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Preliminary Product Design Based on the Cumulative Functions Concept

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Abstract: This article presents the new concept of cumulative functions and its use in the preliminary product design phase. The first part of the article concentrates on the cumulative functions concept. There is a description from the manufacturer's perspective of product functions followed by the customer's perspective of product functions. Combining these perspectives leads to the creation of the new cumulative functions concept. The second part of the article concentrates on preliminary product design, where the cumulative functions are used. It consists of three main parts: Morphological analysis, Crude design structures and Evaluation of product design variants.

Keywords: *product; product design; cumulative functions*

1. Introduction

The most important life cycle phase for determining the costs of a product is the design phase. Most of the product costs are influenced in this phase. [1] Costs can be influenced here with a much lower impact than during the production phase. Even if Industry 4.0 is applied in a company or modern tools for optimisation of the production system are used [2][3][4], the design phase is still the most important phase for determining product costs. So it is very important during the product design phase to look at the product from this complex perspective. It is important to involve not only the manufacturer's requirements to ensure the functionality of the main product, but also the customers' requirements with a target price that the customer is willing to pay. A systematic approach to determining product functions is the subject of this paper. Both the manufacturer's and the customers' perspectives are respected in this approach. The outputs of the approach link the functions related to the two perspectives into one type of function – a cumulative function.

2. Current Approaches to Functions

Functions mentioned in the literature concerning the Target Costing method [5] are frequently divided into 'hard' and 'soft' functions according to the following definitions [6]:

- ***Hard functions - essential to the core functionality of a product to meet the essential product requirements. For example: car brakes.***
- ***Soft functions - functions that a product does not need to have, but the customer requires them. For example: luxury equipment in the car.***

Hard functions are often taken for granted by the customer. On the other hand, soft functions are usually crucial for whether or not a customer decides to buy a product.

This division of functions corresponds to that used in Value Analysis methodology [7], where functions are related to 'usability' (corresponding to hard functions)

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and to 'personal popularity' (corresponding to soft functions). From these two corresponding divisions of product functions, the terms 'hard' and 'soft' functions are used in this paper.

Another division of functions is the division into:

- *Product functions from the manufacturer's perspective*
- *Product functions from the customer's perspective*

Product functions from the manufacturer's perspective include functions that enable the product to work; the customer usually assumes that these functions are present in the product. Regarding the functions from the customer's perspective, those functions that the customer perceives as important are relevant, and these functions greatly affect the product's saleability. Of course, the list of functions from the manufacturer's perspective also tries to consider functions that the customer perceives as important, to ensure the product's saleability, but they are not given as strong emphasis as in the customer's perspective. There is a similar situation related to the functions from the customer's perspective, which also include some functions that enable the product to work.

It seems that functions from the manufacturer's perspective correspond to hard functions and functions from the customer's perspective correspond to soft functions. In fact, functions from the manufacturer's perspective contain both hard and soft functions with a dominance of hard functions. Functions from the customer's perspective include soft and hard functions with soft functions dominating. Both perspectives contain both types of functions - hard and soft - but in different ratios.

Furthermore, this paper uses the concept of product function from the manufacturer's perspective and the customer's perspective, because it better reflects the nature of the functions as they are used for creating new cumulative functions.

The concept of cumulative product functions is to link the functions related to the manufacturer's and the customer's perspectives. The reason for this new approach to functions is to obtain a single perspective that is sufficiently respectful of the individual perspectives and completely covers the functions of the product.

Below is described the procedure for obtaining the cumulative functions on the basis of the two different perspectives.

3. Analysis of Functions Related to the Manufacturer's Perspective

In this part of the paper we analyse the product functions from the manufacturer's perspective and specify product requirements. This information is used to determine the cumulative product functions. The engineering department is responsible for this step.

The functions related to the manufacturer's perspective are determined using the specification of the requirements for a given technical product/system(s) with an assessment and analysis of their compliance, including the indication of risks. The abbreviated name for this used in the paper is: 'the specification of the product requirements'. It was selected because it has been developed by and used at the Department of Machine Design, University of West Bohemia in Pilsen. The use of the specification of the product requirements was recommended by a specialist from the Department.

