ENGINEERING DESIGN IN A DIFFERENT WAY: COGNITIVE PERSPECTIVE ON THE CONTACT & CHANNEL MODEL APPROACH

A new approach for the engineering thinking process

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Abstract.

Engineering design often involves the integration of new design ideas into existing products, requiring designers to think simultaneously about abstract properties and functions as well as concrete solution constraints. Often designers struggle to reason with functional descriptions, while not fixating on existing solutions. This paper introduces the Contact & Channel Model (C&CM) approach, which combines abstract functional models of technical systems with the concrete geometric descriptions that many designers are familiar with. By locating functions at working surface pairs, they receive a concrete location in mental models. The C&CM approach can be applied to analyze existing product descriptions and synthesize creative new solutions for parts of the system or for entire new systems. At the moment the approach is being developed into an complete modeling and problem solving approach. C&CM has been used for several years in undergraduate engineering teaching at the University of Karlsruhe (TH) and is increasingly being introduced into industry by its use in research and development projects, by its students and its alumni.

1 Introduction

Engineering design deals with the eternal tension between keeping well working solutions and coming up with new ideas. The majority of engineering designs are modifications from existing solutions. This modification process can be very creative and involve the unexpected generation of novel ideas, for example when trying to contain change within one system. However, it can also be a very tedious series of well-understood steps. Designers often struggle between these two ways of working. How can they make themselves come up with new ideas when they have to, but also do routine tasks efficiently? The standard answer of engineering design research is to come up with focused methods for particular aspects of problem solving: methods for idea generation, such as TRIZ or brainstorming, methods for solution evaluation, such as FMEA, methods for planning processes, methods for selecting resources, etc… (see Ehrlenspiel 2003 and Pahl and Beitz 1995 for numerous examples). Some of these methods are step-by-step guides on how to carry out particular tasks, others such as DSM (see Browning for a review, 2002), provide both a tool kit and a method of visualizing design information. For example, a DSM is a matrix notation of the linkage between different components or different process steps, which can be reordered to find the best order to carry out and to define interfaces between components.

What many designers need is a way to think about the problem that they have in hand, which is congenial enough, that they learn it easily, like DSM, but that gives them new insights into their problem. When designers need to come up with new ideas, they can get fixated on existing ideas and find it difficult to think about the problem in new ways or to go back to basic principles in order to solve it. However, when they are required to solve standard problems, they don't want to have to do something different to what has worked successfully for them in the past. Designers need to be able to use their strengths while overcoming their weakness. While it is very difficult to change the fundamental ways in which people think, it is possible to teach them compensation strategies for some of the weaknesses of their thinking process. Unless it is possible to obtain massive corporate buy-in, a new way of designing will only be taken up if it is intuitive and congenial for practicing designers as well as easy to teach to students. Additionally, it must also fit into the current working methods of organizations and individuals, because thinking needs to evolve rather then being forced to change radically.

This paper presents a new approach to complement existing approaches to design in mechanical engineering, which is currently being developed at the University of Karlsruhe (TH), which challenges designers to think about engineering problems in a slightly different way and with the expressed aim to break fixation and allow designers to return to basic principles when required. Engineering products are described in terms of Working Surface Pairs and Channel and Support Structures (Contact & Channel Model - C&CM). C&CM models can be applied on different levels of detail so that the same type of mental model can be applied at different levels of hierarchy. Every function of the product resides at a particular Working Surface Pair, because a function can't be applied other than through these interfaces. This enables designers to think about abstract functions in a concrete way, because they can picture them at a working surface pair. Figure 1 shows a crane and its corresponding representation in C&CM with the abstraction to the basic elements "Working Surfaces (WS)", "Working Surface Pairs" (WSP), "Limiting Structures" (LS) and "Channel and Support Structures" (CSS). These elements will be described in detail below.

