How C&CM can help the Designer to find the Right Principles

A. Albers[1], N. Burkardt[1], M. Ohmer[1]
[1]Institute of Product Development IPEK, University of Karlsruhe (TH)
albers@ipek.uni-karlsruhe.de

Abstract
The process of developing a technical product is very complex and includes many information not only about the shape and function of a technical system, but also about its manufacturing process, its utilisation and even its recycling and revitalisation on different levels of abstraction. The Elementary Design Model C&CM (Contact & Channel Model) allows to combine information on these different levels. For an efficient storage of experiences made using this way of thinking, rules are developed. An efficient strategy for access makes them a valuable help for designers in their everyday work.

Keywords:
Synthesis, Element Model, Theory

1 INTRODUCTION

Product Development is a process which includes the translation of many different requirements and boundary conditions into a real product including the planning of its manufacturing, utilisation and even recycling and revitalisation.

As these requirements and boundary conditions are formulated from different views on the product and on very different levels of abstraction, the process of including all of them into a technical product it is not trivial.

For this reason the Elementary Design Model C&CM – Contact & Channel Model is developed at the Institute of Product Development (IPEK) of the University of Karlsruhe (TH). The basic Elements of this Model – the Working Surface Pairs and the Channel and Support Structures – combine information about the shape, the function and the processes of a technical system. So they can be used as a link for translating these described requirements and boundary conditions into a real product.

Basing on C&CM, abstract and concrete instructions are developed as a guideline for the designer to implement as much knowledge as possible into the Process of Product Development.

Chapter 2 'The Process of Product Development, -realisation and -Utilisation' of this paper describes the basics of actual Product Development Processes. In Chapter 3 'The Elementary Design Model C&CM – Contact & Channel Model' the basics of C&CM are explained. The implementation of C&CM into the Process of Product Development is described in chapter 4 'C&CM supporting different phases of the PDP on different levels of abstraction'.

The final chapter 5 'Principles and Rules' shows a possibility and examples an efficient storage pf procedural knowledge about product development on the abstracted level of C&CM.

2 THE PROCESS OF PRODUCT DEVELOPMENT, -REALISATION AND -UTILISATION

The development of a technical product is a complex process which involves not only the producer but also the needs of the customer and the competitors. Due to the strong need of reducing the time to market, the Product Development Process (PDP) is often no longer a series of isolated steps. The more complex a technical system is and the more people are working on its development, the steps begin to overlap: e.g. the function of the whole system is to be validated even before the last details are designed. Maybe some important parts are even yet manufactured in this phase of the PDP. A typical example for this way of proceeding is the development of automobiles as these systems are very complex and the challenges from market are very high.

On the other hand, each process of the PDP can influence the later steps as well as the earlier steps. These correlations are visualised in Figure 1: All of the decisions made during designing a product are influenced by other steps. E.g. the expected shape of a product has a strong influence on its manufacturing process. But also vice versa the manufacturing process can have an influence on the earlier phases of the PDP: Maybe a designer will change his first idea of the shape of a product with respect on the costs for the manufacturing process. It is possible that a new law concerning the recycling of a product group will change the conceptual structure of these products or the revitalisation of a product can have an influence on its embodiment design and so on, there are many more examples.

Following all these dependencies is not trivial. They are often formulated on very different levels of abstraction: talking about Product-Ideas requires a high level of abstraction: here only functions are relevant and the detail design of the system does not yet matter. Thinking about the manufacturing process during the concept phase can also be quite difficult as the requirements of production are often depending on very detailed information about parts of the system that are not yet designed.

In spite of this it is very important to be able to manage these different influences on product development due to the above mentioned reason of time.

The Elementary Design Model **C&CM** described in chapter 3 offers possibilities to handle these problems as its basic elements – the **Working Surface Pairs** and the **Channel and Support Structures** – describe a technical system on different levels of abstraction. So it offers a possibility to implement the above discussed requirements into the Process of Product Development.

