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SEVEN YEARS OF PRODUCT DEVELOPMENT IN INDUSTRY – EXPERIENCES AND REQUIREMENTS FOR SUPPORTING ENGINEERING DESIGN WITH 'THINKING TOOLS'

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ABSTRACT

At the centre of the present contribution is the part of the engineering design process in which the embodiment design is created. On the basis of the author's experiences in industrial engineering design and the management of engineering design projects and engineering design teams the attempt is made to describe the creative engineering design process and thus make it more understandable.
The main function of the product is in the centre of company´s interest because cost-effective fulfilment of function is the main selling criterion of any product.
It is shown how function is realized in the interaction of several components of a product and in their interaction with the product's environment.
Engineering design is to think ahead and to document an "embodiment" which is established to enable the function of the product. This process will then be described. On that base possibilities and requirements for academic research to support these activities are shown.
After that, industrial experiences will be described which were gained in working closely with the Contact&Channel-Model. It will be shown that "thinking tools" can help to support the processes necessary for creating a new product.

Keywords: industry, function, embodiment, engineering design process, Contact&Channel-Approach

1 INTRODUCTION

Today, methods are playing an important role in supporting the development process. They help to reduce the number of mistakes, shorten development times and improve the quality of products [1].
The improvement of methods on the one hand and the enhancement of the acceptance of methods in the industry on the other has been the subject of research [2] – [7] of a broadly-spread community for many years now. Great potential is seen above all in the more vigorous dissemination of methods in the industry. For example, in [1] the following conclusion based on field studies is reached: "... a lot of potentially useful methods are only applied seldom or not at all. Additionally, methods are often not carried out in the intended way or are poorly adapted so that the intended goal of these methods – support of the design in certain kinds of work – cannot be achieved."
Methods which are meant here are for example market analysis, target costing, value analysis, QFD, FMEA technology scenario and many methods besides [1]. All these methods require a method moderator, coming from inside or outside the company. They accompany the engineering design team for as long as the method is worked through. This way of proceeding is standard practice today and has proved its worth. In the course of a specified interval of time of a few days the engineering design team works together guided by the moderator according to a method. After that, work proceeds based on the results achieved. The design engineer works for far longer periods without such guidance, but rather on his own or in the engineering design team. His daily work is designing products. **He is thinking about a technical system, which exists only in his head. He is "pre-thinking" the product with his team and above all on his own, in discussion with himself.**
However, in the discussions regarding the requirements of Engineering Design Science, pre-thinking of the product, the embodiment design process, driven by the design engineer, plays a somewhat subordinate role. Weber and Birkhofer formulate this deficiency in the following terms:
"The relation between product properties and their establishing via an engineering design process on one hand and reaching business goals on the other hand has not been considered very deeply." [2]

The creative pre-thinking of new products in the embodiment design process offers in the author's view enormous potential for academic research and methodological support.
"Thinking tools" which support the design engineer every single day in his thinking work towards creating suitable products open up an enormous potential for the faster development of better products.
The following contribution attempts to describe the creative pre-thinking, the synthesising of products on the basis of experiences gained in industrial product development, to make them more vivid and to point up deficits in the support. At the same time, he knows full well that the synthesising of products is never a straight-forward process, never unfolds in a rational way and that creativity will always remain an "art", too.

2 THE FUNCTION

Function occupies the central position in the development of products. The fulfilment of a function is ultimately the purpose of products. Function-fulfilment thus becomes the justification for the existence of every product and the necessary condition for the economic success of the product [8].
In order to illuminate this statement more clearly, function will be considered from various points of view in the following.