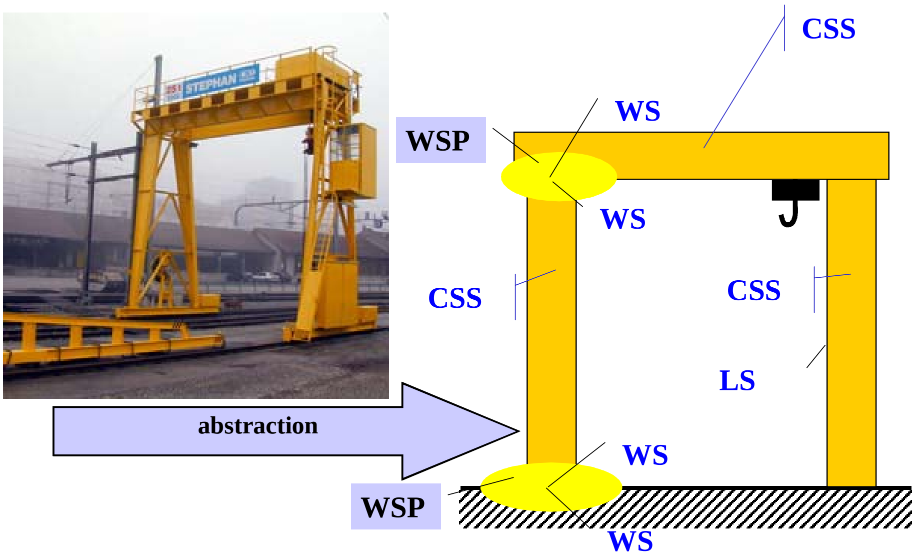

Figure 1 A Crane abstracted to its Working Surface Pairs and Channel and Support Structures

This method has been developed over the last years motivated by the difficulties students and engineers have with analyzing a concrete product in abstract terms and linking abstract concepts, such as a functional model, to a part of the system. The way of thinking of successful engineers was observed over years of industrial practice and in many university projects. These engineers seem to be able to generate specific ad hoc descriptions of part of the problem on the right level of detail to reason about a specific problem highly effectively, because they know the aspects of design that are relevant to the given problem. It was abstracted and formalized in C&CM, which generates descriptions for problems as and when required, by assigning a working surface pair to a function at the appropriate level of detail. For example, in order to assess wind resistance the entire surface of the crane is one working surface interacting with the working surface of the wind in the function wind resistance. The description can be discarded as soon as the problem is solved, i.e. when the wind resistance has been calculated. However, the same surfaces of the crane can form part of a different working surface pair. For example the lateral surfaces of the pillars could form a Working Surface pair with another object in case of an accident or parts of the surface could form a Working Surface Pair with rain and corrosion.

As the method is developed and applied to problems of higher complexity, it is becoming increasingly evident that it is also possible to describe entire systems in a C&CM way. A C&CM description then comprises a model of the product on different levels of detail, its use and its interaction with other objects or the environment. C&CM is currently in the transition from an informal approach of designing, that is intuitively correct and practically successful, to a complete theory of technical systems with axioms, operators and rules. In the time honored German teaching tradition of Humboldt, new research developments are instantly incorporated into undergraduate teaching. This allows theoretical developments to be tested for their intuitiveness and utility. As engineers the developers of C&CM are fundamentally more interested in the quality of the solutions that are generated using C&CM and the endorsement it is receiving in industry rather then the theoretical soundness of the theory itself.

In this paper we argue, how this intuitive understanding of engineering thinking is supported by the literature on design cognition (section 2) and how the power of this approach comes from its ability to make engineers think about their problems in a slightly different way without alienating them. The basic elements of C&CM will be explained in section 3 and the operations that can be performed with them in section 4. Section 5 discusses the application of C&CM in teaching and industry. In the conclusions the effect of C&CM is reviewed and conclusions of its effect on human cognition are drawn.

2 Design Cognition

It is not surprising that designers struggle to innovate. In this section we will argue that way designers typically think and the experiences that they have made, biases them towards thinking along the line of existing solutions. Innovation is embedded in existing products and production methods with multiple constraints; with a complex product there is a great deal to remember. Designers typically either work on specific components or they carry out a certain function. For example in helicopter design a specialist team works on the undercarriage and that is all they concentrate on whilst dedicated people work on stress analysis and load calculations. These different specialists work in what Bucciarelli (1994) terms different *object worlds*. Each group has its own way of looking at design problems: shared background knowledge, concepts and terminology, problem solving procedures, and skills for creating and making sense of visual representations of various kinds of design information. However there are general mental processes, which are shared by designers regardless of their object world.