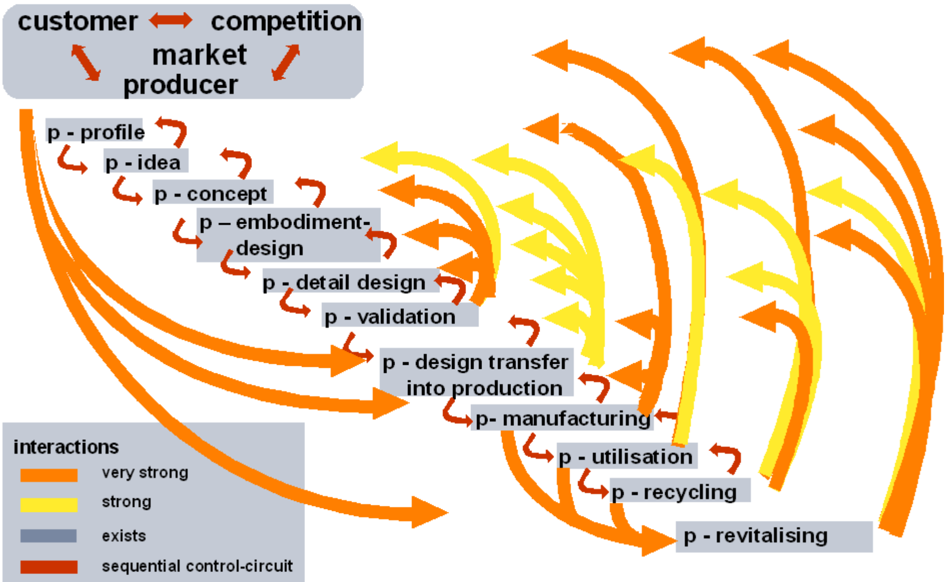

Figure 1: The Process of Product Development, - realisation and -utilisation

3 THE ELEMENTARY DESIGN MODEL C&CM – 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 challenges in engineering thinking outlined above.

C&CM is a new scientific approach of describing products on different levels of abstraction regarding functions as well as shapes and connecting these levels of abstraction. It is developed at the Institute of Product Development (IPEK) of the University of Karlsruhe (TH) basing on important design theories like those of Hubka [12], Roth [11], Koller [13] and others. As the model is conceptuated in an open way, it is possible to implement C&CM into many standard engineering methods like FMEA, QFD, TRIZ and others. So using these methods can be supported and their application fields can be enlarged.

The successful application of this model to several design problems in research and also increasingly in engineering practice [1] shows that this model is a great help for designers. One of the reasons for its success may be that it is developed to support designers in their “normal” thinking process and does not force them to reduce the system to very abstract elements that they can no more assign to the real elements of the regarded technical system.

The following section 3.1 provides a 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. Section 3.2 explains the basic elements and operations at a concrete example for a deeper understanding of the theory. In section 3.3 some possibilities of using C&CM in the engineering thinking process are outlined.

3.1 Basic Definitions in C&CM

Conventionally engineering products are modelled by components with defined geometry, which are grouped into sub-system and systems. C&CM takes a different cut on the geometry, by using **Working Surface Pairs (WSP)**, which carry out functions and **Channel and Support Structures (CSS)** that sit between the working surface pairs and link them. This idea was originally purposed by [6]. With the following definitions any technical system undertaking any function can be described:

Working Surface Pairs

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. It is very important to understand that technical functions can **never** be fulfilled in **one single** Working Surface but always in at least one **Pair** of Working Surfaces. This is one of the main aspects that enriches C&CM in comparison to the models and methods from literature [8], [10], [11]. The consequences of this consideration is described in detail in [1].

Working Surface pairs are represented on different levels of abstraction: On the one hand, they are real surfaces of the technical system that are in contact with other real surfaces of the system. So the designer can always locate them and has a representation of them in mind. On the other hand all technical functions of a system are fulfilled in Working Surface Pairs. That means that they also have a representation on the very abstract level of functional description of technical systems.

Having a representation both on the geometrical as well as on the functional description of systems, they are the bridge between these levels of abstraction and they can be used for switching between them without the need to switch between two very different, nonconnected descriptions of the same system.

Working Surface Pairs take part in the exchange of energy, material and information within the technical system. Every link of the system and its environment is realised via Working Surface Pairs and the flow of these system variables inside the system from one part to another is also represented each by a Working Surface Pair inside the system.

Channel and Support Structures

Channel and Support Structures are physical components or volumes of liquids, gases or spaces containing fields, which connect **exactly two** Working Surface Pairs and channel the flow of the system variables energy, material and information between them.

The properties of the Working Surface Pairs and Channel and Support Structures of a system define its function.

Further Elements

Further elements (Limiting Surfaces, Remaining Structures etc.) complete this Model and allow to describe each technical system with C&CM on the described different levels of detail. A complete set of the definitions in C&CM can be found in [6] and [7].

