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THE SYSTEMATIC EVALUATION OF DIFFERENT APPROACHES IN MODELLING FUNCTIONS TO ACHIEVE SUCCESS-ORIENTED DESIGN OF ENGINEERING PRODUCTS

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Abstract

To achieve success-oriented design, one must be able to compare cost and benefit for the whole product and for individual product elements. The role played by function modelling will be of great importance to this comparison. Only in respect of the functions of the product can the cost and benefit be represented simultaneously and thus render direct comparisons possible. A number of approaches to assist in the modelling of product functions are described in the literature on value analysis and design method. This paper assembles these approaches into a systematic scheme, examining how (and whether) they can support success-oriented design. A rough evaluation of the various approaches is first made, and those which prove suitable are put to exemplary use on a transformer. Then a fine evaluation, which includes a score model, provides more detail on the evaluation scheme, so that the approaches investigated can be given a rank order.

Keywords: functional modelling, function costs, cost-oriented design, value engineering

1. Elements of success-oriented design

It is obviously the goal of all engineering design to produce a successful product. Success can be measured in comparing the turnover (price multiplied by quantity sold) with the costs generated for the company by this turnover (see Figure 1). To analyse and predict product success, representative figures will be required for the inputs and outputs of the production process – i.e., not only for the generation of the goods but also for their consumption (see also [11, p. 1]). In the engineering design context, it is then a question of how best to influence each of the figures (that for the turnover and that for the cost of the turnover, which are both success factors) so as to improve the product's eventual success. It is possible to change the turnover for the product, i.e. item price and quantity sold, by modifying the product benefit and/or the turnover costs (the latter by modifying the consumption of resources).

The goal of success-oriented design of a product can thus be described as "improvement of product benefit and reduction of resource consumption". To bring this down to operational level in engineering design, it is necessary to break down the goals into targets for individual elements of the product – the components or the functions, for instance. If one takes the components, it is easy to get a representative figure for the costs but not for the benefits. That leaves the functions as the only factors susceptible to demonstration of both costs and benefits. The functions are thus of central importance in configuring a product for maximum success (see Figure 1). The benefit which a product owes to its functions will relate to the market segment the product is designed for, and Conjoint Analysis is one way of estimating it.. Function costs, on the other hand, have to be obtained from the company where the product is produced. The costs are usually generated by the components the product consists of. Different approaches for the calculation of component costs are explained in [3]. From the components, the costs can be allocated to the functions [9, 10, 12].

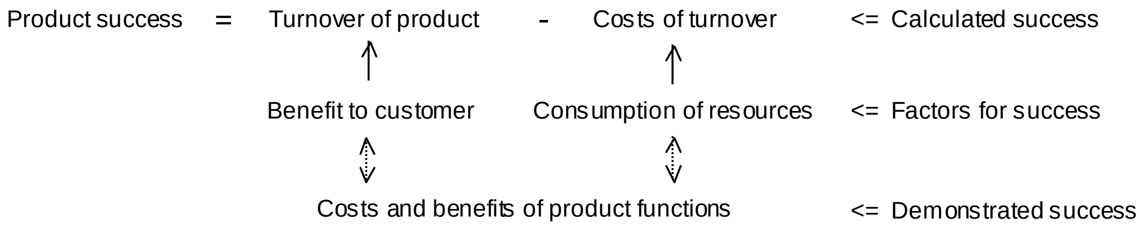


Figure 1. Functions and their importance for success-oriented product configuration.

Cost-oriented engineering design, which is to be seen as part of success-oriented design, is at heart a cost-oriented selection of alternatives (see also [11, p. 2]). The product with the minimum costs will be the one likely to cost least by virtue of the choices made for it out of a given array of design options.

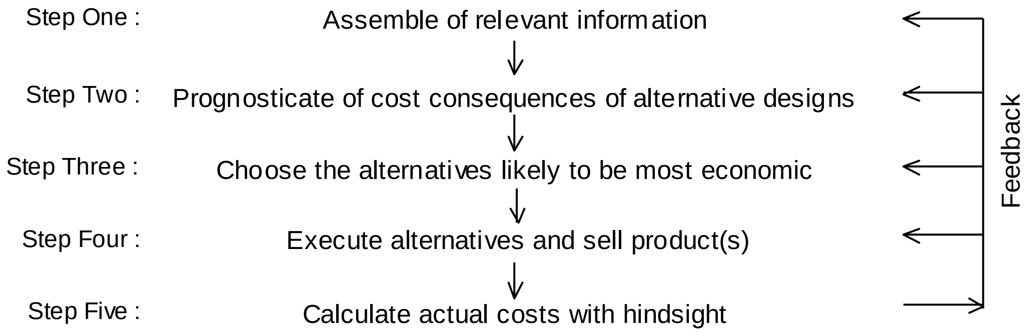


Figure 2. Procedure in cost-oriented engineering design.