2.1 DESIGN COGNITION

Designers interpret visual and verbal information using the concepts comprising their object world to develop mental representations of design ideas. They may have multiple representations of the same design. Some of designers' mental representations are mental models that they can use to envision how the artefact will behave (see Johnson-Laird 1983). While some mental models are models of how thing works, others map inputs to external behaviour – a user's-eye view. Designers with similar expertise will have very similar mental models, but it is easy for both designers themselves and outsiders to overestimate the similarity of their thinking. For instance we have met diesel engine designers with superficially similar backgrounds who employ radically different mental representations.

Many designers think visually and have very vivid mental imagery. Anecdotal evidence indicates that mechanical engineers are usually extremely visual and think about problems by mentally manipulating the geometry in their heads. Several mechanical engineers we have interviewed describe this as akin to a "CATIA system in their head". More analytical engineers such as stress engineers often think in terms of the correlation of parameters required to achieve a target performance. Some of them have commented to us that while they can construct mental imagery at a push, they do not naturally think in images.

Designers' mental representations of designs are limited: they may only include part of the design, and there is no guarantee that these are consistent or even coherent; people may only recognise the limitations of their mental representations when encounter questions they cannot answer. Research on mental imagery (see Kosslyn 1980 & 1994; 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 is partly because the capacity of working memory is limited; Miller (1956) famously assessed its capacity as seven plus or minus two chunks. The richness of mental representations depends on the complexity of the chunks. The reliability of memory recall depends largely on the richness of the relationships between the elements to be remembered; this is increased by creating mental images of to-be-remembered information. Chunk size has been found to influence the accuracy of memory recall of, for instance, electronic circuits (Egan and Schwartz 1979) and architectural drawings (Akin 1978).

Many designers however think about new designs with reference to existing designs, using mental representations including physical embodiments as well as functions and performance factors (see Schön 1988; Oxman 1990; Eckert and Stacey 2001, for discussions of the roles of types of design elements and individual examples in design thinking). This provides them with very large chunks and enables them to handle large and complex information, because details can be constructed from the reference point as the focus of attention moves to them.

However, this locks them into tacit assumptions about the structure of the new design that are very difficult to escape – a phenomenon known as *fixation* (see in the psychology of problem solving: people copy recently-encountered previous examples even when they are clearly inappropriate). For instance, one out of several studies on fixation in design (see Purcell and Gero,1996, Jansson and Smith, 1991) showed design students a mug with a mouthpiece and told them to create a non-spill mug without a mouthpiece: despite this instruction, the majority of designs incorporated a mouthpiece. In many fields, experts will possess memories of a greater stock of relevant designs and will be better able to find an appropriate model, but will find it harder to escape closer matches to the present situation and stronger situation-action associations. Thinking is channelled both by conscious awareness of situations and goals, and by associations in memory: what the psychologists call mental set. People with expert knowledge have both richer and stronger associations between elements of their factual knowledge, and more specialised mental procedures. Thus, they can focus recall from memory and mental actions more narrowly. This can be an advantage, but mental actions can embody tacit constraints inherited from previous similar problem situations that are no longer relevant, leading to incorrect or unsuccessful problem solving (Whiley, 1998). It can lead designers to produce excessively conservative designs.

Breaking fixation requires developing mental representations of what the design should do that abstract away from physical embodiments. Getting designers to do this is a major purpose of many prescriptive design methods. Axiomatic design (Suh 1990) instructs engineering designers to begin with a functional breakdown and develop the concepts on a high level of abstraction, then break the function down further and then develop the form from it until the design is fully defined. Many engineers find abstract functional thinking very difficult; students who have learnt the axiomatic design method vary enormously in how easy they find it to use. One reason why thinking in terms of abstract functional relationships is difficult is because functional properties are associated in memory with physical embodiments, which are hard to consciously ignore, and because the relationships between the components of functionally-imagined systems are sparse and more-or-less arbitrary, so they do not serve as effective cues for remembering each other. By contrast, actual machines and descriptions of physical structure have rich, non-arbitrary, mutually reinforcing spatial relationships that are relatively easy to visualise and remember, and that are effective retrieval cues for spatial information in memory. Causal relationships such as noise transmission are not salient parts of primarily geometric representations.

