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THE IMPORTANCE OF THE INTEGRATION OF DESIGN METHODS IN ROBUST ENGINEERING DESIGN

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1 Introduction

Conceptual design is a very challenging and important stage of engineering design. Developing and selecting concepts of the future products implicitly determines its costs. In addition, the majority of product flaws are caused in the conceptual phase. In most cases they are detected late, during the production and use phases, and correcting them often demands much of the company divisions' time and energy, which in turn increases product costs. The faulty concepts, which remain unidentified and uncorrected during conceptual design, usually manifest themselves during production and/or use and can result in product malfunction or even failure, and accordingly increasing costs. Every product is developed to be as profitable as possible. Therefore, reaching a cost target is an important objective of product development. In making each decision in the product development process, it is important to consider the impact on the future costs of the product. Moreover, product flaws or faulty concepts can also be regarded in the sense of undesired behavior, like noise, vibration, or frictional heat. These undesired functions affect the product's performance and reliability. This hinders the requirement of robust design to ensure customer satisfaction, which is an essential part of integrated product development. The IPD approach starts with the understanding of customer needs and the management of requirements, considers the whole product life cycle, and leads to a continuous improvement of the design process, including the use of design methods [see for instance 6].

2 State of the Art

Although the efficiency and effectiveness of numerous product development methods has been proven, and the application of these methods in practice is increasing, methods have not represented an inherent part of product development processes up to now. A main reason for reserved method application is that users are often not able to select, adapt, and apply adequate methods independently [1]. Another fact is that new methods and new buzzwords (e.g. Design for Six Sigma) appear continuously. For practitioners in industry, it is difficult to keep track of the numerous existing methods. Several detailed and well-established collections and descriptions of methods already exist [e.g. 4 and 5] as well as an easy-to-use approach to obtaining a holistic overview [9]. However, for maximum assistance to engineers, the combination or integration of such an approach with specific method learning support and specific ways of method adaptation is essential.

Several methods aim at supporting the designer by anticipating product malfunction or failure during design in a systematic way and suggesting remedies and preventive measures. The most important are the analysis of former malfunction/failure cases, the Fault Tree Analysis, the Failure Mode and Effect Analysis (FMEA), the Hazard and Operability Studies (HazOpS) and the Anticipatory Failure Determination (AFD).

With the aid of the Fault Tree Analysis, designers can seek out the possible flaws or disturbances that would cause functional failure by negating the functions of the function structure one by one, i.e. by assuming that they are unfulfilled [2]. Failure Mode and Effect Analysis (FMEA) is a formalized, analytical method for the systematic identification of possible failures and the estimation of related effects. The main goal is to avoid or limit risks. Thereby, possible failures are determined together with their causes, consequences, risk factor, and test and remedial measures are suggested [2]. The technique Hazard and Operability Studies (HasOpS) is used for identifying potential hazards or operability problems caused by deviations from the design intent of new and existing process plants. The goal is to review the plant in a series of meetings, during which a multidisciplinary team methodically brainstorms the plant design. The success of HazOpS depends mainly on the completeness of the data used as a basis for the study, the technical skills and insights of the team and the ability of the team to use the approach as an aid to their imagination in visualizing deviations, causes and consequences [5]. The methods presented so far have in common that the process of failure prediction proceeds linearly from an articulation of the technical system's functions to what may occur if there is a failure or an absence in deliverance of these functions. The analytical line of logic follows the design intent. One drawback of the methods stems from the process used to determine failures which is essentially a brainstorming exercise, initiated by probing which failures might occur. Anticipatory Failure Determination (AFD) is a TRIZ-method with which the user can thoroughly analyze given failure mechanisms, obtain an exhaustive set of potential failure scenarios and develop inventive solutions to prevent, counteract, or minimize the impact of the failure scenarios. The approach to determining potential failures is the reverse of the one used in conventional approaches such as FMEA or HazOpS. The idea is to invent, cause and create failures [6].