Levels of resolution

One important fact for the description of a technical system in terms of C&CM is that the **resolution** regarding the system does not have to be constant in each detail. It can be chosen variably depending on the focus of interest: E.g. drivers of an automobile are not interested in the function of the motor or the gearbox. They can reduce the system “car” to the Working Surface Pairs that are concerning their interaction with the system – with the seat, the steering wheel, the pedals, the gear switch and with those surfaces that are relevant for the optical design of the automobile. Maybe they will also regard the Working Surface pairs that connect the automobile with its environment. Those are meanly the contact areas between the wheels and the street and between the outer surface of the car and the environment. But as average drivers they will probably not be interested in details of the power train. So they combine all the single Working Surface Pairs and Channel and Support structures between the pedal and the street to one Channel and Support Structure that includes all the properties of the subsystems between.

Engineers developing the gearbox of the car will be interested in more details of the power train. So they can see the subsystems “motor”, “clutch” and “gearbox” as Channel and Support Structures that are linked via Working Surface Pairs. The gearbox itself can again be regarded more exactly by dividing it into the Working Surface Pairs between the gearwheels (this is maybe the most intuitive level of abstraction as here the Channel and Support Structures are represented by the parts of the system). Even more details of function can be described using a more detailed “micro-resolution” of the system: A EHD-contact can be describes as many parallel arranged Working Surface Pairs between the two solid bodies – e.g. the flanks of the gearwheels – and between the solid body and the lubricating fluid.

For understanding these effects, it is not necessary to change the resolution of the whole car into this detailed view. As the different levels of abstraction can be combined intuitively, developers can set their own focus on the system without losing the view for the whole system and the consequences of the changes that they make.

Describing different functional phases

Working Surface Pairs and Channel and Support Structures can exist always or only at certain times in a system depending on the regarded technical function.

Some subsystems of a technical system will maybe not always fulfil a function. E.g. the air conditioning system of a car including all its Working Surface Pairs and Channel and Support Structures will not have to work when it is not hot outside. So all of its Working Surface Pairs are remaining at their place and can be used when necessary.

Some other Working Surface Pairs are existing with the hope never to use them, they are designated to be used only in case of emergency like for example a fire extinguisher. During the normal operation of a technical system the fire extinguisher will hopefully never be used so in this case it will never have a Working Surface Pair with another subsystem (except maybe one Working Surface Pair for fastening it). So normally it will never have any function (as functions are linked to Working Surface Pairs).

Some other Working Surface Pairs are maybe only used once during the manufacturing process. After this they will never again fulfil any function so these Surfaces are no more Working Surfaces when the manufacturing process is finished. An example for this is explained in detail in section 4.1.

3.2 Describing a product in C&CM – a simple example

The following description of a crane as a simple technical system will give a better understanding for the basic elements of C&CM. It is only a very simple system so the strength of C&CM to handle complex problems will not be highlighted. More details about handling complex systems with C&CM can be read in [7].

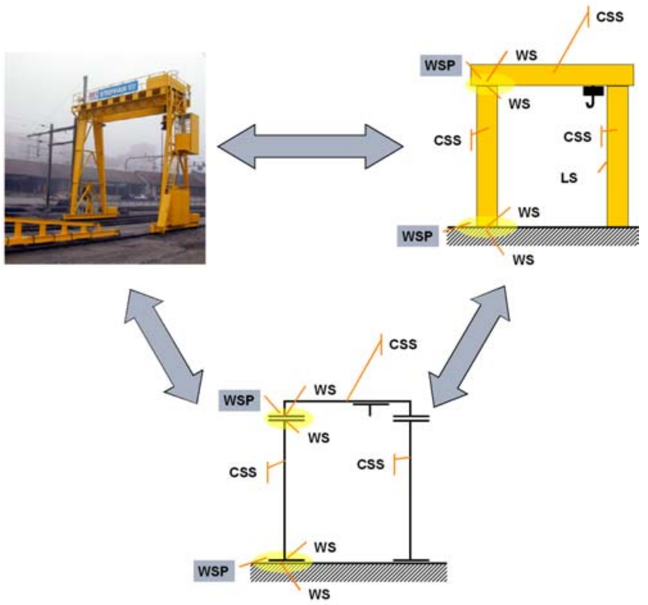

Figure 2: The abstract description of a product in C&CM

Figure 2 shows the Working Surface Pairs (WSP) and Channel and Support Structures (CSS) of a crane in different levels of geometrical abstraction, when it only has to carry its own weight. For example, the left pillar has two Working Surface Pairs with its environment: At the top Working Surface Pairs, the weight force of the beam is transmitted into the pillar. At the lower Working Surface Pair, this force is transmitted from the pillar into the foundation. The CSS between these Working Surface Pairs transmits this force from the upper Working Surface Pair to the lower one and does not store it. This pillar is a minimal technical subsystem as it has the minimal number of Working Surface Pairs and Channel and Support Structures that is required to fulfill a technical function. (This can be validated easily by a mind-experiment: leaving away one of the Working Surface Pairs or the Channel and Support Strucutre will lead to the fact that the weight can no more be transmitted by this pillar).