2.1 Function from the customer's and the company's point of view

In producing companies products are developed in order to achieve economic success. The products must be bought by customers in order to realise this success.
There are of course diverse reasons for buying and all sorts of marginal considerations which influence the customer in his decision-making. Ultimately however all of these can be traced back to one single reason: the customer believes in the product. He believes that the product fulfils the purpose which he expects from the product. This purpose of the product is also designated the function of the product. The function is not only of technical nature in regard to the decision whether to buy the product or not. It can also be a function which is difficult to measure or a function which is motivated emotionally. The "non-technical" function is often conveyed by the actual product but it can sometimes be fulfilled for example by the image of the product brand. Thus a car can apart from its technical function as a "means of transportation" serve the purpose for the customer as a "mark of social status".
Before he decides to buy, the customer weighs up the benefit against the expenditure required to achieve the benefit. Cost-effective fulfilment of function is thus at the centre of his decision to buy.
The cost-effective fulfilment of function from the point of view of the customer is ultimately the main selling criterion of any product. Thus cost-effective fulfilment of function moves to the centre of interest of the company.

2.2 Function from the product's environment's point of view

The environment surrounding the product plays an essential role in considering the product's function. "Transport" is made possible for example only by the provision of a road network, by providing an energy supplier, for example at a petrol station, and many other such environmental factors. The function "mark of social status" can only be enabled in terms of a comparison with social status in general in the society in which the car moves. When considering function many factors outside the product need to be taken into account. In the product development these considerations must without fail be taken into account in the target system, otherwise the desired product profile cannot be achieved.
The environment of the product has a decisive importance for its functions since products do not fulfil their function until they are bound into their environment. This is true for any function and not just for the main function which is the purpose of the product [8].

2.3 Function from the product development's point of view

Every product is developed for a specific purpose. Beside the economic utility for the company it is to provide a functional utility for the customer. So the function to be fulfilled has a quite decisive importance in the development of the product.
In the following the purpose of the product is to be understood in terms of its technical function which is designed into the product by the product development department in the company. A multitude of

functions in the Technical System must be fulfilled in order to fulfil the one function which the customer is ultimately buying.
This will be shown by an example from the power-tool making industry. In a “direct fastening power tool” which for the customer has the function “easy nailing of metal sheets to metal structures without prior drilling”, more than 200 parts, interacting with each other, have to fulfil more than 500 functions. All activities in the engineering design process serve in the end to realise these functions.

Figure 1. one function for the customer – more than 500 functions realized in product

The design engineer configures the individual parts of the product in such a way that they are set up to fulfil the individual functions in their interplay with one another and in their effect in interaction with the product’s environment. All the individual functions together deliver the main function which is relevant to the customer.

2.4 Function from the product’s embodiment design’s point of view

The function materialises in the embodiment which the design engineer lays down for each individual part of the product. It originates from the many individual functions which the individual parts fulfil in interaction with each other and in interaction with the environment of the product.
In the following there is an investigation of the activities in engineering design which are necessary to realise functions through product embodiment.

3 ENGINEERING DESIGN – A CREATIVE PROCESS

According to the Verein Deutscher Ingenieure Guideline VDI2221 engineering design is “the totality of all activities with which proceeding from a specified task the information necessary for the manufacture and use of a product is gained and which end up in the determination of the product’s documentation” [9].
In the present context the following formulation is suggested: **“Engineering design is the pre-thinking and documenting of an ‘embodiment’ which is set up to enable the function of the product.”**
Here, let the embodiment be the totality of all geometrical, material and other specifying characteristics of the product. In mechatronic products let for example the algorithm in the engine management system be a part of the embodiment.
The embodiment of the Technical System, embedded and interacting with its environment is responsible for the correct fulfilment of the product’s function. This embodiment must be thought out and laid down by the product developer.
The pre-thinking of an embodiment which is not yet in existence, the process of creation by which something new is thought up, is a fascinating activity and one which is very hard to comprehend. This process, which is also designated an embodiment design process or synthesising process of a Technical System, will be scrutinised more closely in the following. By the term synthesis the following should be understood:
Synthesis in the engineering design process is the creation of something new.
The synthesis of an embodiment which fulfils a function thus becomes an essential activity of the design engineer in the development process. He turns functions into embodiment. How does this process of synthesis unfold in the embodiment design of products?