The product price is a significant factor influencing the buying decision. Therefore, enterprises aspire to offer products with a favorable price/performance ratio. A methodology supporting the development of products with the requested characteristics concerning both functionality and costs is target costing [3]. Product development is a multidisciplinary process which involves several departments with different goals. To create products that meet the requirements, all departments have to cooperate and to adapt their objectives to a common goal. The less advanced the design process is, the more options exist to influence the final product costs [5]. In the early phases, only a few specifications are fixed. Therefore, it is hard to predict the effects of cost determinations. The product concept chosen is decisive for the final product costs. As the consequences are diffuse, the concept decision rests mainly on its capacity to realize functional requirements. Faulty concepts usually do not manifest themselves until product production and/or product use, and this can lead to product malfunction or even failure, and accordingly to increasing costs. Since the designers have difficulties assessing the effects of conceptual decisions on the final product costs, the opportunity to increase efficiency is often missed.

3 Objectives

The objective of this contribution is to present an approach for an integrated design process consisting of the adaptation of:

- a new tool for the selection of design methods,
- a procedure to impart design methods in practise,
- a new design method which prevents undesired functions from being induced during solution principle synthesis, and
- guidelines for a successful value engineering process with a focus on conceptual design.

The presented procedure demonstrates the need for different design methods for the creation of robust product concepts. The selection and application of adequate methods combined in an integrated design process is the premise for a successful product development process.

4 Methods

To give an overview of our approach, we derived a model representing the basic steps of integrating methods in engineering design (Figure 1). The process starts with a given design task (PROBLEM) and the requirements on the following product development process and on the product itself. The first process step is the METHOD SELECTION. In order to select the correct method, a tool adequate to the special conditions of the design process has to be chosen. For this purpose, we suggest using the so-called Landscape of Methods (LoM).

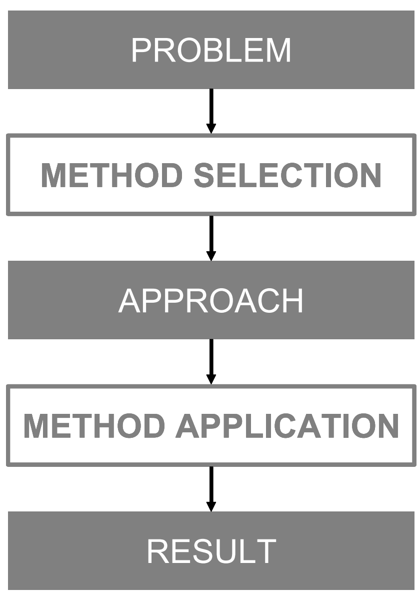

Figure 1. Procedure Model

The application of the METHOD SELECTION results in an APPROACH comprised of methods suited to fulfil the requirements of the particular development process.

To achieve the desired results, it is important to ensure the appropriate application of the approach. This demands that the designer have knowledge of method implementation. The imparting of methods is an integral part of the proposed APPROACH to ensure efficient results.

Provided with the practical know-how, the product designers can accomplish their tasks. The next step in the model is METHOD APPLICATION. The integrated application of known methods, chosen based on the requirements of a particular design process, facilitates the achievement of adequate RESULTS.

4.1 Clarification of the Task

As an example for the application of the model, we describe the original design process of a new injection-moulding machine. Injection moulding is a process with a high energy consumption rate implicating high operating costs. Significant requirements for the developed new type series are, besides processing needs and operational reliability, low power consumption and the achievement of a rigid cost target.

