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DEVELOPING AN ENVIRONMENTALLY FRIENDLY VACUUM CLEANER – A CASE STUDY FROM VISION TO PROTOTYPE

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Abstract

The main aim of this interdisciplinary case study is the realization of a prototype of an environmentally friendly and innovative vacuum cleaner. The paper describes and demonstrates the power of a methodical and holistic product development approach for optimization, beginning with a detailed product and process analysis aimed at clarifying the task and ending with the realization of the developed concept in a workable prototype. The aim of this product development project was to point out weak points and potentials of vacuum cleaners with standard filter bags and to obtain environmental, technical and economical improvements concerning vacuum cleaners with standard filter bags.

The case study presents a comprehensive product development process regarding environmental aspects and demonstrates the reasonable use of simple functional models to support the evaluation of concepts. Furthermore, the case study analyzes aspects of an interdisciplinary cooperation of engineering designers, industrial designers, psychologists, economists and model constructers within the project, and demonstrates how the application of product development methods leads to innovative and fully functional and marketable products.

Keywords: design for environment, environmental analysis, conceptual design, interdisciplinary teamwork, behavioral aspects on sustainability

1 Introduction

Environmental damages are caused by electric consumer products primarily in the use phase [1], [2], [3]. Environmental damage incurred during usage is mainly determined by user behavior, which, in turn, is influenced by the product design [4]. Therefore, a systematical weak point analysis is required, especially of the user behavior. While very general predictions of the effects of system features can be made on the basis of expert assessment, empirical testing is required for more precise estimates.

A methodical product development process is also required to reveal a number of ecological unfavorable behavior patterns and find suitable solutions for the weak points. The development process presented in this paper was carried out according to the phases of the VDI guideline 2221 clarifying the task, conceptual design, embodiment design and detailed design [5], as well as Pahl Beitz [6].

In order to enable the efficient realization of concepts in a final prototype, functional models of concepts were generated. Simple functional models of individual concepts aim at the easy and well-grounded testing and evaluation of critical processes. A functional model for the overall concept serves to carry out experimental measurements to quantify environmental and technical improvements, as well as to ensure the functional interplay of the whole system. This procedure results in well-grounded findings, which are the basis for the prototype. In order to evaluate the improvements achieved, final tests are carried out using the prototype.

With the goal of analyzing situations and processes within interdisciplinary teams, the participants of the project filled out a questionnaire [7].

2 Product and Process Analysis and Development of the Prototype

The extended requirements list takes the results of the detailed product and process analysis into account (Figure 1). The extended requirements list is the starting point for the product development process. The methodological product development process is carried out according to VDI 2221 and Pahl Beitz. To evaluate the developed concept, a functional model was set up. After ensuring the functionality of the developed concept and the environmental, economic and technical improvements an interdisciplinary teamwork of designers, mechanical and industrial engineers, industrial designers and manufacturers were set up.

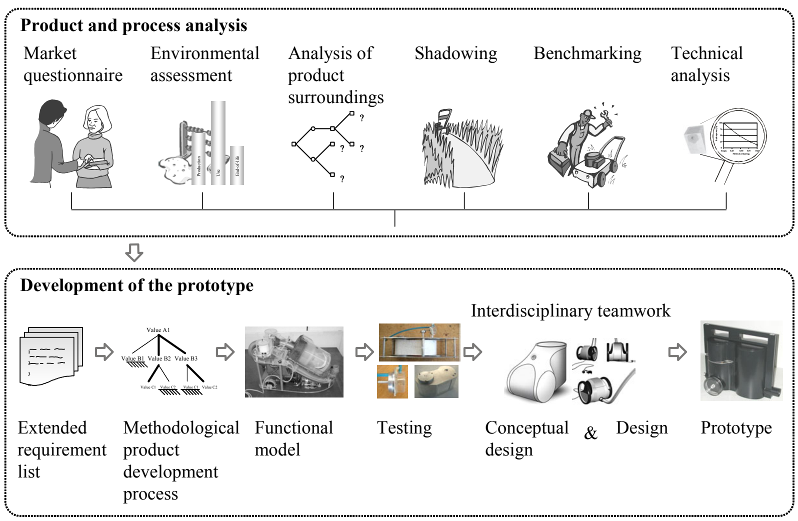

Figure 1. Requirements gathered from various sources and development process

The final result of the development process was the prototype of an environmentally friendly and marketable vacuum cleaner. The following sections describe the product development process in more detail.

