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MODELING OF USAGE HYPOTHESES FOR THE IDENTIFICATION OF INNOVATION POTENTIAL

Michael Riesener, Christian Dölle, Annika Becker, Günther Schuh
Laboratory of Machine Tools and Production Engineering (WZL), RWTH Aachen University, Aachen, Germany

Abstract: *Manufacturing companies are facing increasingly faster changing customer requirements resulting in a rising necessity to faster generate product innovations that enhance the specific customer needs. For this purpose, the product use phase offers considerable potentials. Product usage data can help to validate the assumptions on the product's usage, the so-called usage hypothesis. The usage hypothesis models relevant product functions as well as the development assumptions on their specific characteristics. In the context of a methodology for the identification of innovation potential, this paper presents a proposal for a holistic model of the usage hypothesis.*
Key Words: ***Industrie 4.0, Product usage data, Functional models, Innovation***

1. INTRODUCTION

In today's highly competitive markets, cost advantages in low-wage production regions are challenging manufacturing companies in the machinery and plant engineering sector. [1] Furthermore, the increasing shortening of innovation cycles causes enthusiastic product functions to quickly change to basic functions during the use phase. [2] [3] This means that companies have to offer products with new enthusiastic and beneficial functions in order to successfully compete in the long term. [4] The challenge in this regard is that during product development, developers are often unaware on how exactly these functions can be generated. Therefore, assumptions are usually made about the future usage of the product, which are strongly based on presumed customer needs. In the following, these assumptions are summarized within the term "usage hypothesis", which contains all assumed characteristics of product functions during the product's use phase.

Wrong assumptions on customer needs on the one hand often lead to over-engineered or, on the other hand, not sufficiently developed product functions. [5] Thus, focusing on how customers really use products is indispensable for the design of sustainably successful products.

In this context, the use of agile methods has been established in the development of physical products in recent years. Originating from software industry, agile development methods support the iterative and continuous validation of product increments through the targeted involvement of customers and other stakeholders of the product within defined development cycles. [6] There are two central issues in exploiting the full potential of customer feedback in agile product development: On the one hand, the product cannot be validated as a whole during the development process, but only its increments. On the other hand, increments are usually not tested under real conditions of use, since the product is not yet in usage. [7] It can be summarized that today, agile methods are applied in product development to systematically incorporate knowledge about the product, although the knowledge gained about how products are really used is very limited.

By addressing these circumstances, the product use phase itself offers enormous potential for the targeted (further) development of products through optimization and innovation leading to the continuous increase of the product's value. This principle is exemplified in figure 1.

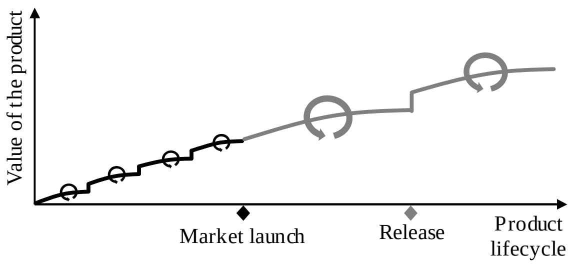

Fig. 1. *Continuous increase of the product's value through optimization and innovation*

An advanced approach in this respect also originates from the software industry. DevOps closely links, as the term expresses, the development and operation phases of software by providing suitable methodologies and data infrastructure. As a result, product usage data can be continuously fed back into development and analyzed, so that the knowledge gained is used to carry out short-cycle releases in operation. The software can thus be continuously improved during its life cycle. [8] [9]

Also for physical products, especially in the machinery and plant sector, the feedback of product usage data into development is gaining rising relevance. Machines and plants are increasingly being transformed into so-called cyber-physical products, i.e. they are connected to each other and to global network via communication facilities. [10] In this context, RWTH Aachen University has been researching the provision of a suitable data infrastructure for several years in the Cluster of Excellence “Internet of Production” (IoP). IoP can be understood as further development of the Internet of Things (IoT), which transfers the idea of the internet, in the sense of a world-wide socio-technical network, to the physical world. [11] IoT is also established as a term for the horizontal networking of cyber-physical products and enables the use of field data such as usage data. [12]

Cyber-physical products thus offer considerable potential for the targeted development of physical products in this sector, in view of the challenges in machinery and plant engineering described above. For this purpose, the authors of this paper are elaborating a methodology to derive innovation potential from the analysis of product usage data. As a basis for this methodology, this paper presents a proposal for a holistic model of usage hypotheses. Since customer needs are mainly fulfilled by product functions, the usage hypotheses should summarize all supposed relevant characteristics of product functions in a holistic model. Within the subsequent analysis of product usage data, this model serves to compare the real product usage with the assumed usage and to identify potential for innovation from deviations. Both the holistic approach for the identification of innovation potential as well as the description of usage hypotheses as its first step are described in this paper. Therefore, the goal of the paper is the presentation of a basis for the data-based identification of innovation potential by providing a model for the description of usage hypotheses.