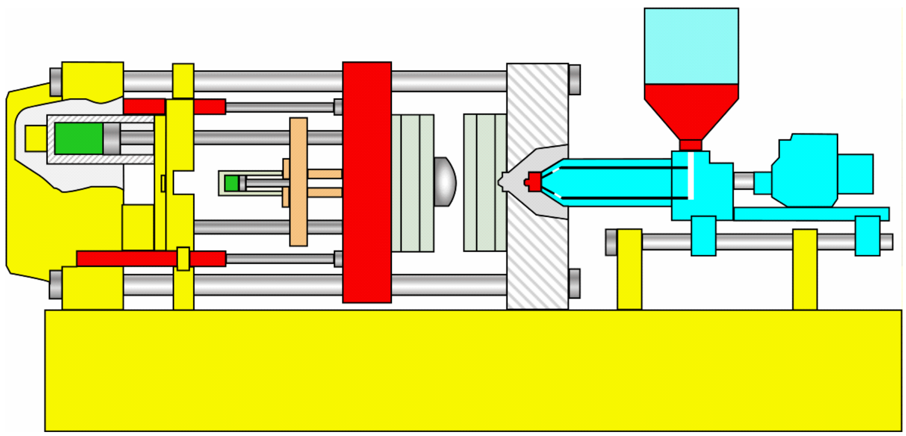

Figure 2. Schematic illustration of the injection moulding machine

A result of the analysis of the existing machine was the high dissipation loss in the moving systems, which causes high energy consumption. Since these components consume about 50% of the entire machine energy, the moving systems play a major role in the design of the new type series.

The clamping unit was identified as a system with a lot of potential to increase the efficiency of the production machine. The requirements for the enhancement of the design of the clamping unit form the basis for the example described of the procedure with the proposed model.

4.2 Method Selection

We used a method selection approach, which utilizes a Situation Questionnaire to identify appropriate methods. The basis for this method selection process builds a so-called Landscape of Methods (LoM), which is shown in Figure 3.

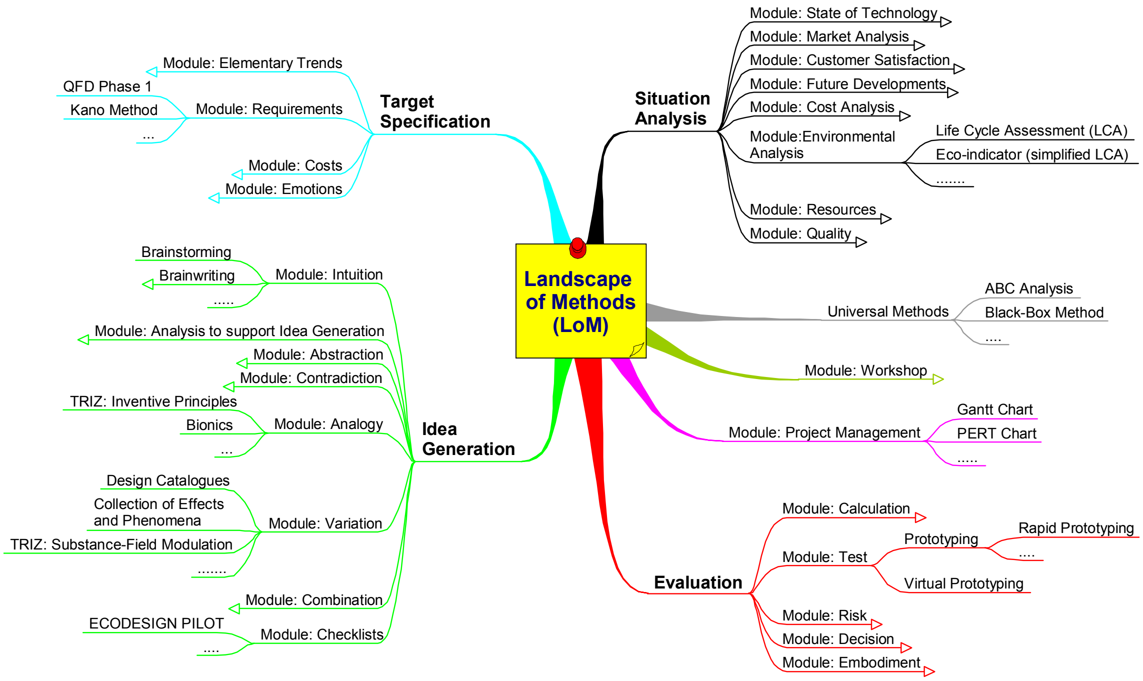

Figure 3. The Landscape of Methods (LoM) [9]