2.1 Product and Process Analysis

The goal of this phase is to clarify the product development task to such a degree that an extended requirements list [8] can be drawn up. The requirements list defines and documents the characteristics of the product. Figure 1 shows that the information for the requirements list can be gathered from various sources, which are described in the following sections.

Market Questionnaire

In the first step a market questionnaire is carried out in order to determine what the customer wants and to get a feeling for the customers’ concerns about the environment in regard to the product. Experience shows that an environmentally friendly product is not a guarantee for its success on the market. Therefore, knowledge about the customer, especially in anonymous customer markets, is very important in developing an environmentally friendly that is also marketable [9]. According to the results of the market questionnaire, the rated power is the most important buying factor, followed by the price and the handling (user-friendliness) of the vacuum cleaner.

Environmental Assessment

After ascertaining what the customer wants, it is important to assess which environmental impacts the product has. In the CRC 392 an abridged assessment with Eco-indicator 99 [10] was applied for a standard vacuum cleaner with filter bags. The use phase with its electricity consumption was identified as causing the most environmental impact (Figure 2). About 74 % of environmental impacts results from/during the use phase. Therefore, the greatest potential for environmental improvements lies in improving the use processes. However, it must be ensured that improvements in the use phase do not over-compensate a possible decrease of environmental impacts in production and end of life.

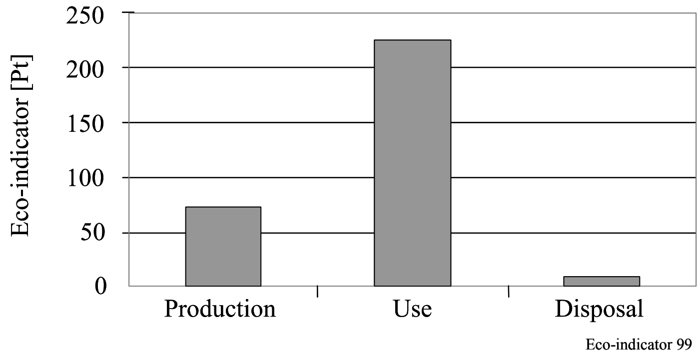

Figure 2. Environmental impacts of a vacuum cleaner with filter bags

Analysis of Product Surroundings

One way to better understand the product system and to deduce requirements is to analyze the product's surroundings, the interaction with its neighboring systems, such as other technical products, other people and its environment [11]. The interactions are directed from the neighboring system to the product or vice versa. Typical questions for analyzing the product are:

- What are the neighboring systems (products, people, surrounding)?
- Which interactions exist between the product and the neighboring systems?
- Which desired and undesired interactions exist or appear (effect, repercussion, side effect)?
- What are the type, duration and frequency of interactions?

The question must be answered for the operational, standby and off modes of the product. By analyzing the neighboring systems of the vacuum cleaner, the problem arose of how the customer determines whether a carpet is clean. This is one reason why the customer cleans certain areas of the carpet twice or more. Therefore, a function for indicating when the carpet is clean helps reduce the energy consumption during the use phase.

Shadowing and methodological analysis of user behavior

By shadowing users the most important process parameters are identified and user behavior is observed. The actual observed "real user behavior" is defined as a superposition of optimal (desired) and erroneous (undesired) behavior (Figure 3). It can be expressed as a statistical distribution between the two extreme values and the normal behavior as the expected value [4].