This function can be described as "**define the distance** between the cross beam and the foundation and **transmit appearing forces**". So there are two kinds of system variables transmitted in the regarded Working Surface Pairs: On one hand there is the **information** of the geometrical position of the upper Working Surface Pair related to the lower one. On the other hand there is a **force** to be transmitted from the upper Working Surface Pair to the lower.

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 fulfill 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 Working Surface Pair at the hook of the crane where a force can be transmitted into the subsystem "beam with hook" and from there over the Channel and Support Structure of the beam into the Working Surface Pairs that inface with the pillars. If needed, the beam can be divided into further Working Surface Pairs and Channel and Support Structures, e.g. those Working Surface Pairs 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 Working Surface Pair at the interface to the neighbour-subsystems (this way of handling different levels of resolution is explained in section 3.1).

Further Elements of C&CM

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 (functional) 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 Working Surface Pair with the Working Surface of the wind. An additional Channel and Support Structure will occur in the pillar that links the Working Surface Pair "wind – pillar" with the Working Surface Pair "pillar – foundation". It is important to keep in mind that the original Channel and Support Structure that connects the Working Surface Pair "beam-pillar" with the Working Surface Pair "pillar – foundation" still exists in this case. Both Channel and Support Structures share the **same** material (and both put load on it!).

For further functions such as corrosion or optical design more and more Working Surface Pairs will be discovered. Every Working Surface Pair will be linked with another Working Surface Pair by a Channel and Support Structure, otherwise it could not fulfill its function.

3.3 The intention of using C&CM

C&CM is intended to be used in different ways. One way is analyse 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 combination 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. 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 can be 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. Analysing 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.

Another way of using C&CM – currently under development – is C&CM as a complete modelling approach, which enables designers 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.

4 C&CM SUPPORTING DIFFERENT PHASES OF THE PDP ON DIFFERENT LEVELS OF ABSTRACTION

As explained in section 2, one of the difficulties in designing a technical system is the fact that each phase of the development process influences the other phases in different ways. The information given in the phases can occur in different levels of abstraction – more functional related or more geometrical related and it is not self-evident how to manage this process.

As C&CM supports the connection of different levels of abstraction as described in section 3.1, it is a tool which can help to improve this process.

The following example in section 4.1 shows the process of integrating the function of a subsystem and the boundary conditions that are given by its manufacturing process. Section 4.2 will give a short overview about the possibilities which this new way of thinking about a product offers to the designer.

4.1 Example

The following example shows the relevance of regarding the simple subsystem „shaft of a gearbox" in terms of C&CM to be able to pay attention to the needs during the manufacturing process as well as during the operation of the shaft.

Shaft of a gearbox

The example bases on a shaft as it is typically used in many gearboxes (see Figure 3). This shaft contains two seats for rolling bearings and two seats for gearwheels that are to be mounted using cylindrical interference fits. It also contains several geometric elements that are depending on its manufacturing process. These elements, their similarities and their differences are discussed in the following sections.

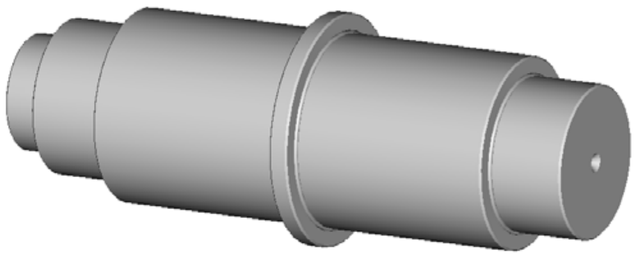

Figure 3: shaft of a gearbox

Working Surface Pairs during the regular operation of the system

As described above, the shaft has Working Surface Pairs with two rolling bearings and with two gearwheels during its regular operation. These Working Surface Pairs are highlighted in Figure 4. Their function will be explained in the following section. As it is a symmetrical situation, only the Working Surface Pairs of one side are explained for this purpose.

The nomenclature will use the term "Working Surface Pair" although the pictures only show single Working Surfaces due to a better overview. But functions are never fulfilled in single Working Surfaces, so it does only make sense to talk about the regarded pair of Working Surfaces including the geometry, the tolerances and other properties of both Working Surfaces of the Working Surface Pair.