The first step in the selection is to determine the overall goals and to answer the related questions. Figure 4 shows the overall goals for the injection-moulding machine. In this case it is necessary to optimize the quality (e.g. low energy losses) and to reduce the costs. The overall goal *new product development* is answered with 'no' because this relates to products which are new to the market.

a	**New product development**	**no**
b	**Optimization of the quality**	**yes**
	Reduction of the development time	**no**
	Reduction of the costs	**yes**
	Reduction of the environmental impact of the product	**no**
c	**Increasing of the degree of innovation**	**yes**

Figure 4. Determination of the overall goals for the case study injection-moulding machine

In Figure 5 a small sample of the questions to be answered in the first step of the selection process is depicted.

	Questions for the increase of the degree of innovation	Answer
37	Is a conscious disengagement from past solutions considered, in order to prepare idea generation?	yes
38	Is a complex setting of tasks sufficiently clearly represented, in order to find a large variety of possible solution options?	no
39	Is it necessary to generate a rather large variety of ideas within short time?	no
40	Are new ideas to become lively by partially (at first sight) unusual suggestions?	yes

Figure 5. Part of the Situation Questionnaire for the case study injection-moulding machine

According to the answer concerning the different questions in the second step, a list of helpful methods is provided. Figure 6 shows the method list for the case study injection-moulding machine. In column 2 of Figure 6 the related “Standard Methods” are listed. In column 3 methods with minimum effort are listed. Column 4 shows the related “Expert Methods” like bionics.

A discussion within the project group leads finally to the methods to be performed. In this consideration all the boundary conditions, such as available manpower and other recourses have to be considered.

Module: Elementary Trends	Ideality	Black-Box	
Module: Costs			
	Target Costing		
Module: Analysis to Support Idea Generation	Functional Analysis		
Module: Abstraction	Progressive Abstraction		
Module: Analogy	Considerations of Different Analogies	Checklists for Bionics	Bionics
	TRIZ: Inventive Principles		

Figure 6. Second step of the method selection process for the case study injection-moulding machine

For the development of the new and improved injection-moulding machine, the methods Target Costing and Functional Analysis were chosen. After this selection, a Classification Form [see 9] delivers a short and concise description of these methods. Meanwhile more sophisticated versions of these methods are available [see 2 and 8] and this information is also included in that particular Classification Form. The results of using these forms will be shown in an integrated approach.

5 Integrated Imparting

The appropriate application of the selected methods is the premise for adequate results. Therefore, the designer needs knowledge of method implementation. The integrated imparting of methods is an integral part of the proposed model.

5.1 General benefit of the landscape of methods

Firstly, the designer should be seen as human with personal and cognitive inclinations. From this point of view, the landscape of methods has several beneficial aspects. The designer has personal and cognitive strengths and weaknesses, which have to be taken into account when setting up such a concept.

Generally, the landscape of methods supports the designer’s orientation and relieves his/her memory. S/he gets acquainted with the essential points of the design process and the overall goal, analyzes the design situation and obtains access to different types of descriptions.

The questionnaire stimulates designers’ thinking, regarding the design process, the context and designing itself. The suggested list of methods provided by the questionnaire increases the chances of choosing a suitable design method and minimizes the chance of hesitating in the process.

The feeling of certainty about the procedure is strengthened by discussions within the team. The discussion stimulates designers' thought processes and prevents missing important facts. Furthermore, the planning process is supported by the selection process of Figure 6. The provided list relieves the planning process and thus helps to leave nothing out.