How designers formulate their problems profoundly influences how and what they design [for instance Glock (2003), Valkenburg (2000)]. The aspects of design problems that designers actively consider when they make major preliminary decisions and invent core ideas exert a powerful influence on the design, notably the characteristics of the site in architecture (Darke, 1979). Research on designer behaviour in a variety of industries has found that expert designers put a lot of effort, typically more than novices, into elaborating their understanding of the problems they are trying to solve – the requirements and constraints the design should meet. Of course, problem formulations are not static; they evolve as designers reflect about their designing activities [Schön, (1983), Glock,2003)] and discuss them with others [Valkenburg (2000), Stumpf. and McDonnell (2002)]. Problem framing is a skill that is developed with practice, but sometimes reframing the problem to see the design challenge differently is the key to success.

3 Describing a Product in the Contact & Channel Model

The Contact & Channel Model (C&CM) is a way of thinking about engineering products and well as a model of products. It has been developed to address some of the challenged in engineering thinking outlined above:

- Facilitating the thinking process of successful engineers in a theoretical model to support other designers;
- Breaking fixation;
- Thinking on different levels of abstraction;
- Integrating functional thinking and visual thinking in concrete solutions.

C&CM is intended to be used in two ways. One way is analyze and enhance an existing system, for example to develop a new transmission system for a car. In this case most of the elements are known and the starting point is given in an existing description, for example a bill of materials or a CAD model. C&CM then picks and groups elements of the existing description in a new way, exploring in the inherent ambiguity of how elements of a description are grouped (see Stiny, 2000). These C&CM descriptions are generated for specific purposes and are personal and fleeting. Therefore the coherence between different C&CM description is not an issue. C&CM is used as a way to generate new ideas, by enabling designers to reduce problems to basic principles and think about them in an abstract form that is well anchored in other representations without losing reference to the geometrical representation of the system. Analyzing an existing system in C&CM terms can draw designers' attention to functions and their realisation, which is difficult to see in other models, that don't combine functional and geometric descriptions.

The second way - currently under development – is C&CM as a complete modeling approach, which enables designer to describe the functionality and the geometry of the system in C&CM concepts and provides them with a set of methods, tools and techniques to developed new designs effectively and efficiently.

This section provides a very brief overview of the general approach, but excludes rules to handle special cases. For example an extension to the approach to model the interaction of a product with fields such as magnetic fields or gravity has been development, but will be excluded from this paper.

3.1 THE BASIC ELEMENTS

Conventionally engineering products are modeled by components with defined geometry, which are grouped into sub-system and systems (see Figure 2 on the left). C&CM takes a different cut on the geometry, by using working surface pairs, which carry out functions and channel and support structures that sit between the working surface pairs and link them. This idea was originally purposed by (Albers and Matthiesen 2002). With the following definitions any technical system undertaking any function can be described:

Working Surface Pairs are all pair-wise interfaces between a component and its environment. This can be solid surfaces of bodies or boundaries with surfaces of liquids, gases or fields which are in permanent or occasional contact with the Working Surface. They take part in the exchange of energy, material and information within the technical system.

Channel and Support Structures are physical components or volumes of liquids, gases or spaces containing fields, which connect only two Working Surface Pairs.

Limiting Surfaces are surfaces that are not involved in fulfilling the regarded function of a system. But they are potential working surfaces. E.g. the side of the crane pillar in Figure 2 only needs to be regarded as a working surface, when wind is considered or when it fulfils any other function that the designer has to think about.