The specification of product requirements is part of the Theory of Technical Systems. An essential part of the Theory of Technical Systems is a specific model of a general transformation system. The model itself contains a transformation process with a transformed object and the tools needed for its transformation. [8] The Theory of Technical Systems itself is based on the main concept which is the use of a transformation to meet needs. It considers a need that is satisfied by a transformation. An object is transformed using tools. The transformation itself is controlled and the tools that are used for it are technical tools, so it is a 'technical transformation'. [9]

The original purpose of the specification of the product requirements is to fulfil and clarify the task assignment for the engineering departments. The output is product properties. [10] The product properties are also called 'product functions' related to the manufacturer's perspective. Originally, according to the Theory of Technical Systems, the output of the specification of the product requirements stays in the engineering department. In the proposed concept the output is linked to the functions related to the customer's perspective. The result of this linking is that the cumulative functions go back to both the engineering department and the controlling department, which gives increased coverage of the functions from both perspectives.

A software application was created to support the specification of the product requirements, which reduces the time spent on the task.

The following can be used as sources of information for the specification of product requirements [11]:

- *State of the art analysis*
- *Regulations, standards, etc.*
- *Market/customer requirements*
- *Internal organization decisions*

Various methods [11] can be used to determine the specification of the product requirements: brainstorming, questionnaires, etc.

The procedure for creating the specification of the product requirements consists of the following steps [12]:

1. Specification of basic design data for the proposed technical system

2. Product-Business (P-Business, P-B) specifications of the technical system requirements

3. Product-Design (P-Design, P-D) specifications of the technical system requirements

4. Evaluation and analysis of fulfilment of 'P-Business' requirements of the technical system

*5. Evaluation and analysis of fulfilment of 'P-Design' requirements of the technical syste*m

It is important to be aware that the specification of the product requirements is set by the engineering department, so the emphasis is on product functions from the manufacturer's perspective.

The output of this step is the definition of the product functions from the manufacturer's perspective and their usefulness. The output also contains product evaluation according to various aspects, and the indication of potential risks. [13]

4. Analysis of Functions Related to the Customer's Perspective

This section of the paper concentrates on the definition of product functions related to the customer's perspective and their usefulness. The analysis of functions related to the customer's perspective together with functions related to the manufacturer's perspective is necessary to determine the cumulative product functions. The marketing department is responsible for this analysis.

The proposed procedure to specify product functions related to the customer's perspective is based on market research among potential customers (users). The basic product information determined from the product analysis provides the preliminary information for market research. The customer segment also needs to be determined. These preliminary steps are not part of this paper, as the paper starts from the market research phase.

A suitable method for market research to identify product functions related to the customer's perspective is a questionnaire. It is intended to get specific answers from a large number of potential customers. This can be done digitally or on paper. A suitable structure of the questionnaire consists of the following sections:

- *Name of questionnaire – a basic description, generally related to the investigated product.*
- *Product introduction – product introduction in one paragraph.*
- *Selected functions - pre-selected product functions, including questions related to their scale of importance.*
- *Suggestion of functions by respondent – the respondent proposes functions s/he perceives as essential on a scale of importance related to each function.*
- *Proposed product price – the price that the respondent is willing to pay for the product (target price).*
- *Respondent data – the data needed for possible segmentation of customers or other purposes (statistical, etc.).*
- *Acknowledgment – last, formal part of the questionnaire.*

The questionnaire contains a table with selected product functions. The respondent has to choose the scale of importance of the selected functions. The selection of functions is based on information from customers who use the products, either made by the company or by a competitor. It can also be based on internal information from the company using brainstorming. In addition, the respondent has to be able to include other functions that the product should contain from his/her own perspective on a scale of importance. This is considered in the third and fourth parts of the questionnaire - and is related to product functions. Regarding the determination of usefulness and the scale, the respondent can use a point method. The point method helps him/her to determine how important a particular function is for him/her.

The product functions related to the customer's perspective are identified based on the questionnaire. These are mostly related to soft functions and partly to hard functions. Soft functions are mostly highlighted by respondents; as hard functions are taken for granted. In the questionnaire, the respondent is also questioned about the price that he/she is willing to pay for the product (target price). This is based on price intervals where the

respondent determines the price range acceptable for him/her. The option to write the exact price is also given to the respondent.