Deliberating upon the descriptions of the design methods helps the designer remember the suitable design method and its content. It is very important to provide different types of descriptions for the same design methods. The types of description can vary from a very rough description that only includes the main functions of the design method and the structure to a sophisticated description that includes all aspects and possibilities of the methods.

These benefits make it obvious that the landscape of methods can serve as an integrated imparting concept in practice.

5.2 An integrated imparting concept

This chapter encompasses the functions of a simultaneous imparting of design methods in the design process. Above all, it will highlight the factors which need to be considered to create a practical concept in order to make the design methods effective and practical. The imparting of the chosen design method is an essential point to achieving a good result of the design process. Especially the imparting during the design process is of high relevance, one has to observe the designer's position in the design process, his/her problems and needs.

The designer's starting position in practice includes three main components with which the designer has to deal (see Figure 7): The stage of the design process with the overall target, the context and the pool of available design methods. The task of the designer is to identify the three components and match them in order to provide an efficient action [10]. In order to successfully fulfil these tasks the designer has to dispose of a well-founded knowledge about the design method.

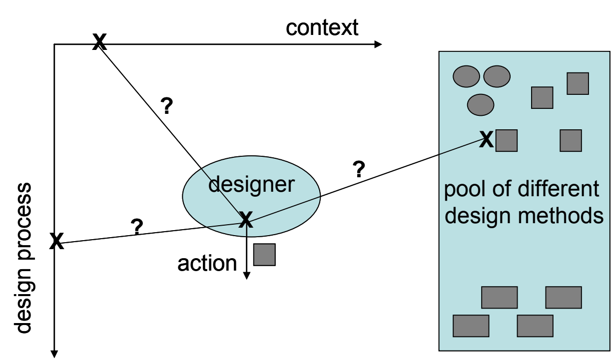

Figure 7. Designer's starting position

One cannot expect that designers dispose of a sophisticated knowledge about all design methods. So, a designer can choose a description according to his/her level of knowledge about design methods.

An integrated imparting concept based on the landscape of design methods have to provide the matching process and the successful application of the design method. The landscape of design methods can provide these requirements with the questionnaires and descriptions of design methods.

Of course, the levels of descriptions cannot be adapted to everybody's individual level of knowledge. A sensible amount of descriptions might be three.

The first description level might meet the requirements of designers, who know the method and already have experience applying the design methods. The second description level might provide information about the design method for designers who know the design method, but do not have experience in their application. The third and sophisticated level of descriptions should include information for designers who neither have knowledge of design methods nor experience applying them. Naturally, the different levels of detail also make it possible to choose different types of descriptions in compliance with the available timeframe and personal interests.

Furthermore, the descriptions must conform to the natural human thought process and memory. It is important to expand one's knowledge with a well-structured description and a clear and consistent terminology.

A very important aspect of the Landscape of Methods is the integration in the practical development process. It is crucial to see the design method in relationship to the practical process. Design methods only make sense in the context and application. Thus, a useful application of the design method is provided by an integrated imparting.

The landscape of methods as an integrated imparting concept of design methods helps to overcome the typical problems when designing and applying design methods (see Figure 8). The questions regarding the context, the design process, the personal prerequisites and the questions concerning the innovation and completeness provide an adequate assessment of the context, an identification of the design stages and the overall goal and thus a suitable selection of the method. In addition, the designer has the chance to choose a description of the selected design method in compliance with his/her personal prerequisites, timeframe and interests.