3.2 DESCRIBING A PRODUCT IN C&CM: A SIMPLE EXAMPLE

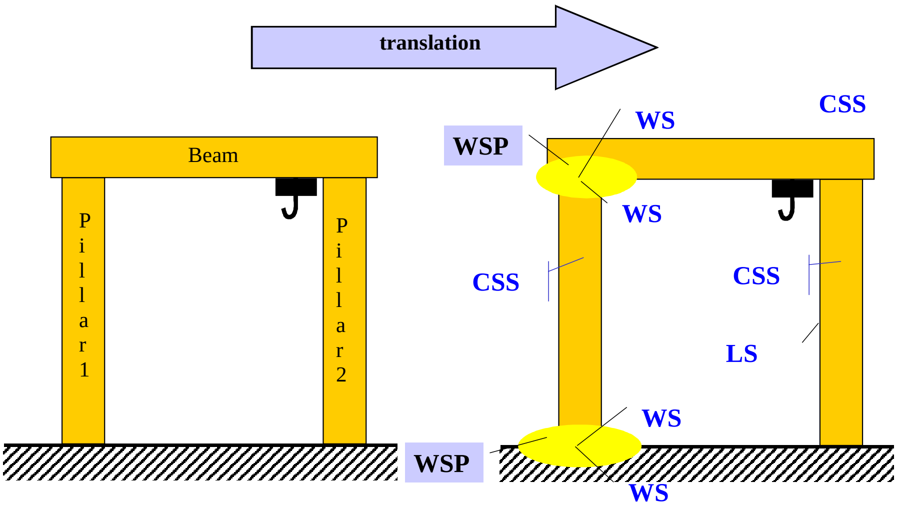

Figure 2 Translation from a component representation to a C&CM approach

Figure 2 shows the Working Surface Pairs (WSP) and Channel and Support Structures (CSS) of the abstracted crane (see figure 1), when it only has to carry its own weight. For example, the left pillar 1 has two WSP with its environment: At the top WSP, the weight force of the beam is transmitted into the pillar. At the lower WSP, this force is transmitted into the foundation. The CSS between these WSPs transmits this force from the upper WSP to the lower one and does not store it. This pillar is a minimal technical subsystem as it has the minimal number of WSPs and CSSs that is required to fulfil a technical function. This function can be described as *"Define the distance between the cross beam and the foundation and transmit appearing forces"*. Removing one of the both WSP or the CSS the pillar could not fulfil this function any more.

Regarding the cross beam in Figure 2 there are the Working Surface Pairs where the forces are transmitted into the pillars but there are no Working Surface Pairs where these forces are transmitted into the beam itself. As long as there is no Working Surface Pair where any forces are transmitted into the beam it will not fulfil any technical function. (There is a WSP between the field of gravity and the cross beam that induces a large amount of force into the beam. But carrying its own weight is not the main function of a crane so this is not shown in figure 2).

Giving the crane a function means using an additional WSP at the hook of the crane where a force can be transmitted into the subsystem "beam with hook" and from there over the CSS of the beam into the WSPs that infaces with the pillars. If needed, the beam can be divided into further WSPs and CSSs e.g. those WSPs where the hook is linked with the rope, where the rope is connected with a barrel and so on. But if these details are not of interest for the moment they can be regarded as a black box with each a WSP at the interface to the neighbour-subsystems.

The lateral surfaces of the pillars do not fulfill a technical function. They do only limit the CSS of the pillar so they are regarded as "limiting surfaces" (LS) for the present case. But if the designer regards the same system from another perspective, the same surface of the pillar can also be a Working Surface. For example, if the crane is used outside, the designer will have to calculate the wind load for the crane. In this case the lateral surfaces of the crane will fulfill a harmful additional function "*transmit the wind load into the pillar*" so it is a Working Surface that generates a WSP with the Working Surface of the wind. An additional CSS will occur in the pillar that links the WSP "wind – pillar" with the WSP "pillar – foundation". It is important to keep in mind that the original CSS that connects the WSPs "beam-pillar" with the WSP "pillar – foundation" still exists in this case. Both CSS share the same material (and both put load on it!).

For further functions such as corrosion or optical design more and more WSPs will be discovered. Every WSP will be linked with another WSP by a CSS, otherwise it could not fulfill its function.

3.3 THE THEORICAL GROUNDING OF C&CM

In mechanical engineering all psychical systems have to follow Newton's third axiom: "action = reaction". If the system boundary is sufficiently extended during the analysis of a technical system a feedback loop of interactions or "causes and effects" will develop. A simple example is the analysis of power transmission in technical parts. In the case of stationary systems this loop is generally closed, in dynamic systems of power transmission the loop can be also closed very easily with through energy storage, although this might be delayed. The C&CM has three fundamental hypotheses about technical systems, which so far have not been falsified:

1. **Non-Singularity of elements** Every basic element of a technical system fulfils its function by interacting with at least one further basic element. The actual function – and thus the desired effect – is only possible by the contact of one surface with another surface. In the example of the crane, this is reflected by the fact that the function "transmits force from the beam to the pillar" is only possible as both parts are permanently in contact.
2. **Situatedness of function**: Every function is exclusively determined by the properties and the interactions of the two Working Surface Pairs and one Channel and Support Structure connecting them, which can be treated as a black box, containing other working surface pairs and channel and support structures
3. **Unlimited Model**: Every system that fulfils functions contains of the basic elements Working Surface Pair and Channel and Support Structure, which can occur in any number, order and form.