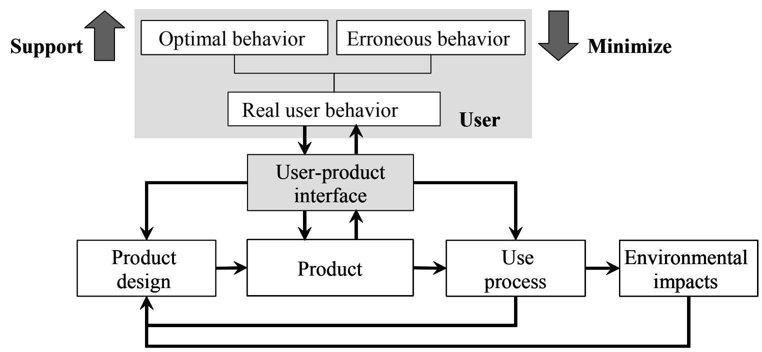

Figure 3. User-product interface

Use tests showed that the vacuum cleaner was not turned off while moving furniture, plants, etc. This resulted in higher energy consumption during the use phase. The optimal behavior would have been to move all hindering objects before starting to vacuum. Therefore, a function for turning off the vacuum cleaner or putting it on standby while idle would be a direct measure in improving the environmental performance. This improvement option will not be followed up in this chapter, but will be implemented in the final vacuum cleaner.

Besides shadowing, it is reasonable to apply a methodological supported analysis. Therefore, methods like the FNMEA [4] which is derived from the well-known FMEA, are suitable.

Benchmarking

Benchmarking consists of comparing competitors' products to determine how they achieve certain functions and why they use particular modules and parts. The overall goal of benchmarking is to combine the best practiced solutions for each sub-function in order to make an "optimal" product.

First, the overall product function must be compared. This includes an analysis of the electrical energy consumption (operational, stand by and off modes), as well as the consumption of other processes and auxiliary materials. Besides the overall function, the function of each module and part must be understood by simply disassembling and analyzing the products. After analyzing each product, the "cross-product comparison" begins to identify the best solution for each sub-function, evaluating the environmental, economic and technical performance. A good approach can be found in Eenhoorn and Stevels [12]. In the following example, the focus was on the different filter systems. For this comparison, a life cycle assessment using SimaPro 4.0[1] was carried out for the use phase (Figure 4). Through the assessment it was found that the cyclone filter system is the most efficient.

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[1] SimaPro 4.0 LCA software. PRé Consultants bv, Amersfoort, The Netherlands.

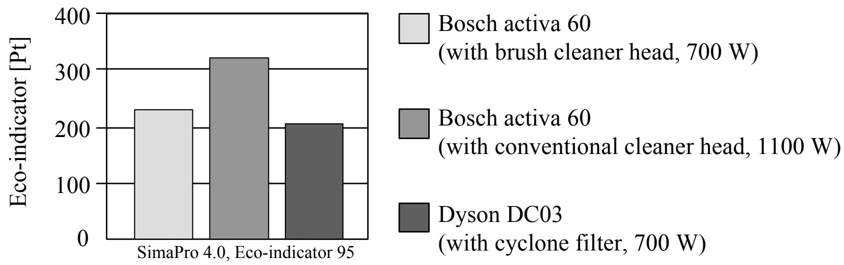

Figure 4. Life cycle assessment of different systems of vacuum cleaners

In addition, an abridged assessment using Eco-indicator 99 method was carried out comparing a vacuum cleaner with a water filter (L'Ecologico) and a conventional filter (Bosch). Because of the high water consumption, particularly for cleaning the dust container, the environmental impacts of the water filter are generally much greater.

Furthermore, sucking experiments showed that using a brush cleaner head, compared to the conventional cleaner head, leads to an increased intake of dust (Figure 5). The main result of these investigations is the preference of the cyclone filter principal in combination with a brush cleaner head. The cyclone filter principal is independent of the fill level of the dust container.