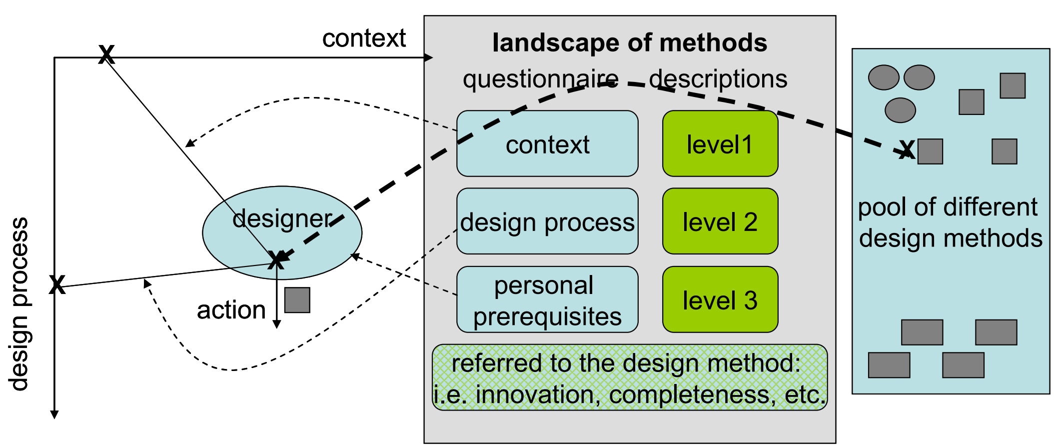

Figure 8. Integrated imparting of design methods in practice

With the benefit of the landscape of methods the designer is in a more appropriate starting position to fulfil the demanded requirements of a design situation. Particularly, the aspect of integration and the stimulation of thinking up such an imparting concept provide for a better design quality and thus, better results, especially in the early phases of design.

6 Method Application

The application of the chosen methods depends on the designers' personalities and experiences, and the quality of the imparting process. The model presented focuses on the proper selection and adapted imparting of the design methods. The application of the chosen methods Functional Analysis and Target Costing for the development of the clamping unit of the injection moulding machine are described in this chapter.

6.1 Identifying and Processing Undesired Functions

During conceptual design, the intended product functions are fulfilled by selecting the appropriate solution principles. In general, and as a result of inherent properties, solution principles perform other functions besides those for which they were selected. Analyses of various types of solution principles showed that undesired functions induced during solution principle synthesis can manifest themselves as disturbing factors either by reducing the input of an intended sub-function or by producing an undesired output.

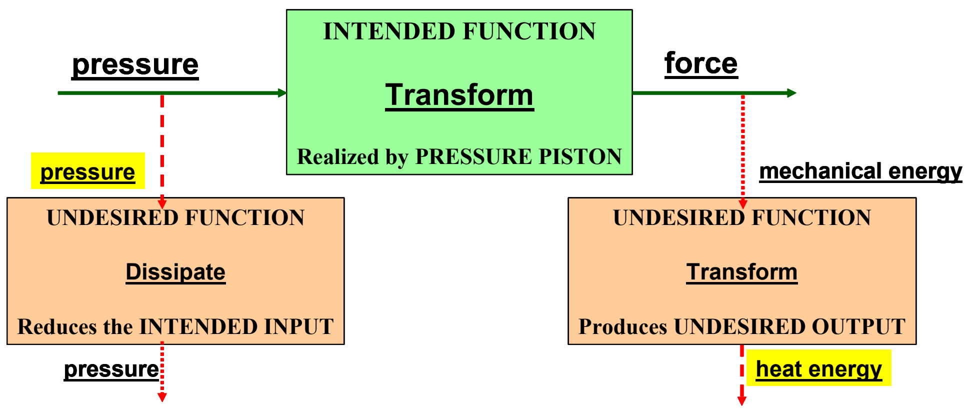

Figure 9. Identifying Undesired Functions During Conceptual Design

For example, to fulfil the intended sub-function *transform pressure into force*, the solution principle pressure piston is selected. The analysis of the pressure piston revealed the inherent properties friction between piston and cylinder and pressure loss, from which the undesired functions *transform mechanical energy into heat* (which produces an undesired output), and *dissipate pressure* (which reduces the intended input) can be abstracted.