3.4 C&CM DESCRIPTIONS AND NOTATION

C&CM allows modelling of both the component and the environment in the same way. So the parts of environment can be modelled as channel and support structures, which interact on one working surface, as illustrated in the example of wind resistance. If, within a technical part, neither energy, material nor information is conducted, a Channel and Support Structure does not exist. The Channel and Support Structure only occurs together with Working Surface Pairs.

This is not a unique description for each product, but depends on the purpose of the description. C&CM description takes a particular viewpoint on a product while excluding factors that are not of interest. This is a very rich description of a product that is generated to solve a particular problem that has been previously identified. Through the grouping and regrouping of elements into working surface pairs and Channel and Support Structures a focused description can be generated on different levels of hierarchy. As illustrated in the example of the crane, the entire surface of the crane is seen as one working surface as far as wind resistance is concerned, but broken down into more detail for other functions, such as carry load. As we will argue later, the description treats lower levels of hierarchies as “black boxes” that are subsumed in the higher level description.

C&CM is an approach to designing as well as a mind set for looking at design. To avoid restricting a designer’s individual way of thinking, it does not require a prescribed notation, but can be used in conjunction with other product notations. However, a set of verbal or visual annotations is under development (Albers et al., 2004) for recurring features of C&CM. This notation is based on graphic symbols defined in (DIN ISO 1101). This is an international industry standard for the entering of form and positional tolerances in technical drawings. Symbols for Working Surface Pairs and Channel and Support Structures as well as common properties such as the transmission of the system quantities, material, energy and information and some more detailed properties such as the positive or frictional force transmission are being developed. These notations make it easier to express properties of sketches and drawings, which enables designers to create properties that could not previously be expressed visible and therefore perceivable. A C&CM will support designers to express functions on sketches and drawing through the symbols of their associated working surface pairs. A simple example for such symbols in an abstracted sketch of a link between a shaft and its guide is shown in Figure 3.

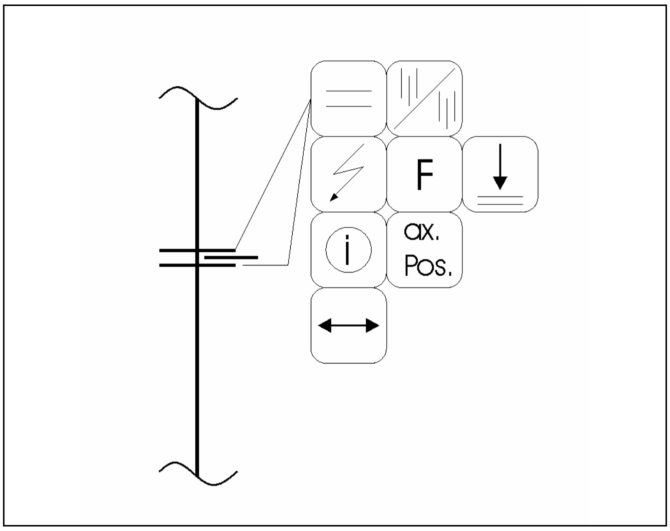

Figure 3: Example for the notation of WFP-descriptions in sketches

3.5 HIERARCHICAL DESCRIPTION OF SYSTEMS - FRACTAL STRUCTURE

Herb Simon point out in Sciences of the Artificial (Simon, 1969) that a complex engineering system is an almost decomposable system, which can be thought of as hierarchical, while never quite neatly decomposing broken down into sub-systems. Complex systems form lattice structures rather than trees, i.e. lower level sub-systems need to belong to more than one higher level system. Engineers reason effortlessly on many different level of hierarchy from minute details of components to sub-systems overarching the entire design, however it can be very difficult to describe a system coherently on the same level of detail across the entire system.

The C&CM approach works on all levels of detail applying the same basic modeling elements. In the example of the crane, the function of " load of the pillar" can be described as a two WSP and one CSS, but it comprises the beam itself, the hook, the rope, the barrel, and all elements of its drive and fastening. If required this "black box" can be looked at in more detail. The definition of the WSP and CSS is tailored exactly the function it carries out, so that for this purpose the details of the sub-system comprised in it can be ignored.

4 Designing a Product in the Contact & Channel Model

The pervious section introduced the basic concepts of C&CM, while this section introduces some the basic operations and gives a flavor how more specific rules can be support a designer. At the end the relationship to other design methods is discussed.