3.1 Analysis and synthesis in the engineering design process

The synthesis of the function-fulfilling embodiment is never accomplished in a single step. It is in fact another process within the product-development process [10]. The design engineer thinks up an embodiment which he supposes will achieve the desired purpose well. This embodiment is then usually turned into a prototype and examined with experiments and tests. The product is analysed in terms of its ability to fulfil its function. The analysis which is carried out here is never done without good reason, but always for further development or to validate market maturity. For this step of validating the product it is essential to integrate the relevant product environment appropriately. Function fulfilment, as stated above, only arises in the context of the environment system and can therefore be assessed only in interaction with it. The process of making inferences from the given embodiment about the possible function is denoted the analysis of the Technical System. In the following "analysis" should be understood as:

Analysis in the engineering design process is the drawing of inferences from the given embodiment about the possible function with consideration of the environment of the embodiment.

On the basis of the results of the product validation, in other words the analysis, the system is usually improved. In a new synthesis step a changed embodiment is developed. This embodiment can be analysed in the next step. These iteration loops are usually repeated until the result of the function analysis can be rated as sufficiently good. The loops of manufacturing, validation and embodiment design which are mostly repeated several times and which can take up long periods of time to run through shall be denoted in what follows as "macro-iteration loops".

Quite similar iterative loops of synthesis and analysis with comparatively very short periods take place in every phase of embodiment design of the product development in the head of the developer. In contrast to the iteration loops just described, these short-period iterations shall be designated "micro-iterative loops".

While the developer synthesises an embodiment in his head, he analyses this virtually present embodiment immediately in terms of its fitness for the purpose for which it was designed in order then to synthesise it in a different form and analyse it once more. This iteration takes place in the head of the design engineer for as long as it takes him to decide that his idea, an embodiment which often exists only in his head, is sufficiently good to fulfil its intended function. He documents the product he has thought up in terms of its geometry and the material from which it is to be constructed, lays down measurements and material specifications, and a new macro-iteration loop can take place.

The creation of something new, the synthesis in the product development, is inseparably bound up with the analysis.

The author is of the unproven conviction that generally analysis precedes any synthesis. The synthesis is influenced by experiences and observations which the design engineer has made before. Even unconsciously, the design engineer makes use of experiences and observations in his engineering design activity. The more his experiences and observations have been deposited in his head, the more easily he can, mostly unconsciously, find new uses for them. If this conviction is true, then a process of synthesis never begins with a synthesis but rather, and much earlier, with an analysis which at the point of execution has still got nothing to do with the product to be synthesised later on. It follows then:

Product developers synthesise on the basis of earlier, sometimes unnoticed, analyses. Analysis is the basis of the synthesis and without prior analysis there is no synthesis. **Something new always arises on the basis of the analysis.**

Original design, the synthesizing of a product which is completely new for a company is thus based on products which the design engineer has one way or another perceived. Every change or adaptation in the engineering design which take place more frequently in companies is based on the analysis of earlier products. Here analysis precedes synthesis.

According to the experiences of the author, the importance of analysis for synthesis is often underestimated. If the understanding of the problem is sufficiently good, most of problems can be solved by experiences made before. That is another reason why nearly all solutions seem pretty simple in retrospect. **Analysis occupies an important place in the engineering design process and is the basis of synthesis. Hence a "thinking tool" for supporting the creative synthesis process must necessarily support the analysis.**

Talent, experience, creativity, inspiration, all play their part to complete the “micro- and macro-iterative loops”. The basis of all of them however is the **recognition of the connections between function and embodiment** and to that end the system to be developed must be understood sufficiently well.
If the design engineer is to be supported exactly here, he needs a tool, a “thinking tool”, which supports his thinking for analysis and synthesis equally and makes it easier for him to recognise the relations between function and embodiment.
More will be said about this in 3.3.

