lies in:

1. The understanding gained through the process of the model building.
2. The results gained through building the model.
3. The knowledge that is captured in the model.

The designers who build the model must see personal benefit in the model building. While the reuse of the model is of benefit for an organization, it is difficult to encourage designers to do modelling well without this. They might try because they are requested to build the models, but they are more likely to give up when they run into problems.

Expressing models: Many engineering models, such as CAD models, have clear modelling conventions and tools with which to express and interpret the models. This does not generally exist for functional modelling. The engineers we encountered used spreadsheets to write down functional models. This makes it hard for them to modify and maintain the models. Models that are generated in an ad hoc fashion are often only clear to the person who generated them.

5.2 The trouble with functional modelling approaches

Many of the problems designers have with functions, however, do not arise from the notion of function as such, but from the challenges of applying particular functional modelling approaches. The position papers by Vermaas (2013) and Goel (2013) show the plethora of different functional modelling approaches, many of which rarely reach people in industry. However, even if they do, people in industry can find them hard to apply.

Modelling approaches in text books and academic papers are usually illustrated with examples, such as hair dryers, which illustrate different elements of the models well, but are far smaller in scale than many of the products that the designers are working on. A diesel engine or an entire car are far more complex. Having a complex product requires way of expressing a big model or focusing on particular aspects, which requires drawing clear system boundaries around aspects of the product or producing high level models that hide detail in a principled manner. These decisions themselves can be hard for designers.

Some modelling approaches require a particular level of abstraction in their model, for example instructing designers to express functions independently of the embodiment of the product. The methods are designed to force designers to break free from existing preconceptions of the product to enable them to come up with innovative solutions. However, this is still hard for designers who are used to thinking about specific products with specific functional decompositions. As the example of the diesel engine company

shows this often goes deep into the organizational structure of the organization. Failing to break free from an existing product structure given the designers the impression they fail in carrying out the modelling.

Modelling approaches are often better suited to one class of problems than another, for example for mechanical systems rather than for mechatronic systems, or for new product development as opposed to incremental design, making it difficult for designers to apply them to their particular problem and situation. Many of the functional modelling approaches are embedded into wider systematic design approaches and the designer feel that unless they follow every step of the whole methodology, their individual models are worthless. However, they often don't have the time to follow a whole modelling approach. While the prescription is intended to help them it can also be very off-putting to designers. Designers can also be put off by the terminology used in the different modelling approaches. Not only might the concept of function be explained in ways that they are not familiar with, but also the terminology that they use to explain functions can be difficult.

5.3 Summary: What the designers want

Designers want easy to follow methods that they can understand without a huge learning effort. They want to see a fairly immediate benefit to applying the methods to their own work. For functional modelling it is important that designers enjoy the modelling and get something out for themselves in terms of their own understanding. If they need to learn a modelling approach, because it is not intuitive, they need training materials which are clear and intuitive. The explanations need to help them to deal with exceptions (e.g. lubrication) and difficult situations (e.g. mechanical to control interfaces). They need a clear way to write their models down and understand the models that they have generated. A model that is difficult to read in the end is also often difficult to build. Designers don't want to use modelling approaches that make them feel guilty or inadequate. In functional modelling this is particularly an issue around functional models that are closely linked to an existing product structure.

The lack to consistent application of functions modelling illustrate that none of the current functional modelling approaches have become a prevailing paradigm for functional modelling and meet these criteria of easy to learn and easy to apply. While some modelling approaches are easier to learn than others, modelling inherently requires training and effort. Engineers need to accept that they will have to invest this effort into learning a functional modelling approach well and practise applying it. This requires training students in functional modelling at university. It also requires persistence with functional modelling in industry, for which engineers need to recognise the benefit of building the models and negotiating their meaning with each other. This involves investing time in particular in early stages of the design processes, which is difficult to justify for individuals unless functional modelling is incentivised by the organisation and anchored in the company processes.

6 Conclusions

The case studies presented in this paper illustrate that function is for most engineers a fluid concept, where the same word has very different meanings depending on the context at the intersection of company jargon, academic methods and intuitive everyday meaning.

Function is a problematic concept for practising designers. They have to describe that which is not form about a product and don't have easy and intuitive ways of doing so. Rather than being able to adopt and apply a coherent and explicit definition of function, designers fall back on their everyday language understanding of function. Reading a definition of function at the beginning of a paper or a training session is not enough to change people's notions, they need systematic training to adopt a particular view, which then becomes hard to unlearn. Adopting a specific functional modelling approach is a considerable commitment and effort and needs organisational support and persistence. Designers in industry are most likely to use functional modelling if it is part of established approaches, like QFD or FMEA, which are applied across their industry sector and are pushed through the formal processes in their organisations. While both

methods advocate an integrated design approach, they are in practise mainly used to generate requirements and therefore structure processes, rather than for design synthesis tasks. At present functional modelling largely stands outside of the tools and methods that designers use to adapt, generate or analyse new design. Functional modelling is not well integrated with CAD system or design analysis software, nor are there obvious procedures for closing this gap.

Functional modelling has the potential to act as a means to integrate different groups in an organisation who usually work in different object world with their own representations and modes of thinking. For example system engineers who integrate mechanical and electrical design with software design use functional breakdowns of products to understand the need for integration and identify interfaces. Testing engineers plan and carry our tests of products against product requirements, but also need to understand under which circumstances a component for system needs to carry out a particular function. Engineers who plan and design product platforms need to be aware of functions shared across multiple products. However, none of these groups can usually refer to a common model.

There is little evidence that the rich academic debate around function is recognised in industry. Therefore designers miss out on much of the benefit they could gain from thinking in functional terms and building functional models. If they create functional models, they need tools and training to do so, as the example of the FAD models shows. Rather than rigid prescriptions, they need pragmatic ways of handling concepts which show them a benefit. The rich meanings of the term *function* are complementary and designers drift through different meanings from purpose to flow or behaviour. In teaching them about functions it might be an exposure to that richness they would benefit from most both in terms of the views on function and the places in design processes functional thinking would be beneficial.

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