The disturbing impact of undesired functions on the product itself can often be reduced to a tolerable measure or eliminated by changing the internal product environment, either by rearranging it or by replacing the disturbance and/or the disturbed component. The external product environment, however, is not as easy to modify. Figure 10 depicts the different types of counteractive measures, which can be employed to process undesired functions with disturbing impacts on the product and / or on its environment.

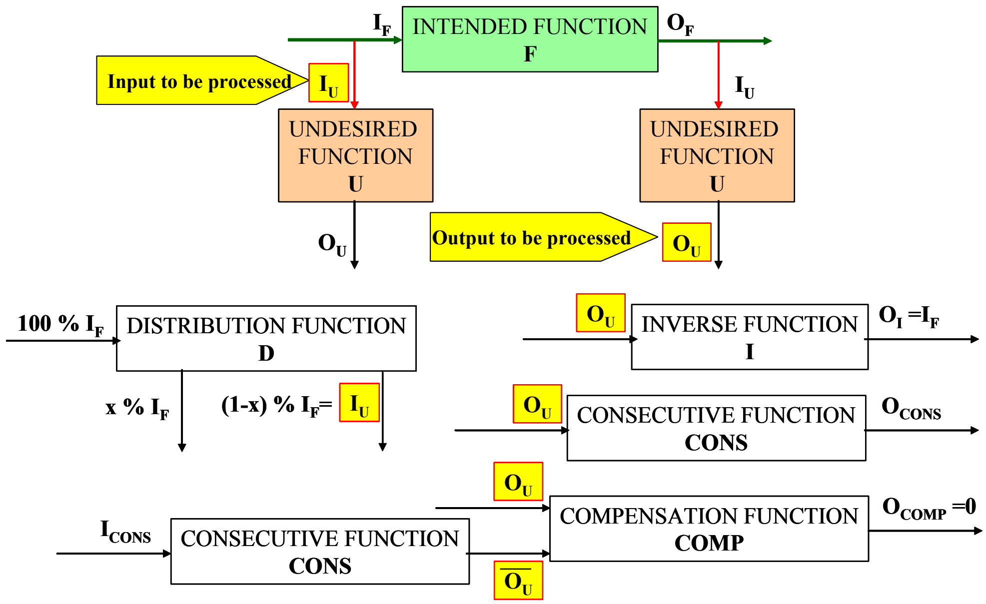

Figure 10. Processing Undesired Function

The method for processing the undesired functions induced during conceptual design is selected according to the requirements of the product to be designed. Hereby, the factor cost plays an important role.

6.2 Target Costing

The costs of a product could also be seen as an undesired product function. It is a fact that this inevitable characteristic varies with the product concept. Therefore, it is very important to evaluate the consequences of determinations on product costs in the conceptual stage of design. As the product costs are an important factor of the design of the new injection moulding type series, the method target costing was chosen applying the landscape of methods.

The first steps of target costing, determining a target price and setting a target cost, were accomplished with the definition of the requirements of the clamping unit. The value engineering process is an integral part of the product development process. The product costs are closely connected with engineering decisions of the designers. A close multidisciplinary cooperation in product development facilitates the achieving of competitive cost targets.

The value engineering process starts with an overall cost target for the clamping unit, which is divided into partial targets for the product components. The defined values are listed in a cost control file, to which all designers working on the product development process have access. Parallel to the development of a product, the results of available cost prognoses of all components are stored there. Having all cost prognoses contained in one file enables the visualization of the actual achievement of the cost targets during the value engineering process.

Figure 11 shows the development of costs in the course of conceptual design. Whenever a decision must be made, the effects on the costs of optional alternatives have to be evaluated. The results support the choice of the most favorable design alternative. If concepts have been chosen, where the undesired functions become evident later in the process, the branch breaks off. The designers can resume proceedings from an earlier point in the determination stadium.