3.2 More efficiently to the appropriate embodiment

According to Karl Popper, who strongly influenced the “theory of knowledge” [11] every gain in knowledge is characterised by trial and error: “The method by which one works towards solutions is as a rule the same: it is the method of trial and error” [12]. Insights and knowledge arise through the recognising of errors within a theory.
According to the experiences of the author, “good” design engineers get to functionally suitable embodiment variants faster, in fewer iterative steps. The amount of knowledge gained for the next step from a given analysed embodiment seems to be greater. The good product developer recognises the functional error while he is analysing the embodiment he has created – his “embodiment theory for function fulfilment". He learns from the error he has identified and employs this knowledge in later syntheses. The likelihood to reuse this gained knowledge increases through the way to store it with the appropriate degree of abstraction. According to the experiences of the author, successful design engineers possess an appropriate ability for abstraction. This abstraction can be achieved on the basis of appropriate model-building. “Thinking tools” should support exactly that.

3.3 Reduction to the essential - or dealing with complexity

To predict the functions of a product in detail is often not easy, even for the specialists in a company. The analysis of actual functions of given Technical Systems, which often differ from the desired functions, takes up large parts of the industrial development time.
The analysis of the actual functions becomes especially difficult through the binding-in of the Technical System into its environment. Interactions arise between the Technical System and the environment. Because of that, total system complexity arises. Complexity is a measure of the indeterminacy, the over-supply of possibility or the lack of information [13]. Complexity in terms of the product development stems above all from the influences of the environment on the function, which are hard to predict accurately, and from the excess of possible environments when the technical product is later put into service [14].
The direct fastening power tool shown in Figure 1 makes this especially clear. Both interactions – with the steel structure of the building and with the operator of the tool – influence the function of the tool. The anchorage of the nail in the base material can be influenced enormously by the vibrational characteristics of the steel structure of the building and by the strength the person presses the tool on the material to fasten. These interactions with the environment of the tool are neither measurable with arbitrary precision nor predictable for all applications of the Technical System.
The total system consisting of Technical System and environment is complex. The complex total system is relevant for the function.
The product developer has to deal with both the complicated nature of the Technical Systems and the complexity of the total system. He has to find an access to understanding the systems. Human beings often have difficulties dealing with complicated things. With real complexity on a one to one basis humans cannot deal at all [14]. They can only do so if they use efficient filters to reduce the complexity.
Access to understanding complex Technical Systems is achieved then via filters. The Technical System must be simplified. It must become as simple as possible but not too simple. The filter must be chosen correctly. That is difficult. Nothing is as difficult as making something as simple as possible but not simpler [15].
Norbert Bolz, who is concerned with the interactivity of human beings and technology, says that complexity can only be mastered on the basis of simple dynamic model building. According to Meboldt this means for the model-building of complex systems that the model is based on simple and unambiguous rules which can be applied dynamically in the building of the model [15].

Complex Technical Systems can be mastered on the basis of simple dynamic model-building. Complex Technical Systems must therefore be simplified if they are to be intelligible to the human being. This is achieved where models are developed which make things simple but which at the same time retain what is relevant for understanding the function. At the same time the model-building must be done in a dynamic way, in other words be different and adapted for every particular problem posed.
This then is the strategy to make the complexity manageable:
Reduction to the essential, dynamic, on differing levels of detail. "Thinking tools" for supporting the creative synthesis process must support that.

3.4 Outcomes of the engineering design - embodiment documentation

The result of the thinking activity of the design engineer is ultimately the geometrical and material definitions of individual parts which are documented in a Technical Drawing and administered centrally in the company. The product is fabricated on the basis of these documents.