There are five steps in the procedure for cost-oriented design (see Figure 2). Step Three is the really vital part of cost-oriented design. This is when the choice is made of the design alternative thought likely to be the most economical – which is a direct decision about which consumables are in future likely to be most in shortage. Step Two is a prognosis of the costs likely to be generated by the various alternative designs assembled. Step One is to assemble the information both available and relevant to the decision-making process. This information will include not only standard manufacturing costs but also details of life-cycle considerations already necessary to take into account. Once the choice has been fallen on one alternative, the product can be turned from an idea in to reality and then sold (Step Four). With hindsight (Step Five) the costs actually generated are recorded and can then serve as a foundation for further decision-making.

The evaluation of functional models to achieve success-oriented design appears as the core of the paper. The following questions are being discussed in the next chapters:

- How and with what methods can a functional model being evaluated?
- What criteria should be involved with the evaluation?
- Can the existing functional models being ranked according to their usability to achieve success-oriented design of engineering products?

The different functional models applied in the paper are supposed to be seen as examples. Other models, might be found in theory and practice, are invited to be subject of further evaluations. The core of the paper is the idea to evaluated functional models in order to select the one with the maximum usability to achieve success-oriented design. An evaluation like this can also be the starting point for the development of rather sophisticated functional models.

Chapter two of the paper presents a general (abstract) scheme of stages in modelling functions. This scheme, if applied to functional models, gives a fingerprint of the different approaches. A rough evaluation using a checklist is given in chapter three. The goal of the chapter is to check, whether the approach meets the fundamental requirements of cost-oriented design. The functional models, which have passed the rough evaluation, are being applied at a product (transformer) in chapter four. Last but not least the main criteria are structured and a score model are applied to give a more detailed evaluation (see Chapter Five).

2. General scheme of stages in modelling of functions

A number of approaches to the modelling of product functions is presented by various authors in the literature on value analysis and design method. Among the most significant are the approaches of Ehrlenspiel [3], Koller [5], Pahl/Beitz [6], Rodenacker [7], Roth [8] and the FAST (Function Analysis System Technique) diagram and the "function tree" found in the value analysis field [2]. The present authors have analysed these and drawn them up into a general, abstract scheme of stages for the modelling of functions (see Figure 3).

What unites or differentiates the approaches is revealed by the form the approach takes at each step. On analysis, they have specific characteristics, such as the scope of the information at Step One or the manner in which the function is described at Step Two or the way in which various functions are combined at Step Three. As these characteristics and how they affect the method are a sort of fingerprint for a particular approach, many well-known approaches can be presented in the system.

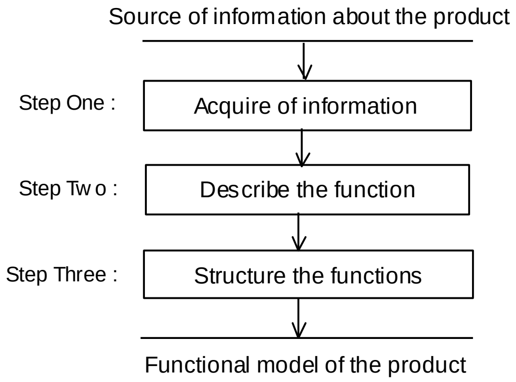


Figure 3. General scheme of stages in modelling of functions.

3. Rough evaluation using checklist

The rough evaluation of the function modelling in the various approaches is best done with a checklist. This method enables as many factors relevant to a decision to be assembled as possible, so that the analysis of the problem can be correspondingly systematic. In the use of a checklist there will normally be two steps. First the list has to be constructed to include all aspects of relevance to the decision. At the second stage the problem has to be rated by experts on all the criteria included in the list [1, S. 407].