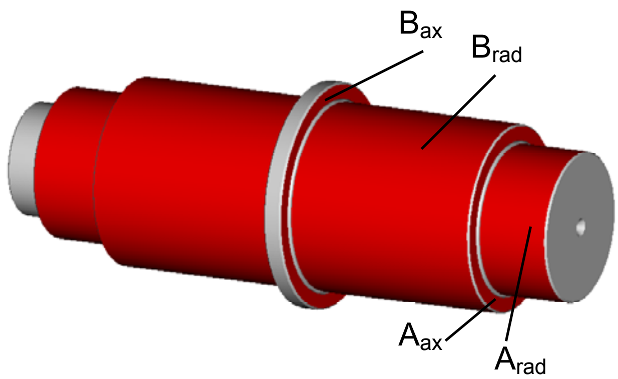

Figure 4: Working Surfaces of the shaft

The Working Surface Pairs marked with 'A' have the function to transfer radial (A_{rad}) and axial (A_{ax}) forces from the shaft into the bearing. This is a transfer of

- **forces**: the forces that are transferred into the system by the Working Surface pairs 'B' (see below) are channelled to the regarded Working Surface Pairs 'A' and here into the next subsystem, the rolling bearing. Both kinds of forces, radial and axial, are transferred perpendicular to the Working Surface Pair that means by form closure.
- **information**: the axial and radial position of this shaft in relation to the housing is defined by these Working Surface Pairs.

This Knowledge is very important for the manufacturing process as these functions define the required quality of the Working Surfaces (according to the quality of the accompanying Working Surfaces, see also [2] and [4]) like measurements, tolerances and roughnesses. So this knowledge about the function of this geometric element defines its manufacturing process. Both knowledge – about the geometry as well as about the function are stored in the Working Surface Pair and its geometrical and functional description.

The Working Surface Pair 'B_{rad}' has the function 'transfer the rotation from the gearwheel mounted on it to the shaft'. As the Working Surface Pair is supposed to fulfil its function via a cylindrical interference fit, the axial force and the torque (i.e. the product of the tangential force and the radius) are transmitted tangential to the Working Surface Pair that means by force closure.

So there is again a transfer of force (as explained above) and information – the rotation speed and angular position of the gearwheel in this Working Surface Pair. Without knowing the main function of this system it is not yet possible to give details about the **main flow** in this Working Surface Pair – energy or information. In a printing machine the main flow will probably be information, in an excavator it will probably be energy, according to the main function of the regarded system.

Working Surface Pairs during the assembly process

The axial Working Surface Pair 'B_{ax}' has a completely different function:

As all of the forces (radial, axial and tangential) between gearwheel and shaft are transmitted in the Working Surface Pair B_{rad}, there seems to be no additional function for this Working Surface Pair. And indeed if we would leave this Working Surface Pair away, the system would still fulfil its function. So we can say that this Working Surface Pair has no function during the operation of the system.

Nevertheless, this is no contradiction. As we have seen in section 3.1, not all of the Working Surface Pairs fulfil their function at the same time, not even during the same step of the PDP.

The function of Working Surface Pair B_{ax} is defined for the assembly process of the system: it defines the axial position of the gearwheel in relation to the shaft. So there is **no** transfer of energy but **only information**. After the assembly process of the system the Working Surface Pair does no longer have a function and so it could be left away.

Keeping this in mind it is possible to define the properties of this Working Surface Pair according to its function. Now it is even possible to think again about the position of this Working Surface Pair: Maybe it is be possible to use any other axial surface of the shaft for a positioning in an assembly gadget and an additional Working Surface Pair between the assembly gadget and the gearwheel for the positioning of the gearwheel on the shaft. So the shaft shoulder in the middle of the shaft could be left away and the maximum diameter of the shaft could be decreased.

There are many more possibilities to change the properties of this and of the other Working Surface pairs that are needed for the assembly process. But following the argumentation of this section makes clear that C&CM is able to help the designer thinking about existing and new solutions as it connects both the geometry and the function of systems in its basis elements, the Working Surface Pairs and the Channel and Support Structures.

Working Surfaces during the Manufacturing Process

There are more Surfaces of the shaft that are not yet explained. Figure 5 shows two additional Working Surface pairs 'C' and 'D' that are used during the manufacturing process of the system:

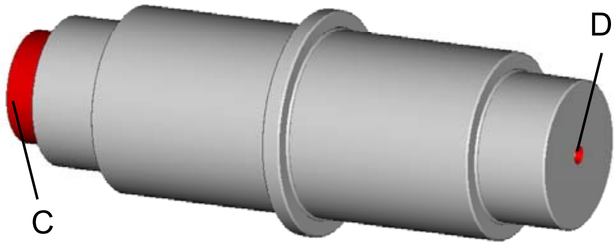

Figure 5: Working Surfaces for the Manufacturing Process

Both of these Working Surface Pairs are used for fixing the shaft in the manufacturing machine, in this special case a lathe.