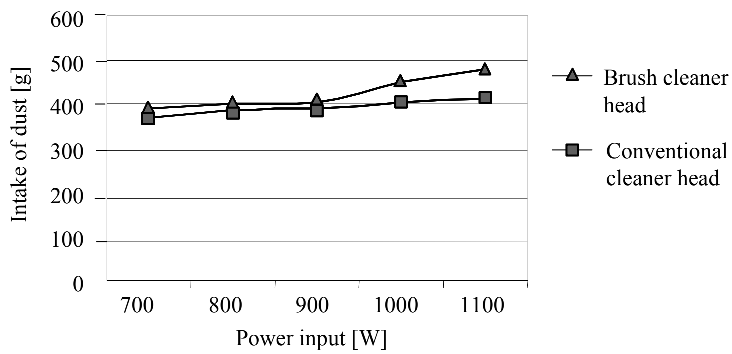

Figure 5. Intake of dust through different cleaner heads

Technological Analysis

The interdependence of the fullness of the dust bag and the suction power was determined by sucking experiments. The suction power, and therefore, the environmental damage caused by vacuum cleaners, strongly depends on the fullness of the dust bag. The suction power is reduced by 50 % if the dust bag is half-full (Figure 6). Therefore, it is very important to identify working principals that minimize losses of suction power. It is important to know that the same mechanism applies to fine-mesh filters. With an increasing amount of fine dust, the suction power at the cleaner head is also reduced.

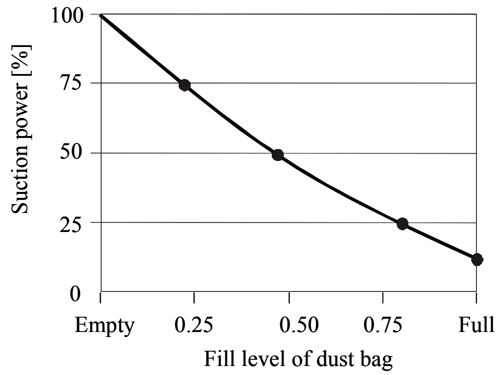

Figure 6. Interdependency of suction power and fullness of dust bag

Figure 7 shows the interdependence between the intake of dust and the airflow rate for standard filter bags. There is no need to increase the airflow rate beyond 200 watts. An overall efficiency of about 20 % requires a motor rating of circa 1000 watts.

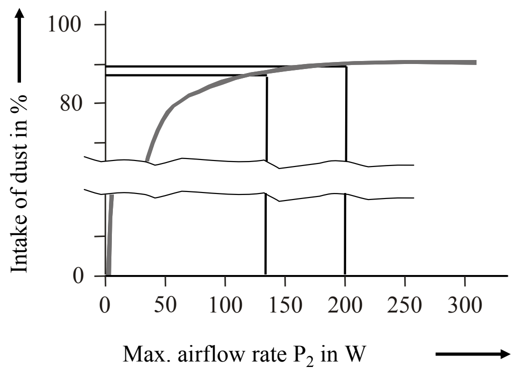

Figure 7. Airflow rate and intake of dust

The market questionnaire shows that the rated power is the most important buying factor, followed by the price and the handling (user friendliness) of the vacuum cleaner. There is a gap in the information between the customers' knowledge and technical requirements. To ensure the marketability of the vacuum cleaner this gap must be closed.

The holistically analysis mainly reveals that the use phase with its electricity consumption causes the most environmental impact. The environmental assessment shows that the cyclone filter system is the most efficient.

2.2 Development of the Product Concept

Integrated Product and Process Development (IPPD)

The Model of the IPPD [13], [14] (Figure 8) considers environmental issues already during the development process, anticipates and defines processes within the whole product life cycle and considers environmental, technical and economic criteria.