Questionnaires from individual respondents are evaluated and the most important product functions are determined. The questionnaire is evaluated as follows:

- *A list is created with individual functions from the third and fourth part of the questionnaire (for all respondents).*
- *Names of the functions are compared and the same functions with different names are clarified (this is done in cooperation with the engineering department, which validates the equivalence).*
- *The usefulness is calculated. The values of the scales of individual function importance are used to calculate the usefulness. It is calculated as follows: the sum of the scales of all the respondents related to a particular function is divided by the total sum of the scales of all the functions of all the respondents. The usefulness calculation uses the following formula:*

$$U_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \qquad (1)$$

U_i – Usefulness of function i [%]; v_i – sum of scales from all respondents related to function i [-]; n – number of functions [-].

- *Selection of the most important functions. In order to maintain a sufficient number of functions for further processing, there should be at least five selected functions. The upper limit is chosen by the fact that the more functions there are, the harder it is to work with them. An appropriate number based on the author's experience is up to fifteen functions. Suitable functions are selected based on their usefulness. If the number of functions is adjusted, it is necessary to perform a recalculation of usefulness - the sum of usefulness of all the functions is 100%.*

The output of the analysis is the determination of product functions related to the customer's perspective, including determination of their usefulness. Also, the target price of the product is determined. The output is linked with the output from the analysis of the product functions from the manufacturer's perspective in the next step, which is related to cumulative functions.

5. Cumulative Product Functions

In order to meet customer requirements while respecting the requirements of the manufacturer, it is necessary to successfully define the product functions. The product functions are the basis of the inputs for the engineering and controlling departments. The engineering department uses them during the design phase of the product and the controlling department during cost calculation. The output of the specification of the product requirements provides the most important product functions related to the manufacturer's perspective. The most important product functions related to the customer's perspective are obtained by evaluating the questionnaires. The cumulative product functions are obtained by linking the two perspectives.

The linking of the two perspectives can be represented by **Figure 1**. **'M'** represents the product functions related to the manufacturer's perspective and **'C'** represents the product functions related to the customer's perspective. The target is to maximize the coverage of both perspectives.

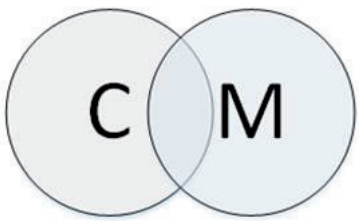

Fig. 1: *Linking the customer's and manufacturer's perspectives.*

The procedure for determining the cumulative product functions is as follows. First the functions related to both perspectives are compared to find out any duplicates. This comparison and a detailed examination is done by the engineering department together with the marketing department. Any duplicate functions are removed. The output of the procedure is a table with cumulative functions where recalculation of usefulness has to be done.

There need to be also mentioned the limitation of the approach, the main one is the time needed for the approach to be performed. The engineering and marketing departments need to be involved, so the time of both departments is consumed. So for the cheap products with low production quantity it needs to be decided if the approach is effective to be applied.

The limitations of the research itself that the author is aware of can be the fact that even if the research of the available literature by author was done, many companies can have their internal approaches that can cover the topic in other interesting way. Because of unavailability of these potential approaches, they cannot be examined and potentially involved.

6. Product Design

The basis of the product design phase is the definition of the product and its cumulative functions. The product design phase is concerned with the design of individual product variants, and the creation of individual concepts (crude design structures) of the product. Morphological analysis is used to determine the concept variants, and it allows the examination of the widest possible range of possible concepts. Next, these variants are evaluated in terms of how they meet the technical requirements for the product.

The product design procedure is shown in the following diagram.

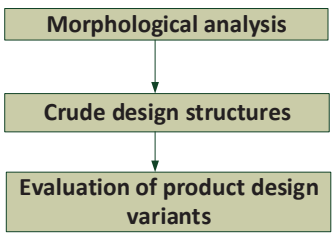

Fig. 2: *The product design procedure.*

6.1. Morphological Analysis

Morphological analysis is a suitable method for creating variants of a product design. It "systematically identifies all possibilities of solving the problem through individual attributes and it combines them into different combinations to create an ideal solution" [10].

The inputs for morphological analysis are the results of the previous phase - the cumulative functions of the product. The cumulative functions are the basis for defining the function holders. Function holders show the possible fulfilment of the cumulative functions by its functional principles or by a specific part (machine part).

The morphological analysis is based on the morphological matrix shown in the table below.

When the morphological matrix is determined, the first function holder for each cumulative function is selected and the feasibility of this design option is examined. Afterwards, all the individual combinations of the function holders are examined and the feasibility of the individual proposals is assessed. The goal is to explore all the combinations and select feasible designs. An example of the selection procedure is shown in the following table.