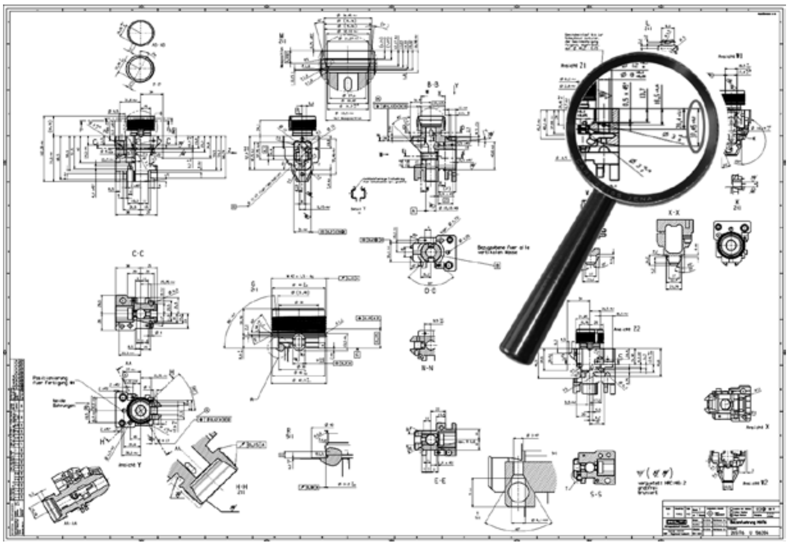

Figure 2: Technical Drawing of an individual part of the tool shown in Figure 1 (not legible for reasons of confidentiality)

A particular thought process led to every measurement, to every individual tolerance depicted in the Technical Drawing. Embodiment and function were discussed together in the head of the product development engineer. The result is the documentation of the embodiment. Figure 2 shows such documentation in the form of a Technical Drawing of a component part of the tool depicted in Figure 1. More than 600 tolerated features specify the component part. In what way which embodiment feature contributes to which function is not documented although the function ought to be the most important reason for the embodiment feature. The connection between embodiment feature and its origin, the relevant function, is not documented. It must be re-thought every time the embodiment is questioned.
A study in industrial enterprises has shown that most design engineers are familiar with function structures and appreciate them as sensible and profitable. In this study it proved to be impossible to uncover a single distinct function structure in any case. In a few cases, the design engineer was able to find a function structure on paper among his own documents [18]. **Functions are not very unambiguous, if they are documented at all, and are not associated with the embodiment documentation.**
This lack of appropriate association with the embodiment, suitable formulation and central documentation leads in practice to problems and inefficiency. In every discussion of the documented embodiment the reason for the embodiment, the connection with the function, has to be thought through again. The attempt to retrace thought processes appears practically continuously from the moment a first embodiment suggestion is available. Especially big problems arise when the trains of thought of the design engineer have to be recreated by other people. This is often the case for example with the development of a new generation of products or with tolerance discussions with production in projects in order to reduce costs.

At this point, there's an example regarding the tool depicted in Figure 1. The fabrication drawing (Figure 2) shows the documented embodiment of one of the more than 200 individual parts. About 600 tolerated features specify this single part. In discussions regarding cost-cutting, increases in the tolerances of individual measurements were considered among other matters. If a particular tolerated measure is discussed with a view to a possible cost reduction, design engineers who in the main did not think up the product in the first place have to work backwards to find out what functional influence exactly the measurement under discussion has on the various functions. In so doing, they have to get a grasp of the functional context since the component part can fulfil functions only in interaction with other parts in its environment. A function formulation such as "force transmission" will not help in any way. It lacks a connection to the features of the various component parts and to the environment, all of which fulfil the function together.

3.5 Interim conclusion

Function is at the centre of product development.

The daily work of the design engineer is the creation of an embodiment which enables desired functions to be fulfilled. The design engineer discusses function and embodiment simultaneously alone or in the team. In so doing he forms connections between function and embodiment. Analysis and synthesis are inseparably connected with each other in this discussion process. There is no synthesis without analysis.