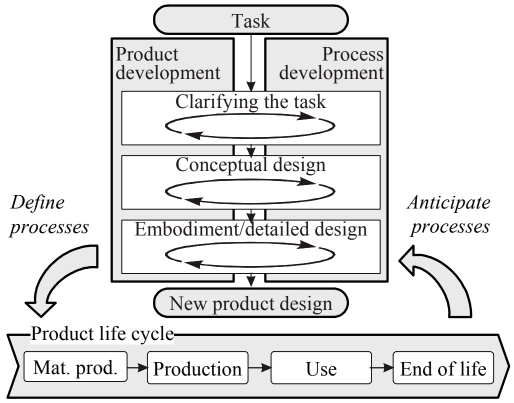

Figure 8. Integrated product and process development

The IPPD is a prerequisite to perform Design for Environment and shows the need for product- and process-related information and communication of a wide range of interdisciplinary experts on relevant life cycle processes. So the results of the user behavior found in the analysis have to be considered already in the early stage of product development.

Product Concept

The concepts developed for an environmentally improved vacuum cleaner are based on the analysis described above. One goal of the conceptual design was to minimize the loss of suction power due to clogged dust bags and fine-mesh filters. This goal should be achieved independently of the user's behavior.

Figure 9 shows exemplary evaluation results for the loss of suction power in different filter systems as a result of vacuum experiments. The separation of coarse-grained dust is achieved by using a cyclone filter. Its airflow resistance is nearly independent of the fill level.

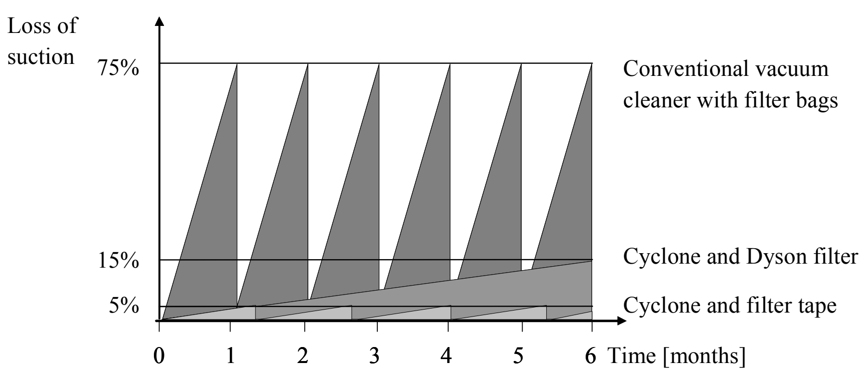

Figure 9. Loss of suction of the developed filter system compared to existing systems

The separation of fine dust is achieved by a rolled-up filter tape. Just a little part of the filter tape is in the calibration flume (Figure 10). The filter tape is transported depending on its degree of pollution so that the lost of suction is minimized. This is done by measuring the pressure difference in front and behind the filter tape using a difference depression sensor.

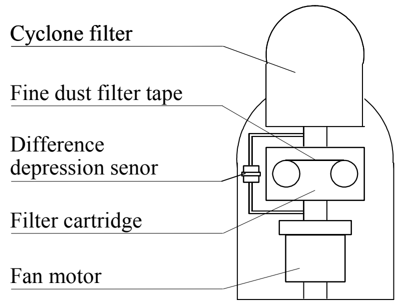

Figure 10. Design concept to reduce the loss of suction power

One disadvantage of the cyclone filter principal is the restricted level of filtration. Therefore, various filter principals were identified by analyzing existing solutions, using intuitive methods, and systematically creating variants [6]. Finally, possible solutions were evaluated and one solution was selected for the detailed design.

2.3 Realization of the Functional Model

With the aim of testing the function and evaluation of the benefit of the concept, a function model was realized (Figure 11). The main requirements are the verification that the concept works, the selection of the filter tape and the dimensioning of the filter system. This leads to the following requirements: Minimal effort, simple construction, accessible components for inspection and exchange, automatic transportation of the filter tape, easy exchange of the filter tape, high leak tightness of the system, output of the difference pressure signal, pc-interface for data acquisition and data processing.

Figure 11. Function model of the vacuum cleaner

The cyclone filter and important components were taken from an existing vacuum cleaner. The components were arranged according to functionality and airflow. The sandwich construction structure was applied to ensure the accessibility of the components. The cyclone filter, which must be emptied frequently, and the filter system, which must be inspected at any time, are placed on the top level. In the lower level components like the chassis, fan motor, power supply, are located.