To evaluate the function modelling approaches mentioned above, a checklist can be used with a minimum of two criteria, firstly whether the approach admits of recording and evaluating the benefit to the customer, and, secondly, whether it permits the use of resources to be shown in relation to the functions. Each of these criteria can be formulated as a direct question:

1. Is it possible to record and evaluate the benefit of the product to the customer with the aid of the function model?
2. Does it offer the possibility of allocating use of resources (costs) attributable to the product to be shown in relation to the individual functions?

Ehrlenspiel's method of function analysis is top-down: it starts with the whole product and divides it up into a function structure. The overall function of the product is described as an operation with relations, by means of a starting state and a resulting state of the "operator". The relations are those between the two states and the operation (see figure 5). An "operator" is either a sort of material, a signal or a form of energy, on which the operation is performed. By dividing up the overall function into less complex partial functions, a interlinked structure of functions is produced in which the outcome state of one partial function can be interpreted as the outset state of another function. This function structure makes it possible to produce data on the objective benefit of the product but not its subjective benefit. In principle it seems possible to allocate product costs to functions but the fact that they are so much interlinked makes clear allocation rather difficult.

In Koller's work the functions are derived from the purpose of the engineering product. Thereafter the overall function is subdivided into function elements down to the level at which it can be no further broken down. These "element functions", formulated in the abstract and standardised, are derived from basic physical operations using forms of energy, types of material and signals. Such elemental functions have hardly any usefulness in the representation of customer benefit; the abstraction of the formulation is a factor with the same effect for allocation of real cost details.

Function analysis according to Pahl/Beitz begins by determining the tasks performed by the structural elements, such as the components and individual parts. These tasks are then the basis of the description of the simple (at first) (sub)functions using a noun and a verb. The (sub)functions are linked by means of a flow of materials and signals and energy. Abstraction permits the (sub)functions to be subsumed into an overall function. As the Pahl/Beitz approach starts with the individual part and proceeds to the whole, it can be designated as bottom-up. However, as in the case of Ehrlenspiel, only the objective benefit of the product can be recorded. In principle, the allocation of costs to functions appears possible.

Rodenacker describes a synthesis of functions which starts with the basic problem to be solved. From this is derived the product's overall function, which first divides up into a tripartite structure of basic logical functions: "Link", "Separate" and "Lead". Then the partial functions and the technical principles can be allocated to these three basic functions. The division into three basic logical functions suggests that this function structure is inappropriate to the registering and evaluating of the benefit to the customer. All the same, it would, in principle, be possible to allocate the costs to the functions.

In Roth's method, the overall function is analysed on the basis of the demands to be put upon the product. The overall function is divided into less complex partial functions and these are, in turn, linked into a net-like function structure by flow values. To find the optimum solution, the individual partial functions are each replaced by one of 30 abstract function formulations, for which solutions in principle have been worked out and catalogued. The functions being abstract formulations, they are suitable neither for calculation of individual costs nor for the determination of the benefit to the customer.

The function tree in value analysis is created on the basis of the construction itself. First the functions of the elements of the structure are described using a noun and a verb and then linked logically either by Purpose/Means or How/Why – which gives a hierarchical structure. Within the function tree, functions can be organised according to various criteria: the benefit they are intended to bring, their degree of importance, and level they occupy in the hierarchy. This way of modelling functions allows both subjective and objective benefit to be expressed and also costs to be apportioned (by varying the complexity, a facility offered in this method).

Table 1. Rough evaluation of each approach in modelling function, using checklist.

Approach	**Criterion 1: “Benefit”**	**Criterion 2: “Cost”**
1. Ehrlenspiel	Yes (though limited)	Yes (though limited)
2. Koller	No	No
3. Pahl/Beitz	Yes (though limited)	Yes
4. Rodenacker	No	Yes
5. Roth	No	No
6. Function tree (value analysis)	Yes	Yes
7. FAST diagram (value analysis)	Yes	Yes (though limited)

The FAST diagram is created from an analysis not only of the product specifications but also of the construction. The functions derived from the construction are described by a noun and a verb. A logical path is laid between the higher function which describes the purpose of the product and those functions which are accepted as fulfilling the conditions predetermined as necessary to the overall purpose. On the logical function path, the basic function is set, as are the partial functions necessary to the performance of that basic function. It is possible to complement the logical path with parallel functions and also with “undesired” functions. This is another approach which permits customer benefit to be fully taken into account. The allocation of costs presents rather more of a problem as the complexity is only variable to a limited extent.