Working Surface Pair 'C' (Figure 6) is used for clamping the raw material of the shaft in the lathe (it must be manufactured itself before it can fulfil this function). So there is both energy (the torque and the revolutions for the process) and information (the exact position in the machine) transmitted in this Working Surface Pair.

After the turning process this Working Surface Pair is no more used. The Surface changes into a **Limiting Surface** and the Channel and Support Structure changes into a **Remaining Structure** for the rest of its lifetime. It will not fulfil any additional function during the operation of the machine. So the whole surface could be removed if this would mean an advantage for the whole system (reducing weight or measurements). But removing this material also means causing additional costs, so this must be decided regarding economic aspects.

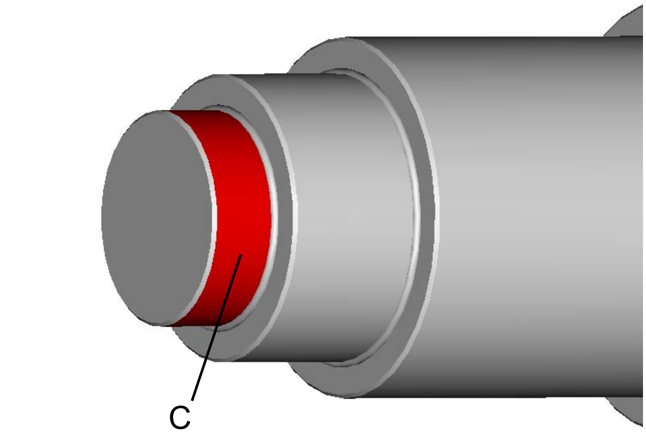

Figure 6: Detail – Working Surface Pair ‘C’ for clamping

The function of Working Surface Pair ‘C’ could also be fulfilled by one of the Working Surface Pairs ‘A_{rad}’ depending on the manufacturing process. In this case the same Surface of the part would fulfil different functions during the PDP. This is only possible because the requirements to the surface for both functions are similar and because the two functions will certainly never be fulfilled at the same time.

Working Surface Pair ‘D’ fulfils a similar function. It is also used for fixing the shaft in the machine during the milling profess and it also loses its function after this process. But a main difference to Working Surface Pair ‘C’ is the main flow of system variables over this Working Surface Pair: Its main function is defining the radial position of the shaft in the machine. Although there is a certain force necessary to fulfil this function, the main flow is **information** in this case.

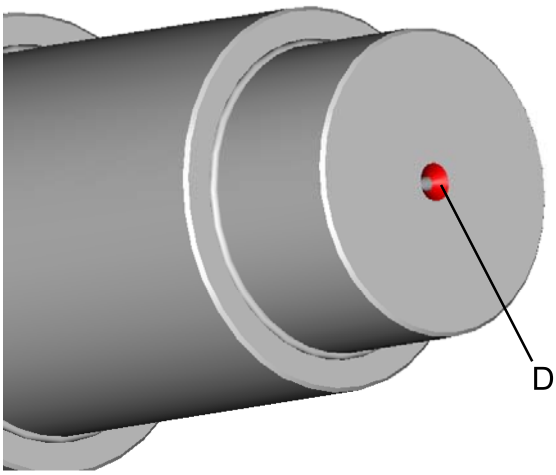

Figure 7: Detail – Working Surface Pair ‘D’ for centering

Depending on the boundary conditions of the manufacturing process, Working Surface Pair ‘D’ could even be left completely away. The price would be a worse quality and worse tolerances of the Working Surface groups ‘A’ and ‘B’ that are later important during operation, but actually manufactured.

4.2 New approaches

There are several new approaches how the designers can use C&CM in their thinking process to improve the quality of the designed system regarding the above mentioned knowledge.

Using C&CM for a better overview over the process chain ‘from market to product’

Having all phases of the PDP in mind during the designing process, is very important for a good overview and for the reduction of the time to market. Using C&CM in their thinking process as described in section 4, designers are able to adapt many boundary conditions of other phases into their choices.

Neglecting some phases consciously during other phases

Mostly this is a great advantage to have all phases of the PDP in mind. But there is also a danger of running into fixation because the changes in a system often influence many steps of the PDP. Designers will always be influenced by former considerations about the system.