4 MODELS AND MODEL BUILDING

Human beings build models of their environment in order to make it comprehensible to them. Design engineers are no exception. They build models, above all implicitly in their thoughts, in order to be able to deal with complex Technical Systems. Now following is a detailed discussion of this.

4.1 The meaning of models

It is well known, and certainly since the appearance of Stachowiak's "Allgemeine Modelltheorie" ("General Model Theory") of 1973, that knowledge is achieved only within a model or through models [16]. Reality as such cannot be perceived. Only a model of reality is available. In general, models have three essential features: the feature of depiction, the feature of abbreviation and the pragmatic feature [16]. According to this view, models are always models of something, that is to say they are depictions, representations of natural or artificial originals which themselves can be models again. They do not in general capture all attributes of the original depicted by them, but only those which seem relevant to whomever is creating the model and/or is using the model. To that extent they are not assigned to the originals as such but rather fulfil some of their replacement function for particular subjects using the model in the framework of particular time scales confined to particular conceptual or actual operations [16].

To build a model of reality a model is needed. This model to build a model is generally denoted a "meta-model". Meta-models contain as abstract models no concrete authoritative knowledge. They provide the structure without concrete application. On the basis of these meta-models, so-called formal models can be built for a specific application [14].

Human beings who have dealings with each other need models in common on the basis of which they can build models. For according to Stachowiak and his general philosophical outlook:

"*All knowledge is knowledge gained in models or through models and all encounters with the world in general need the medium 'model'*."

These meta-models must be self-consistent and definite. Model-building on the basis of these models is, in contrast with what was alleged above by means of three essential features of models, never unambiguous and is often indistinct as well.

4.2 Model building on the basis of the Contact&Channel-Approach

The Contact&Channel-Model (C&C-M) is a model for building models of Technical Systems. Its aim is to support the creation of the product. It is completely and unambiguously defined by three fundamental hypotheses and the definition of the two embodiment-function elements – working surface pair and channel and support structure. On the basis of the C&C-M, models of all Technical Systems can be built [8, 15].

The model has been developed over the past 10 years by a group of researchers around Albers at the IPEK - Institute of Product Engineering Karlsruhe at KIT (Karlsruhe Institute of Technology). It sets out a possible way of supporting the daily work of the design engineer described above. It is suited to analysis and synthesis simultaneously and reduces the complexity to what is relevant for questions concerning function and linked embodiment. The "thinking" of the design engineer is moved via the working surface pair away from thinking about component parts so that the interaction of the component parts with each other, which is relevant to fulfil the regarded function, moves to the forefront of the consideration. It is dynamic, which means that it is applicable on various levels of detail in always the same way and manner. This characteristic is denoted the fractal character of C&C-M [8, 10]. In order to distinguish better the meta-model C&C-M, with the help of which Contact&Channel-Models of a Technical System can be built, from the built C&C-M, the meta-model was renamed Contact&Channel-Approach (C&C-A) in 2010. The appellation C&C-M was retained for built models of Technical Systems.

4.3 Model building - simple but not easy

The model building discussed in 4.1 depends very much on the model builder and on the moment when the model is built. Thus there cannot be just one C&C-M of a Technical System but an unlimited number of models which distinguish themselves arbitrarily from each other. The only thing, that all these models have in common are the firmly laid-down principles in the fundamental hypotheses.

Thus according to the experiences of the author, the C&C-A is a very simple approach, but the building of a C&C-M by contrast is not easy. The application of the C&C-A is successful in the concrete individual case and this is always new and different. Mostly it has never cropped up before in that way or has never been experienced by the design engineer before in that way. Thus the principle can be simple, but its application in the concrete individual case can be extremely difficult. With the application of the Contact&Channel-Approaches not only must this be understood but many concrete details of the given situation as well. Thus with the building of the C&C-M it is not only a matter of the C&C-A, but it is also a matter of the talent of the model builder when it comes to integrating the relevant details of the given situation into the built model in an appropriate way.