The rough analysis of the various methods is summarised in Table 1. If either of the two criteria for assumption of the approach into the test is not fulfilled, that approach is ignored from now on. The remainder are tested in the next stage on production of an electricity transformer, and subjected to detailed evaluation with a score model.

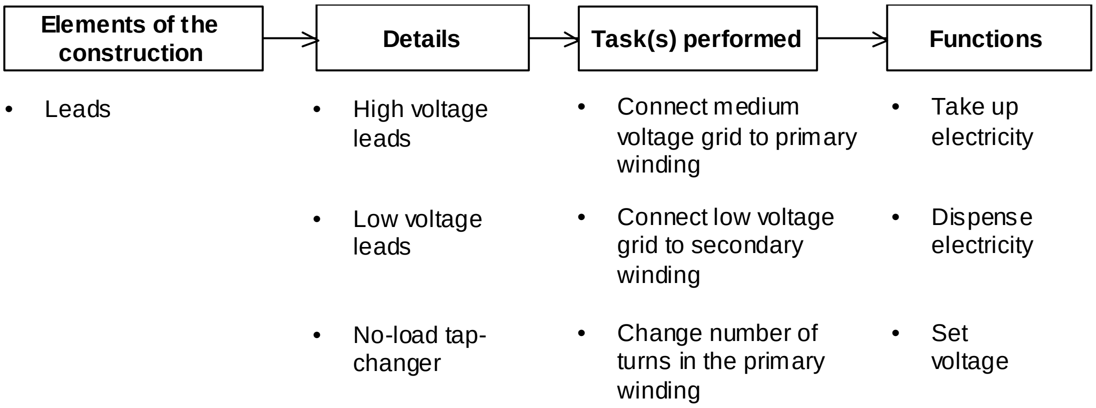
4. Use with a transformer as example

The four selected approaches to function modelling were applied in the transformers department of WEG Indústrias S.A., Blumenau, Santa Catarina, Brazil. The company WEG has not yet used any functional models in the design process. The attempts at modelling were carried out as the project of a student from the Department of Production and Operations

Management of Ilmenau Technical University in Germany which was to lead the “Diplom” (equivalent to Master’s).

The subject of the present investigation was a distribution transformer which turns 13.8 kV into 220 V or 127 V with apparent-power of 75 kVA. Such a transformer, for use in the setting of urban electricity distribution, is the product to which the four function modelling approaches selected in the rough evaluation are applied for exemplary purposes.

In Step One of the general scheme of stages in modelling functions, the information-gathering stage (see chapter 2), the construction, the costs structure, the customer requirements (in the form of the technical specifications) and the manufacturing process were analysed. Differences were found between the approaches because they embraced different things under the concept of a “function”. In value analysis, functions are all effects a technical product or its component parts has or have. The effects will include subjective ones, such as social kudos or aesthetics, as well as the objective ones necessary for the product to function technically in use. In addition, the effects include those exerted over the entire lifetime of the product. For these reasons it is necessary before creating the function tree and the FAST diagram to collect details of more than simply the construction – information is also required on the manufacture, the intended installation, the potential use and the eventual disposal. For the design methodology approaches, information on technical customer specifications and on the construction is sufficient.



Elements of the construction	Details	Task(s) performed	Functions
• Leads	• High voltage leads	• Connect medium voltage grid to primary winding	• Take up electricity
	• Low voltage leads	• Connect low voltage grid to secondary winding	• Dispense electricity
	• No-load tap-changer	• Change number of turns in the primary winding	• Set voltage

Figure 4. Example of how functions are derived from elements of the construction.

The bottom-up approach will start the analysis with details of (for example) the core, the windings, the supporting structure, the leads, the tank, the insulation oil and the bushings. From the tasks performed by these components, the functions can be described with a noun and a verb. The “leads” example given in Figure 4 shows how the functions can be derived from the details of the construction of these component parts and the tasks they have to perform.

The no-load tap changer, for instance, as a detail of the leads, has the role of altering the effective number of turns within which the switch-over takes place between taps on the high voltage winding. The result is that the same lower voltage is always taken up despite variations in the higher voltage system.