4.1 BASIC OPERTIONS IN C&CM

To support designers using C&CM, some rules and heuristics have been generated, which give heuristics on different levels about how to solve technical problems.

To generate new ideas rather, for four operations can be defined, which underlie more specific rules:

1. Add Working Surface Pairs and Channel and Support Structures together
2. Remove Working Surface Pairs and Channel and Support Structures together
3. Change the properties of Working Surface Pairs
4. Change the properties of Channel and Support Structures

For example if the crane is used outdoors the function *avoid corrosion* can be added to the system. There are several possibilities for fulfilling this function with different basic operations:

- An additional Working Surface Pair and Channel and Support Structure can be added in form of paint. The paint will form one Working Surface Pair with the pillars and the beam and another Working Surface Pair with the atmosphere. These newly created Working Surface Pairs both have the property not to react with each other in a chemical way so the corrosion can be avoided.

- Another possibility is to change the property of the Working Surface Pair "crane-atmosphere" itself so that there will be no corrosion, e.g. stainless steel could be used.

There are many more possibilities to avoid corrosion. They all fit into the four basic operators.

To make it easier for the designer, these possibilities have to be structured and the way they are applied must be described. A first step is to formulate concrete rules that help the designer to solve special problems.

The abstraction in terms of C&CM helps designers to avoid fixation, because it forces them to think through the problem in a logical way. In the example, the designers would have to ask themselves: how could I add a WSP and CCS (e.g. by adding paint) or how could I change the property of the WSS (e.g. stainless steal). This forces them to step away from what they know about crane (they are not make of stainless steal), yet they can think in concrete term. Maybe in the particular application stainless steal is the only answer.

4.2 SPECIFIC RULES

In each design situation many operations like design principles (Pahl and Beitz 1995) could be applied. However, a number of solution heuristics can be applied for classes of problems. Figure 4 shows an example rule, where two fundamentally different solutions are given together with some examples of how this could be carried out.

Problem	Create a Detachable Connection	
Solutions	Frictional Working Surface Pair is to be added to the technical system	"elasticity“ of a Channel and Support Structure must be increased so that that form closure within the technical system can be deleted
Example	clamping or screwed connections	snap-on caps are a good example

Figure 4 Example of a Rule

The concrete rules are provided on several levels ensuring the availability of approaches for solving completely new problems as well as offering concrete solutions for problems, which have occurred before and could be solved successfully. The next step will be to classify and structure the rules and develop an easy notation.

These rules are akin to patterns, a term that refers to an abstractly-formulated solution to a recurring problem, together with a description of the type of problem it fits and the consequences of using it. The idea was introduced into architecture by Christopher Alexander (Alexander et al., 1977) and widely adopted in software engineering (notably, Gamma et al., 1995). This notion has long been implicit in much engineering practice.

4.3 USING C&CM IN CONJUNCTION WITH OTHER METHODS

C&CM is a way of thinking that helps the designer to deal with the analysis and the synthesis of technical systems both in one single tool. Most existing methods and representations of technical systems are only applicable to either the analysis or the synthesis process. However, since designing requires continuous switching between synthesis and analysis of the design, a single representation is very helpful.

Theories like those of Roth (1994), Koller (1976) and Hubka (1984) provide powerful approaches for the modelling of technical systems, based on functional descriptions of products. C&CM adds deeper insights by linking function not to single parts or single surfaces but to Working Surface Pairs. This step provides a better understanding for the location of functions in a product.

In C&CM it is possible to isolate an individual problem from the technical system at any time of the design process, solve it and integrate the solution into the entire system to check the effects of the changes on the entire system either with C&CM or intuitively in the case of very simple systems.

The application of C&CM is complementary to other methods. C&CM supports many classical design methods and have generated high-grade solutions when combined with other methods such as brainstorming, FMEA or TOTE. Almost all classical design principles and guidelines (Pahl and Beitz, 1995; Beitz et al., 1994) can be integrated into this working method by an analysis with the aid of C&CM.

5 Evaluation and Application

C&CM has been developed as an approach to thinking about design as a response to perceived needs of students and industry. While the approach is still being developed, it is already used in teaching and in industry.

5.1 FUTURE WORK ON THEORETICAL STATE OF C&CM

Current and future efforts on C&CM are aiming at sustaining the basic definitions of the model and extending its applicability to complex problems in industry and academia.