C&CM also offers the possibility to regard the system from a very abstract point of view. In case of the development of a very new product it is possible to design a system in the first step only by defining the Working Surface Pairs and Channel and Support Structures according to the relevant functions during operation. On this abstract level of functions the danger of being fixated on special solutions because of some boundary conditions is quite low. Nevertheless the step from an abstract solution to a concrete design is not very difficult as the defined Working Surface Pairs define both form and function.

Of course it is necessary to implement the other phases of the PDP in the next step, but this explained short phase of neglecting them offers many possibilities to find innovative solutions for given problems.

5 PRINCIPLES AND RULES

The discussed examples show the value of using C&CM during the complete design process of technical systems. Although C&CM can often be used intuitively, it is also important to save experiences made in former development processes for being able to use them in future projects.

An approved method to support this is creating guidelines, principles and rules which enable designers to document their experience with a technical system. Although literature already provides a large number of these rules, new ones are constantly developed.

This chapter shows how existing knowledge is implemented into C&CM and how new experiences can be saved in the same way for a better access to it. After a short summary of existing principles, rules and guidelines in section 5.1 some ideas about implementing them into C&CM and classifying them in terms of this Method is shown in section 5.2. The following section 5.3 finally gives an example for a concrete, easily applicable rule.

5.1 Principles and Rules from literature

Saving and transferring the gained experience of a professional working designer is an important component for guaranteeing a company and a market economy permanent success.

Apart from the Element Model C&CM literature [8], [10] (and many others) provides a large number of classical principles, guidelines and rules on different concrete levels, which are supposed to help fulfilling the requirements of technical systems.

Additional to the classical principles, guidelines and rules new ones have been established based on for instance new experiences or technologies. One current example is the micro technology, where new experience is gained in some Centres of Excellence in Research and is consistently transformed into new design principles, guidelines and design rules. The design guideline „micro-oriented" is one example of the "Sonderforschungsbereich 499", which considers the special impacts of the manufacturing processes of micro technology with all its restrictions [3].

All these principles and guidelines are formulated in different abstraction levels. Most of them are located on the shape level, e.g. the principles of force transmission. In order to achieve an improvement it is not necessary to change one of the functions or partial functions of a technical system but to alter the shape of a system while keeping the given function. Some of the guidelines and principles have also been formulated on the abstraction level of the functions, e.g. the principle of task sharing or self-help. A change in this area is only possible by altering the function or partial function of one or more machine parts.

Current research at IPEK is developing a set of rules and principles, consistent with the abstract level of the Element Model C&CM, which may be a help to the designer in all phases of the PDP as well as for problem solving. The designer should be enabled to consistently apply the existing guidelines on this clearly defined abstraction level of the Element Model C&CM. Since the C&CM-method is shape-oriented as well as function- oriented, the simultaneous consideration of this both levels of abstraction during the design-process is possible.

Thus, the applicability of the existing guidelines and principles are to be made easier on all abstraction levels by making them consistently available on a very abstract level. At the same time a method is needed by means of which it is possible to move from this abstract level very quickly to a real shape level.

Furthermore, a strategy is to be pointed out by means of which these rules can be applied on the abstract level of the Element Model and implemented into the real level of shape.

5.2 Meta-Rules

Principles and guidelines that are included into the C&CM-Model can be divided into different groups, depending on which changes are made and how they are carried out in order to improve the result:

One group only concerns the Working Surface Pairs of a technical system. This includes among others the principle of assembly-oriented design, wear-oriented design and corrosion-oriented design.

A further group only influences the Channel & Support Structures of a technical system. It contains creeping and relaxation-oriented design, deformation-oriented design as well as some of the principles concerning energy and force transmission.

Apart from that there is a group which concerns the complete Working Structure of the technical system, i.e. the Working Surface Pairs essential for the function as well as the Channel and Support Structures. This group is relatively big and contains e.g. the principles of nearly flawless design, the principles of safety engineering, the principle of self-help and the risk-oriented design.

A further important organising criterion overlapping with this is the way the changes concerning the application of the principle or the guideline in the technical system are realised. This will be illustrated by means of the example for corrosion-oriented design in section 5.3. In general, there are four possibilities for changing a technical system:

- **Adding** Working Surface Pairs or Channel and Support Structures
- **Removing** Working Surface Pairs or Channel and Support Structures
- **Changing the properties** of Working Surface Pairs, including their relation to other Working Surface Pairs or Channel and Support Structures and
- **Changing the properties** of Channel and Support Structures.