The different concept conveyed by function in value analysis as compared with design method means the two types of approach vary not only at Step One but also at Step Two, in the function description. In all four approaches, the technical functions are usually described by noun and verb and represented in a sort of Black Box (see figure 5). These descriptions can be complemented with features and characterisations of features to make them more concrete.

The non-technical functions, of equal importance to the customer benefit (for example, social kudos and aesthetics) are not adequately covered by the way design method models functions. In value analysis, however, they are shown as soft functions and described with features and characterisations of features.

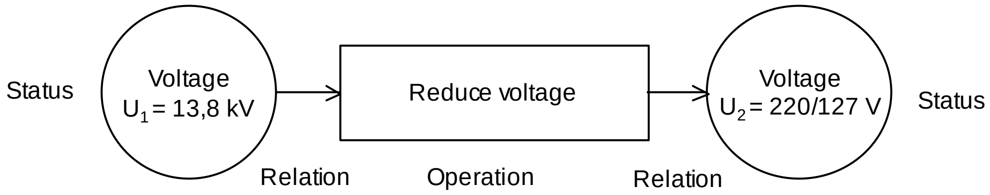


Figure 5. Description of a transformer’s technical function.

In Step Three of the general scheme offered above for modelling of functions, the latter are linked into a network according to defined structuring rules, or set out as a hierarchy. How the functions are linked in the FAST diagram is shown for the transformer.

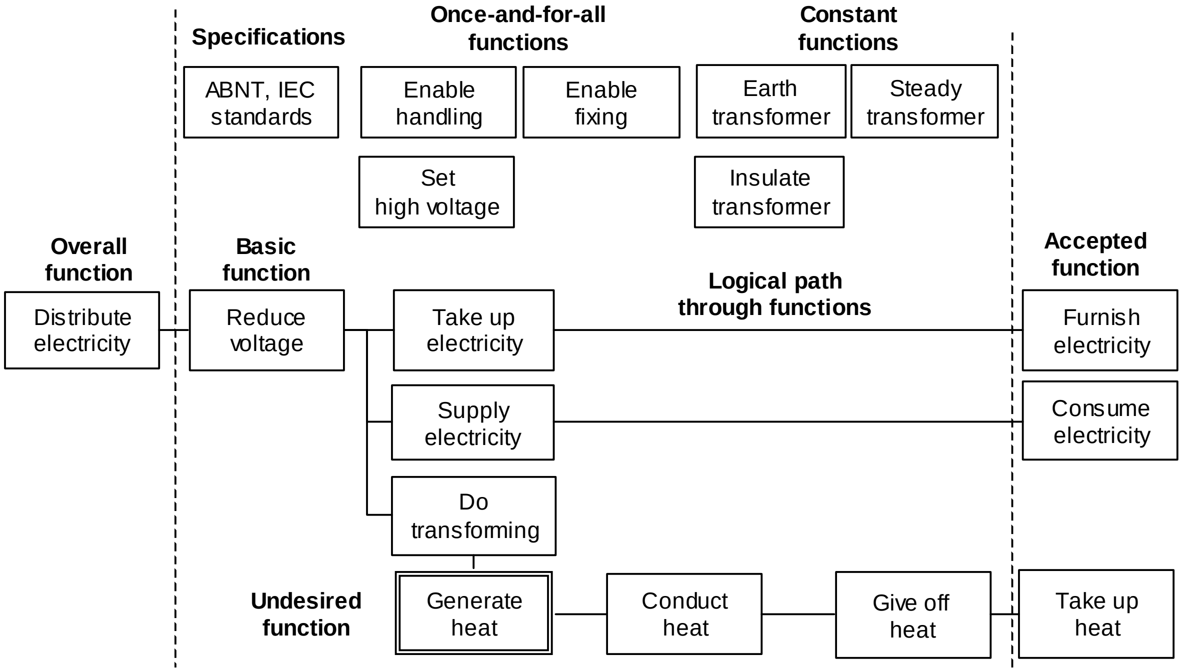


Figure 6. FAST (Function Analysis System Technique) diagram for the transformer.

The starting point for the logical path on which the functions are organised is, in this example, the overall function of “distributing electricity”. To distribute electricity economically it is necessary to reduce voltage, and that is the reason of the transformer – its basic function. To carry out the transforming – i.e. the reduction of the voltage – the electricity has to be first received and then sent on again. The receiving can only take place if electricity is furnished, and the sending on can only take place if electricity is being taken up for consumption. Losses arise during the transforming process: what is lost is heat, which is initially conducted by the insulation oil to the surfaces of the transformer and then radiated into the environment. These three functions, the furnishing of electricity, the sending on of electricity and the giving off of heat, are thus “accepted” functions (see Figure 6).