C&CM will be developed further from a representation of technical systems to a framework for modeling systems and solving problems. Further rules like those of section 4.2 are added and a classification of these rules will be developed. The link to existing methods like FMEA or SPALTEN (Albers et al., 2003d) will be developed further through the integration of these methods into C&CM. Further methods for analysis and synthesis of technical systems as well as for problem solving basing on C&CM are under development.

5.2 APPLICATION OF CCM

At the Institute of Product Development of the University of Karlsruhe (TH) C&CM is successfully applied in research and industry projects. It is taught throughout several successive undergraduate courses as a way of interacting with technical systems.

As other German universities, the Institute of Product Development carries out many projects with industry. In these projects the elementary model C&CM has enabled researchers to find high-quality solutions in a very simple way. One example is a successful solution for the improvement of the friction contact between the pin and the disc of a CVT transmission in a current Center of excellence in research (Albers et al., 2003a). The approach has lead to several actual and pending patents.

The C&CM model has been applied in lectures in the last 5 years through the entire curriculum of the Karlsruhe Education Model for Industrial Product Development, which applies new findings from research immediately in teaching (Albers et al., 2000). As early as in the basic lectures “Mechanical Design I-III“ – a compulsory course for every student in their first and second year- C&CM is presented as a fundamental approach to designing. The very first lectures of Mechanical Design explain

C&CM as a basic way of regarding every technical system. Similarities and differences between systems and machine parts are explained using C&CM. In the following lectures of the main diploma “Methods of Product Development“ and “Integrated Product Development“ all technical problems are approached by means of this elementary model.

Karlsruhe students put design into practice as they were taught by C&CM. The first students who have been taught C&CM have now finished their studies and take this new way of thinking into industry. Industry has given very positive feedback. As the students are in positions to hire graduates, they often look for others with C&CM skills, giving the approach a strong foothold in companies. Students working on projects or diploma theses or graduates they employed in their companies have all made only positive impressions.

6 Conclusion

C&CM is not only a method to solve specific problems; it is also a way to consider technical systems and to reason with functional descriptions.

With a small number of simple concepts, all aspects of complex products can be described. C&CM is based on a simple hypothesis. Any design can be represented as Working Surface Pairs and Channel and Support Structures. Modifications can be made through basic operations and a set of rules for specific recurring patterns. Within the same theoretical concepts, it also offers abstract as well as very detailed instructions which support the designers in solving problems they are not able to solve intuitively or for which they cannot find the obvious solution.

C&CM is a flexible, helpful instrument for the analysis as well as for the synthesis of technical systems, which supports the designer’s natural mental process and provides assistance in any step, if required. Many examples of successful product development and problem solving processes with students in projects with industry confirm the strong utility of C&CM.

6.1 INDICATION FROM STUDENT PERFORMANCE

An examination of changes in students’ thinking with and without the application of C&CM in course projects shows that C&CM helps them to understand technical systems better and to carry cognition forward from a known system to a unknown. Since 1999 an annual model test is carried out on students’ ability to analyse. This test has demonstrated that this ability has considerably increased the more C&CM has been used in teaching. Unlike those who had been taught with the “classical“ machine parts method, twice as many of the students who had encountered the elementary model C&CM as the basis of a mental process were able to analyse the function of an unfamiliar machine system with the aid of an engineering drawing. The number of students who were able to find the most functional relevant parts of the unknown system has increased even more during the years. [Albers et al 2003c]

6.2 MEETING DESIGNERS' COGNITIVE NEEDS

As C&CM enables designers to use the same concepts to express designs on different levels of details, it enables them to maintain an overview of a product. The chunk sizes are variable and can be represented visually, so that designers can keep context in mind, when they are switching to abstract analyses of problems. Abstract functions are linked to specific locations in products, which have visual representations, designers can think visually about them. It enables them to switch quickly between abstraction and embodiment. The problem solving rules challenge designers to think through any given problem in a very systematic way. This enables them to break out of fixation by forcing them to abstract from the concrete problem in hand to the solution principle.

C&CM enables and also forces designers to switch frequently between abstraction and detail and between function and form. This is not supported by other methods to the same extent. The close link of form and function makes systems are transparent and allows designers to get closer to the real problems of engineering, which lie in the relationships between parts of a complex system.

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