6.2. Crude Design Structures

The proposals are elaborated into crude design structures (concepts). The crude design structures can be defined as: the real structure of the technical system corresponding to the production and assembly of the technical system from hierarchically arranged building elements (parts...). [10]

The description of the crude design structure [44] includes:

- ✔ *Technical system components/parts and their links (arrangement)*
- ✔ *Shapes*
- ✔ *Dimensions*

Table 1: *The morphological matrix.*

Cumulative function	Functional principle or specific part - function holder		
	1	...	m
Cumulative function 1	Function holder 1 of cumulative function 1	...	Function holder m of cumulative function 1
Cumulative function 2	Function holder 1 of cumulative function 2	...	Function holder m of cumulative function 2
Cumulative function 3	...	...	...
Cumulative function 4	...	...	...
Cumulative function 5	...	...	...
Cumulative function 6	...	...	...
Cumulative function 7	...	...	...
...	...	...	...
Cumulative function n	Function holder 1 of cumulative function n	...	Function holder m of cumulative function n

Table 2: *Example of the selection procedure in the morphological matrix.*

Cumulative function	Functional principle or specific part - function holder		
	1	...	m
Cumulative function 1	Function holder 1 of cumulative function 1	...	Function holder m of cumulative function 1
Cumulative function 2	Function holder 1 of cumulative function 2	...	Function holder m of cumulative function 2
Cumulative function 3	...	...	...
Cumulative function 4	...	...	...
Cumulative function 5	...	...	...
Cumulative function 6	...	...	...
Cumulative function 7	...	...	...
...	...	...	...
Cumulative function n	Function holder 1 of cumulative function n	...	Function holder m of cumulative function n

- *Materials*
- *Production methods*
- *Surface states*

6.3. Evaluation of Product Design Variants

The evaluation is based on the extent to which the technical requirements of the product are met. The next phase of the research will be cost-based assessment.

The evaluation procedure is based on the following steps:

1) Scale determination of cumulative functions.
Each cumulative function has a different significance in terms of product performance, and it is necessary to determine the scale of each individual cumulative function.
2) Evaluation of the fulfilment of cumulative functions by their holder.
Individual cumulative functions are examined and their fulfilment of the function holder is evaluated. The ten-scale is used to find suitable results.
3) Weighted score evaluation.
The obtained values are multiplied by the scale.
4) Product ranking
The total score of an individual variant is determined by summarizing its weighted score.

The outputs of this phase are product design proposals with their significance defined in terms of how they meet the technical requirements. These variants should afterwards be evaluated by cost analysis and the best proposal after both evaluations should then be designed in detail.

7. Conclusions

Current product functions approaches tend to prefer the manufacturers' or customers' perspective. That could lead to product design that not fully corresponds to manufacturer requirements or customer expectations. The current approaches found in the literature are described in the second part of the paper - Current approaches to functions. By the integration of the Theory of Technical Systems approach to product functions and market research approach the new approach is obtained. The paper describes a new approach to product functions that respects the perspectives of both the customer and the manufacturer. The systematic approach leads to the creation of cumulative product functions that cover both perspectives. The main advantages of the cumulative functions approach can be described in the following way. Firstly, better product design (more sensitive to manufacturer and customer), where respecting both perspectives can lead to important advantages on the market. Secondly, the controlling department can use the cumulative functions and target price determination (also an output of the approach) as a basis for the Target Costing method, where the aim is to improve the accuracy of the Target Costing method. The Target Costing method is based on the principle that target cost has to be determined and cannot be exceeded. The target price is necessary information for calculating the target costs. Thirdly, the cumulative functions approach can be used in Value Analysis. Value Analysis is an organized and creative approach that focuses on finding non-contributing costs and reducing them. Non-contributing costs are defined as costs that do not increase quality, durability, or other characteristics desired by the customer. The main purpose of Value Analysis is to obtain the same level of functions of the product with reduced costs. Value Analysis can be used afterwards with various applications, for example to increase the value of the ergonomic design of the workplace, which can support efforts towards ergonomic rationalization.
Future research plans related to topic described in the paper is concentration on integration of the cumulative functions to complex methodology with a new approach to product design through integration of cost management. Output of the methodology is planned to be the product corresponding to the target costs.

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