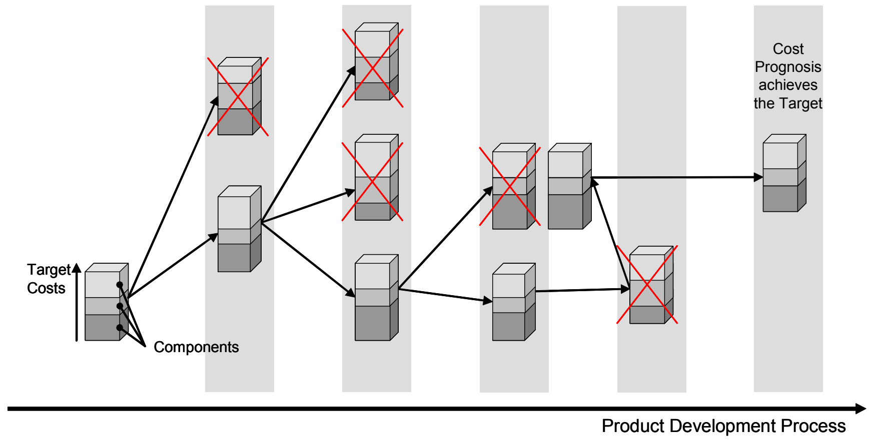

Figure 11. Decision-making during product development

In the conceptual phase, parallel to the introduced method for identifying and processing undesired functions, engineers consider and analyze many building and/or operational principles that could fulfil the intended functions. For every optional solution principle that could lead to optimal product costs, cost evaluations have to be carried out. Applying the proposed guideline, the employees document the results. Thus, the considerations can be integrated into the later design and detailing process. Shared access to the documented data provides the basis for the intensive cooperation of all product development workers. In decision situations, cost evaluations are performed. Thus, the designer is able to analyze the effects of his or her decisions. Following relevant design steps, the results of cost prognoses are recorded in the cost control file. In the case of presumed increased product costs, this file serves to identify the development step that led to the deviation. Suitable measures can be introduced dependent on the reasons for the initial decision. If this is not possible, an adaptation of the subdivision of the cost targets may be reasonable. A cost control file offers helpful support for the observation of the value engineering process for the whole product.

6.3 Case study results

By applying the model of the approach, it was possible to enhance the clamping unit of the new type series for an injection-moulding machine. A sophisticated value engineering process accompanied the new design of the hydraulic cylinder. The proper choice and adaptation of the design methods using the Landscape of Methods and an integrated imparting concept supported the designer in applying the methods for identifying and processing undesired functions and target costing.

With the proper use of the design method, the undesired product function friction could be reduced. This enables a decrease of the energy consumption rate of about nine per cent in the clamping unit. Parallel to the engineering process, prognoses of the product costs were accomplished in every cost-effecting decision situation. Thus, the continuous cost control led to the design of a clamping unit which met the cost target.

7 Conclusions

Product development integrates various disciplines towards a common goal. Because of the variation of requirements on the product as well as on the design process, the application of different design methods is essential. Due to the fact that the design process workers have different experiences and the objectives of the developed products vary, it is necessary to select and apply adequate methods adapted to the special design problem. This applies in particular to robust engineering design.

According to Figure 1 our integrated procedure starts after the problem and task identification with an easy-to-use assistance for method selection leading the way for the imparting of sophisticated versions of standard design methods in practise.

An integrated imparting of design methods in practise supports the application of design methods in an efficient way. The integration of context, stage of process and thinking aspects provide more benefits than the pure imparting of knowledge about the design method. This concept of Landscape of Methods with the consideration of teaching aspects provides a comprehensive approach to introducing design methods in practice with a high use and acceptance rate.

The integrated application of the methods for identifying and processing undesired product functions and an adapted value engineering process in the sense of target costing has proven its practicability. The proper use of methods due to the integrated imparting led to respectable results. The case study which started with high goals shows that an integrated use of suitable methods facilitates the development of robust products.

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