From these rules all changes of any technical system can be derived. However, as the rules are so general a designer with some experience is required to guarantee a safe application in the design process and derive the correct measure from these very generally put rules. The example of the iron girder in section 5.3 will show that a Working Surface Pair can be added at very different places (at its surface or at a place to a metal with an anodic effect) in order to fulfil the originally desired function "Avoiding or at least decreasing corrosion".

Therefore, to provide effective support for designers in their everyday work it is necessary to put an aid at their disposal by means of which they can decide which design principle to choose for solving different kinds of problems. Moreover, a method is to be developed which helps designers to understand how the generally formulated measure - e.g. „Adding a further Working Surface Pair" can be realised in detail.

In a first step a matrix has been developed at IPEK which helps the newly formulated principles and rules, which are presented on the abstract level of the Element Model C&CM, to convert into their previous form and vice versa. The line parameter of the matrix are the principles and guidelines in the until then existing form. The column parameter, however, are the new rules introduced in this paper. Connections between guidelines, principles and rules on the two abstraction levels are highlighted in this matrix. This enables also the less experienced designers to change between the previous, relatively unstructured point of view and the new point of view based on the Element Model C&CM. Thus, they are also able to implement guidelines and principles in a much more effective way.

5.3 Example for concrete rules

As an example for a concrete rule that supports the designer directly during the solving process of a special problem, the implementation of the design guideline ‘corrosion-oriented design’ into C&CM is explained in this section.

This guideline implies that machine systems are to be designed so that corrosion can be prevented. If this is not possible due to technical or economic reasons the design of the technical system is to control corrosion as much as possible and enable the system to fulfil its function despite corrosion. This may be realised by means of ‘corrosion-oriented design’ [8]. Presenting this guideline on the abstract level of the C&CM, the following can be stated concerning the realisation of this guideline: Corrosion is a harmful function always occurring at Working Surface Pairs. In order to avoid or reduce corrosion the following measures can be taken:

- **Removing** one of the Working Surface Pairs causing the corrosion: either the Working Surface Pair through which e.g. oxygen atoms diffuse into the iron lattice of the material and thus iron atoms oxidise or the Working Surface Pair, through which the resulting reflux of electrons can flow from the reactive to the non-reactive reactant. Applied to the example of an iron girder exposed to all kinds of weather this means either protecting the iron girder from the weather or sever the possible conducting connection to a more noble metal.
- **Adding** a further Working Surface Pair: e.g. by varnishing an iron girder two new Working Surface Pairs are added, the first of which is located on the surface of the iron girder. Here the varnish layer adheres to the iron and forms a Working Surface Pair. The second new Working Surface Pair is developed at the surface of the varnish layer between environment and varnish. Only if both new Working Surface Pairs show suitable properties corrosion may be averted. The Working Surface Pair located between iron girder and varnish layer is to have a high adhesion and must not serve as a catalyst for the rusting of the iron girder. The Working Surface Pair varnish - environment is to be weatherproof and must not let oxygen diffuse through the Channel and Support Structure varnish layer. A completely different possibility would be – analogue to the first example – to add a Working Surface Pair at another part of the iron girder enabling the electron flow in the direction of the iron girder when connected with a more reactive metal than iron. This may also serve to effectively decrease the corrosion of the iron girder. This principle is often applied in ships in the form of sacrificial anodes.
- **Changing the properties** of a Working Surface Pair: By selecting an iron girder with different material properties such as stainless steel corrosion may be reduced or even prevented. This may also be realised by changing the properties of the other working surface of the Working Surface Pair iron / environment: Corrosion can also be avoided by selecting a less corrosive environment.

For the question which method is the most advisable there is no general answer, since this strongly depends on the respective environmental conditions of the technical system. Therefore, it is not possible to change the surrounding medium of a pylon as the latter rusts. Neither can an iron girder in a steelworks, which is exposed to very high temperatures, be easily coated with a varnish layer. So the last choice of which of the possibilities is the best choice for a special problem still is a matter of the designers. But using C&CM consequently means to have a reliable basis for this choice.

6 SUMMARY

With a small number of simple concepts, all aspects of the complex Product Development Processes can be described by C&CM. It 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 problems. It 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.

C&CM offers a set of abstract as well as very detailed instructions which support the designers during all phases of the product development process and in solving problems.

Many examples of successful product development and problem solving processes with students in projects with industry confirm the strong utility of C&CM.

C&CM is constantly enlarged by adding further patterns of solution, rules and examples. So it is no longer only a model for describing technical systems. It is developing into a design philosophy which enables the designer to manage the whole process of product development on one common level of abstraction – the level of C&CM.

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