The basic function, “Reduce Voltage”, cannot be fulfilled without the fulfilment of certain once-and-for-all functions and other constantly performed functions. Here the once-and-for-all functions basically relate to installation and commissioning of the transformer. There are also functions which, though not essential to the basic functioning, are still necessary - for instance the requirement that international and/or national standards are conformed to.

5. Detailed evaluation with a score model

A score model is a formalised procedure to assist with decision-making by choosing between alternatives. The decision in question can be made to meet a multidimensional system of goals. The method allocates scores to the alternatives and these scores represent the contribution of the alternative to the achievement of the goals. Value judgements are the criteria for the scores, which are a numerical expression of how strongly the particular alternative is to be preferred [1, S. 412].

The principle in Equation 1 is effectively a simplified form of a score model. B_i is the benefit from alternative *i*. S_{ij} stands for the score achieved by alternative *i* on criterion *j*, and W_j is the weight given to the criterion. The benefit score B_i is then the sum of the weighted scores. The score model can proceed formally through five stages as follows: (1) Formulate criteria, (2) Derive weighting for criteria, (3) Set features of criteria, (4) Score the alternatives, (5) Calculate the benefit scores and rank them.

$$B_i = \sum_{j=1}^{J} W_j \cdot S_{ij} \tag{1}$$

The criteria are defined in the first stage. The two main criteria used for the rough evaluation, “Cost” and “Benefit” must now be subdivided into a system of goals. Criterion no. 1, “Cost”, can be split up into three sub-criteria: 1.1 “Possibility of varying the abstraction”, 1.2 “Possibility of registering the subjective benefit”, and 1.3 “Possibility of registering the objective benefit”. The varying of the abstraction is necessary to control the number of functions to be integrated into the enquiry and the customer understanding for them. It is, namely, necessary to restrict the number of functions to about ten when analysing preferences by Conjoint Analysis. As the benefit of a product is seen not only in its technical performance but also in the social status it endows or aesthetics it possesses, it is important for the function model to enable the analyser to measure subjective as well as objective benefit (see Table 2).

In like manner to the first, the second main criterion must also be subdivided into partial criteria: 2.1 “Possibility of varying the complexity”, and 2.2 “Possibility of generating alternative designs” (see Table 2). Varying the complexity makes sense as a means of influencing the relationships between the components which generate costs and the functions to which the costs need to be allocated if function costs are to be determined. It is, furthermore, a necessity to generate a choice of construction options in respect of any function: only thus will the mechanics of cost-oriented engineering design function properly, so that the option with the best costs for the purpose can be selected. The degree of abstraction in the function description is critical to the generation of options with favourable costs. It is not possible to generate any alternatives at all without a high enough degree of abstraction.

As the purpose, having applied the approaches at WEG to the transformer by way of example, is to complement the rough evaluation with an analysis of how usable they are, a third main criterion is added in this case: “Usability”, with the sub-criteria 3.1 “Information”, 3.2 “Description” and “Structuring”. These sub-criteria reflect the steps in the general scheme here offered for the modelling of functions (see chapter 2). The respective factors (scope of the information, number of functions to be formulated and type of link between the functions) are thus deciding factors in respect of the use of the approach in the function modelling.

Table 2. The approaches ranked according to the score model.

Criterion		WeightingW_j in %		**Ehrlenspiel**		**FAST**		**Function tree**		**Pahl/Beitz**	
1	**Benefit**	W_1	30	S_{1j}	$S_{1j} \cdot W_j$	S_{2j}	$S_{2j} \cdot W_j$	S_{3j}	$S_{3j} \cdot W_j$	S_{4j}	$S_{4j} \cdot W_j$
1.1	Abstraction	$W_{1.1}$	10	6	60	7	70	9	90	6	60
1.2	Subj. benefit	$W_{1.2}$	10	5	50	9	90	10	100	1	10
1.3	Obj. benefit	$W_{1.3}$	10	5	50	10	100	10	100	5	50
2	**Costs**	W_2	40								
2.1	Complexity	$W_{2.1}$	20	3	60	5	100	5	100	7	140
2.2	Abstraction	$W_{2.2}$	20	4	80	8	160	6	120	4	80
3	**Usability**	W_3	30								
3.1	Information	$W_{3.1}$	10	5	50	3	30	3	30	7	70
3.2	Description	$W_{3.2}$	10	4	40	7	70	6	60	8	80
3.3	Structuring	$W_{3.3}$	10	8	80	7	70	5	50	9	50
		Ben. score		B_1	470	B_2	690	B_3	650	B_4	540
		Rank order		4		1		2		3	