2. FUNDAMENTALS

2.1. Cyber-physical products

In order to describe the scope of this paper, machines and plants as well as the term “cyber-physical products” are initially defined. According to [13], machines and plants can be understood as technical structures with the aim to solve technical tasks. Furthermore, they are characterized by their composition of several individual parts or components as well as their control and monitoring units. In an abstracted form, a machine can be understood as a transformation system that is connected to its environment by input and output variables. These variables can be in the form of energy, material or signal. [14] In the context of system theory, a machine can itself be subdivided into any number of subsystems, whereby a suitable system with corresponding input and output variables can be considered at any level of abstraction. [13] The term “mechatronic systems” has characterized the machinery and plant engineering sector since the 1970s. [15] The term “mechatronic” is composed of the terms mechanics and electronics. It describes mechanical systems, which are extended by electronic functions. [16] Since the development of microprocessor technology, information technology has also been regarded as a further component of mechatronic products. Thus, mechatronic systems are composed of a mechanical basic system and the functional and/or spatial integration of sensors, actuators and information processing. [17] The fast progress in the field of microprocessors, both in terms of performance and miniaturization, has opened new possibilities for mechatronics. The proportion of information technology built into machines is constantly increasing and making them “intelligent”. [18] In addition to enabling intelligent machines using information technology, further potential can be exploited by integrating communication and connectivity technology. These not only facilitate the design of mechatronic systems as self-contained intelligent units, but also the connection with other, equally intelligent machines as part of a network. By adding the network factor to mechatronic systems, they become so-called cyber-physical systems (CPS). [18] CPS differ from mechatronic systems in the connection to each other and to global networks via digital communication facilities. [10] This enables CPS to access not only the input from their own sensors, i.e. information limited to their own immediate environment, but also to access available data from sensors and machines all over the world. Due to their networking character, CPS are relevant for this research approach as they enable to access sensor data while product usage.

Since the use phase of CPS is the focus of this paper, it will be shortly classified into the overall product life cycle in the following. The use phase follows the product development phase as well as the production phase and ends with the recycling of the product. The product development process itself comprises the phases of requirements definition and the subsequent product planning, which forms the basis for the development of the product. The subsequent process planning forms the preparation for production. [19]

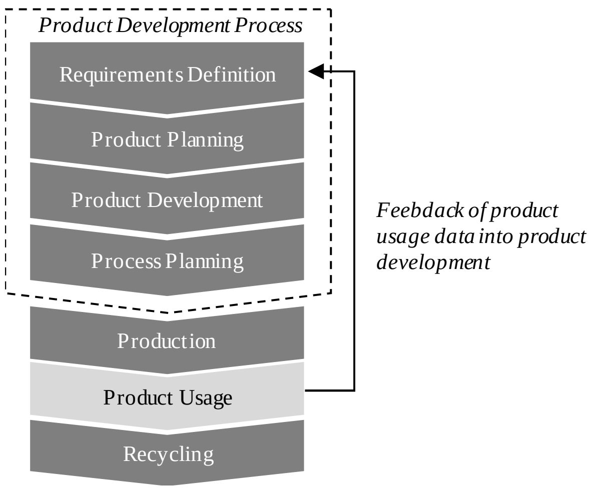

Fig. 2. *Classification of the product use phase*

The classification of the product use phase in the product life cycle and the feedback of product usage data into product development are shown in figure 2.

2.2. Product function models

As described before, the approach for the description of product usage hypotheses shall summarize all supposed characteristics of product functions. Thus, the basis of the usage hypothesis builds a model of all relevant product functions. For this reason, the terms of product functions and product function models are described in the following.

For describing and solving tasks in the field of engineering, it is useful to refer to the term of "function" in order to summarize the desired relation between input and output of a system with the goal of fulfilling a task. The overall task of the product can be expressed by the so-called overall function. The overall function itself can be subdivided into several sub-functions. The meaningful linking of sub-functions to the overall function can be represented in the function structure of the product. It is useful to distinguish sub-functions between main and secondary functions. Main functions are those sub-functions that directly serve to fulfill the overall function, whereas secondary functions contribute only indirectly to the overall function. They rather have a supporting or supplementary character. [13] All functions of a product can theoretically be subdivided so that the lowest level of the function structure only consists of functions that cannot be further subdivided in terms of general applicability. These elementary functions are called generally applicable functions. [13] Every function can be described on a sufficiently abstract level by such a generally applicable function. [20] provides a definition for generally applicable functions by considering the relationship between the input and output variable in terms of change in type, size, number, location and time. A simplified representation of this definition is shown in figure 3.