The filter tape is arranged in a closed cartridge. This enables high leak tightness and an easy exchange of the filter tape in order to test different kinds of filter tapes with different specifications.

The automatic transportation of the filter tape was realized using a stepper motor, electrically controlled by the evaluating system. To detect the pressure difference in front of and behind the filter tape, an electrical difference depression sensor with a linear output signal was used. The processing of the depletion data is realized by a programmable micro processor. The micro processor allows the data processing with a personal computer.

2.4 Evaluation of the Product Concept

To get an impression of how vacuum cleaners are used in private households, a detailed survey addressing 280 persons in three large German cities were carried out. A questionnaire with approximately 20 questions concerning the use and the end of life treatment was elaborated. The age of the respondents ranged from 20 to 70.

The average number of persons in the household was 2.6, and the living space 105.2 square metres, of which 95.06 square metres is cleaned with a vacuum cleaner. Therefore, six filter bags are needed per year and the average service life of the vacuum cleaners is 6.4 years. Based on this scenario, the benefits of the developed vacuum cleaner shown in Figure 12 can be pointed out.

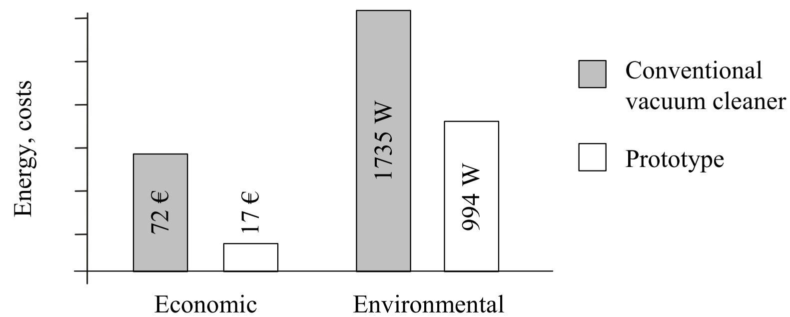

Figure 12. Economic and environmental benefits

The economic benefit depends mainly on the fact that in the use phase no filtering bags are required. But these benefits do not consider the lower energy consumption. The reduction of environmental impacts is achieved through energy efficiency. The technical advantage of the cyclone filter in combination with the filter system is the constant suction power.

2.5 Realization of the Prototype

The function and environmental aspect concerning the energy efficiency benefit can be shown with the functional model of the vacuum cleaner. Several modifications are necessary due to environmental, costs and market requirements.

With the aim of creating an environmentally friendly and marketable vacuum cleaner, a prototype was realized (Figure 13). The main goals were to generate an innovative design for the vacuum cleaner, to minimize the electronic components in order to achieve a high recycling rate, and to reduce life cycle costs. This led to the following requirements: automatic transportation of the filter tape without the stepper motor, easy exchange of the whole filter system, high leak tightness of the filter system, accessible cyclone filter to ensure an easy emptying, and the fulfillment of security and legal requirements.

Figure 13. Prototype of the vacuum cleaner

The filter system consists of the following components: difference depression sensor, filter cartridge and the trigger mechanism. To fulfill the requirements describe above, several modifications are necessary. The separation of fine dust is achieved by a rolled-up filter tape. Just a little part of the filter tape is in the calibration flume. The filter system realized in the functional model works, but requires the consideration of the increasing core diameter.

The concept for the filter cartridge was taken over as far as possible up to geometrical changes. To realize the mechanical transportation of the filter tape, the stepper motor was replaced by a spring. The dimensioning of the spring allows a complete rewinding of the filter tape. The problem of the variable diameter of the reel core was solved by adding breaking reels before the unwinding reel. With every rotation the same length (and the same area) of filter tape were replaced in the calibration flume. This solution requires a release mechanism, which releases the mechanical transportation of the filter tape as a function of the signal of the differential depression sensor. For the more exact interpretation another working model of the system was built. The testing of the system shows that during the suction process, the transportation of the filter tape is not possible. The reason for this is that the filter tape is being held by suction to the retention lattice. Therefore, the adjusting signal of the differential depression sensor must be stored mechanically. Figure 14 shows the substantial components of the filter system.