In the second stage of the score model the individual criteria are weighted to reflect their significance for cost-oriented design. It should be experts who assess the importance of the main and partial criteria. Major importance is bound to be attributed to the main criterion of “Costs”, as the focus is on finding alternatives at a favourable cost (see Table 2). So that the third stage can proceed, establishing characteristics for the criteria, information must be supplied so that the characteristics can be set up for the individual criteria. These characteristics must be so defined that they can be scored in stage four. This study provides for allocation of between 1 (very poor) and 10 (very good) scores. The fifth and last stage involves calculating the benefit score for the various alternatives by substitution in Equation 1 and achieving a rank order (see Table 2).

Transparency and reproducibility can be achieved by evaluating the functional models with a score model. The evaluation will be influenced by three parameters in particular: the definition, the weighting and the scoring of the criteria. As the criteria themselves are derived from the needs of success-oriented design, the weightings should reflect the importance of the criteria for the success-oriented design process. Also, the scores should be connected closely to specific characteristics of the functional models. These three parameters, as set by the authors, can on the one hand be used to adjust the evaluation to different situations. On the other hand, their characteristics will reflect the opinions of the engineers who have done the evaluation.

6. Conclusion

This paper presents function modelling as a means to the end of success-oriented design for engineered products. It demonstrates that success-oriented engineering design makes special demands on the modelling of functions, namely the requirements i) that the benefit to the customer must be recorded and ii) that the costs musts be allocated to the functions. Assessed against these criteria, certain well-known function modelling approaches appear well suited – an example is the function tree of value analysis – and others, such as Koller's element functions, less well suited. Furthermore, conclusions can be drawn, particularly from the fine evaluation, on how function modelling might be honed as an instrument of success-oriented engineering design.

References

[1] Adam D., „Planung und Entscheidung“, 4. Edition, Wiesbaden, 1996.

[2] Akiyama K., „Funktionenanalyse – Der Schlüssel zu erfolgreichen Produkten und Dienstleistungen”, Landsberg/Lech, 1994.

[3] Ehrlenspiel K., “Integrierte Produktentwicklung“, 2. Edition, München, 2003.

[4] Ehrlenspiel K., Kiewert A. and Lindemann U., „Kostengünstig Entwickeln und Konstruieren“, 4. Edition, Berlin, 2003.

[5] Koller R., „Konstruktionslehre für den Maschinenbau“, 4. Edition, Berlin, 1998.

[6] Pahl G. and Beitz W., „Engineering Design – A Systematic Approach“, 2. Edition, London, 1996.

[7] Rodenacker W.G., „Methodisches Konstruieren“, 4. Edition, Berlin, 1991.

[8] Roth K., „Konstruieren mit Konstruktionskatalogen“, Vol. 1 Konstruktionslehre, 3. Edition, Berlin, 2000.

[9] Schlink H., Kein R. and Pereira M. W., “Cost Planning for Functions and Components in Engineering Design – Theory and Application”, Product: Management & Development, Vol. 1, No. 1, Brazil, Florianópolis, 2001, pp. 37-48.

[10] Schlink H., Schneider H. and Höhne G., “The Determination of Function Costs in Engineering Products”, Proceedings of ICED 01, Vol. 1, Glasgow, 2001, pp. 19-26.

[11] Schweitzer M. and Küpper H.-U., „Systeme der Kosten- und Erlösrechnung“, 7. Edition, München, 1998.

[12] Tanaka M., “Cost Planning and Control Systems in the Design Phase of a New Product”, Monden Y., Sakurai M. (Editors), Japanese Management Accounting, Cambridge Mass., 1989, pp. 49-71.

[13] Zangemeister C., „Nutzwertanalyse in der Systemtechnik“, 4. Edition, München, 1976.

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