4.4 Model building - experiences with C&C-A in industry

The author has been applying the C&C-A since 2003 in the industry and, starting in 2005, he introduced it in the product development of a new product range being built up of HILTI Corporation in Liechtenstein. There the C&C-A was employed above all to turn product profiles into products. In discussion with themselves or also in discussions in teams, design engineers built Contact&Channel-Models of the Technical Systems to be developed. These were decisive aids in analysis and synthesis with the engineering design of products. These products are so innovative that entry became possible into a market segment dominated by competitors, and a huge potential for growth could be made accessible. Just five years after starting the development of the new products it was possible to open up a stand-alone business unit.

Inside the company this innovation-success is also associated with the C&C-A, with the result that instruction in C&C-A for design engineers is planned throughout the company. The C&C-Approach has proved itself as a "thinking tool" in the industry!

The degree of acceptance varied very much from design engineer to design engineer. Some design engineers adopted the "thinking tool" quite naturally and put it to work. The majority of the design engineers however needed an acute emergency in order to open themselves up to the C&C-Approach. A very interesting question is: "How can the acceptance of the C&C-A as a 'thinking tool' be enhanced without the need of an emergency?"

Some C&C-Models built according to this approach have made an appreciable contribution to the innovation-success. They were able to depict what was essential for the question posed. Other C&C-Models did not reach the target. How can the building of successful models be supported further? Here is further great potential for scientific research!

4.5 Interim conclusion

Access to complex systems comes through appropriate model building, an abstraction with appropriate reduction of the complex to the essential. In order to be able to build a model a human being needs a meta-model, a model for building models. The meta-model must be "dynamically" applicable on various levels of abstraction in order to deal with complexity. The Contact&Channel-Approach presents a successful approach to building a meta-model on which dynamic model-building can be carried on according to a procedure which is always the same. The models which arise from this procedure are Contact&Channel-Models.

5 CONCLUDING REMARKS

Fulfilling the function in a cost-effective way - from the customer's point of view - is ultimately the main selling criterion of any product. Cost-effective function-fulfilment thus moves to the centre of the company's interest. The function that is relevant for the customer arises from the interactions between many individual functions which the individual component parts fulfil in interaction with each other and in interaction with the environment of the product.

The development of the product has the task of "materialising" the function in an embodiment. The design engineer lays down the embodiment of every component part. Thus engineering design becomes the pre-thinking and documenting of an "embodiment" which is set up to enable the function of the product. The thought process which leads to the embodiment is an iterative process involving analysis and synthesis. In this process function and embodiment must be discussed together. The design engineer must identify and build connections between function and embodiment.

An analysis precedes every synthesis in the development process. The new arises on the basis of an analysis.

A tool is required to support the thought process in the synthesis of the embodiment, a tool which supports the design engineer with analysis and synthesis alike and makes it easier for him to identify connections between function and embodiment. It must be possible for him to abstract in analysis and synthesis with the "thinking tool", to reduce the Technical System to what is essential for satisfying the problem posed and thus to make it graspable in an appropriate manner.

The Contact&Channel-Approach describes such a thinking tool. The author has experience of it in industrial use as an enormously helpful tool. The approach itself is very simple, but the application, the model building in a specific concrete case, is difficult. There is still much potential for further research into and support for model-building on the basis of the Contact&Channel-Approach.

The outcome of the engineering design process is an embodiment documentation in the form of a technical drawing. A particular thought process led to each measurement and to each tolerance shown in the Technical Drawing. Embodiment and function were discussed together in the head of the design engineer. The embodiment is documented in CAD and PDM systems and administered centrally. This is not the case for functions. Functions are almost not documented in industrial companies despite they are rated as important. Documenting the function in terms of its association with the relevant embodiment would make industrial product development more efficient and effective. The Contact&Channel-Approach can provide clues as to how the function can be associated with the embodiment.

Here is enormous potential for scientific research, too.

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