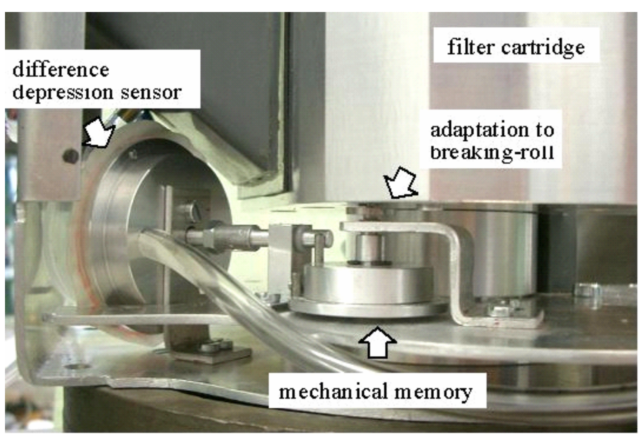

Figure 14. Filter system elements of the prototype

For the mechanical realization of the differential depression sensor in the context of a systematic variation, different partial solutions were determined. To evaluate the partial solutions simple working models were built. The differences of pressure are converted over a diaphragm into a mechanical translation movement. This movement against a laid out spring is effective as an output signal. The output signal is mechanically stored in the release mechanism described before.

The following components are also realized in the prototype: In order to prevent the repeated cleaning of certain areas, a dust sensor for indicating when the carpet is clean is integrated in the cleaner head [16]. A switch on the handle allows for easy turning off the vacuum cleaner. Based on the results of the analysis phase, a brush cleaner head is chosen.

3 Reflection of the Product Development Process

3.1 The Interdisciplinary Project Team

Based on the components of the functional model the prototype is realized in an interdisciplinary team. The interdisciplinary team consists of mechanical and industrial engineers, industrial designers and manufacturers. Figure 15 depicts the groups involved. These groups can be divided in accordance with the following pattern into interdependent interest groups.

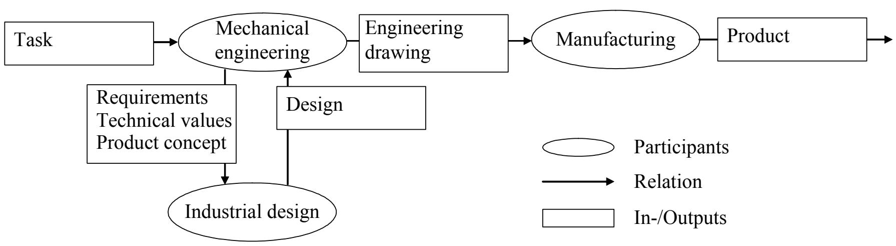

Figure 15. Participants and relations of the interdisciplinary team

The interdisciplinary teamwork was evaluated using the procedure presented in Figure 16. The main elements of the evaluation are the integration of the research associates into the project as participating investigators. The participants of the interdisciplinary projects were interviewed in a questionnaire. In addition, feedback discussions during the project between the participants were carried out.

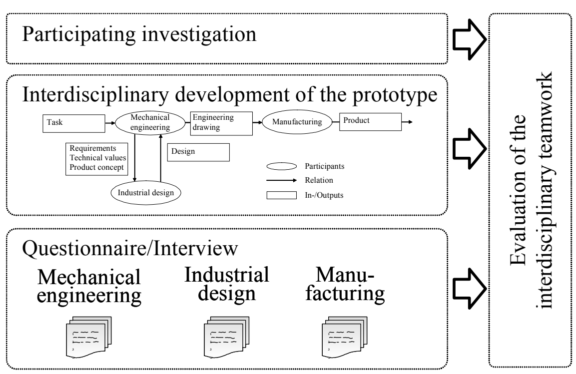

Figure 16. Evaluation of the interdisciplinary teamwork

The interdisciplinary teamwork between the participating groups will be discussed here. The positive effects of such teamwork, as well as the problems, which arise with large projects involving many people from very different fields of activity, will also be mentioned.

The positive effects of such a project are sometimes subject to certain difficulties. The persons involved in such a project gain experience in dealing with those difficulties. If they participate again in such a project they can use the experience gained from the first. The same applies to communication, which is also part of a constant learning process. Synergies exist because of the different groups involved in the case study. Creative ideas arise from the different points of view and expertise of the people involved.

The difficulties arising from teamwork are especially the lack of and inability at communication between the individual groups of different fields of activity. This can be justified to the largest part by the fact that the groups involved greatly represent different spheres of interest and partially also to different types of training. Problems in communication are normal to a certain extent and can only be solved by frequent consultations and intensive discussions.

A further problem, which particularly affects projects, in which trainees are involved, is the lack of experience regarding technical knowledge, as well as the necessary behavior patterns towards other team members.

The following points resulted: The processing and availability of the information received is a critical factor, because it affects one’s own motivation. The coordinating processes strongly affect the motivation. Therefore, an efficient and satisfactory coordination is necessary. There is a low acceptance for trans-sectoral iterations, clear arrangements and demarcations are demanded. Everyone tried first to reach his/her own aims and has just a little understanding for the problems concerning the work of others. Responsibility for misunderstandings was frequently taken on both sides.

4 Results

Regarding the content, the project results in the prototype of an environmentally friendly vacuum cleaner with a remarkable design. The main drive for the solution generated was the significant effect of the user’s behavior on environmental impacts within the life cycle phase ‘use’. The developed concept is mainly characterized by an innovative filter concept using a fine filter tape with life-long dimensioning, which results in environmental, technical and economical improvements. From an environmental point of view, noticeable savings in energy consumption were reached. One main technical improvement is a constant suction power at the cleaner head, independent of the fill level of the dust container and the clogging of the fine dust filter. An economical advantage from the viewpoint of the customer is that expensive dust bags are not needed anymore.

From a methodical point of view, one result of this project is the continuous application of the developed procedure on design for environment. The use of the simple functional models within the design process support an efficient evaluation process of concepts and embodiments, and enables well-grounded decisions. This procedure supports the identification and development of ideas and solutions of a higher quality. Ideas and solutions with poor prospects of successful implementation could be identified very early in the process. The paper describes the step-by-step development of components from very easy to appropriate but sufficient solutions, e.g. the transportation mechanism of the filter system or the pneumatic trigger mechanism.

Aspects of projects within an interdisciplinary field which are critical nowadays are, e.g. the use of different software tools with dissimilar data formats. One reason for this is the various uses of tools, e.g. the visualization of free-form surfaces in the case of industrial designers and deducing machine data by engineering designers.

5 Conclusions and Outlook

It could be said that a methodically supported product development process in the field of design for environment leads to innovative products, which are not only environmentally friendly, but also advanced concerning technical and economical aspects. The way from a detailed product and process analysis that applies product development methodology to the realization of a prototype within this project was demonstrated using the example of the vacuum cleaner. At the time of print, the finishing touches were being put on the prototype of the vacuum cleaner. This project was executed in cooperation with industrial designers to give the environmentally friendly and marketable vacuum cleaner the cutting edge.

The high motivation of mechanical engineers and industrial designers participating in this interdisciplinary project had a positive influence on the results. Furthermore, a greater effort to coordinate the project and to moderate project meetings was necessary due to the different backgrounds of the participants. Everybody was eager to learn about each other's procedures and methods and was interested in the results of the other discipline. Still, the novelty of the other parties' methods sometimes reduces the motivation due to the unknown scope, effort, result and prerequisites of the application.

At present, a final evaluation of the developed concept is being carried out by testing the realized prototype with regard to environmental, technical and economical aspects. Besides environmental and technical experiments, tests with users will be carried out.

6 Acknowledgments

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