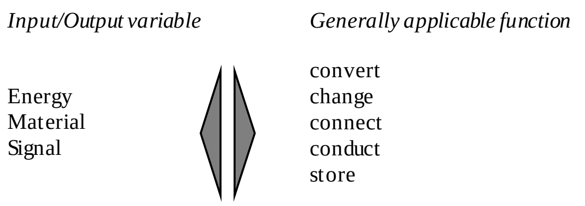

Fig. 3. *Definition of generally applicable functions* [20]

After the description of product functions, the terms "product model" and "function model" will be explained in the following. The concept of models plays an essential role in science and supports to reproduce excerpts from reality in simplified and generalized form. [13] Often, an enormous amount of information and dependencies is summarized in an abstract, structured context to make it more comprehensible. Thus, a model never depicts reality, but only represents an approximation of reality with regard to a specific purpose. Models therefore separate essential aspects from unessential aspects by abstracting reality into simplified images of it. [21]

A product model contains all essential information that is generated during the product development and defines the whole product. The product model is an abstract representation of products and does not consider any time dimension. A common approach to product models is a representation in form of a pyramid. [22] This type of representation can be used to structure different partial models at different levels with increasing degree of concretization and complexity. The basic idea is that the product levels are logically based on each other, but each level can also be considered separately. The results of one level must be able to serve as a basis for the next without loss of information.

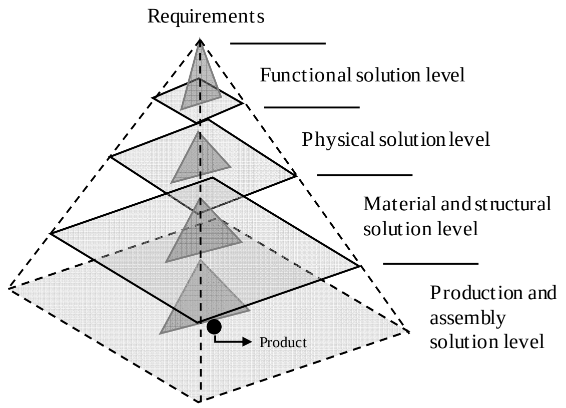

Fig. 4. *Function models as part of product models*

As shown in Figure 4, the top level of the product model pyramid, and thus the one with the highest degree of abstraction, is the functional level. Starting from the modeling of functions, the entire product is determined in the lower levels by the selection of suitable material and structural solutions. [23]

A further possibility of the representation of product models is the division according to requirement space and solution space. Within the solution space, different product levels with varying degrees of concretization are differentiated, whereby the highest level, the functional level, is also the level with the highest degree of abstraction. Below this, the products are increasingly concretized at the impact level and construction level and finally bundled in the whole product. [24]

It gets clear that function models are part of product models. Function models offer the highest degree of abstraction and serve as a basis for further, more concrete designs in the course of product development. The aim of functional modeling is therefore to first define an abstract and thus solution-neutral description of the overall product function and the resulting sub-functions. [22]
As the presented approach in this paper aims to offer the basis for the data-based identification of innovation potential, the term "innovation" should be further detailed in the following as last aspect of the fundamentals.

2.3 Product innovation

Innovations are essential for the survival of enterprises in highly developed economies. In order to achieve sustainable success, manufacturing companies face the challenge of constant change through innovation. The required resources are typically scarce and must therefore be carefully deployed in innovation activities. [25] The term "innovation" in this context means the successful economic implementation of a new introduction or renewal. The innovation is preceded by an invention, which describes the development of a new idea and can be abstract or concrete. [26] In the context of product development, product and process innovations are of particular importance. Product innovations involve the development and marketing of new products or services, whereas process innovations improve the processes of an existing product, e.g. manufacturing processes, marketing processes or logistics processes. [27] In the context of this paper, the identification of product innovation potential is focused. For example, product innovations can be a significant increase in performance, an expansion of functionality compared to previous solutions or the replacement of previous technologies with other, new solutions. [28] To further detail the term of innovations, a distinction can be made between incremental and radical innovations. Incremental innovations on the one hand can be understood in the context of product development as the further development of an existing product, service or process, for example the development of a new product generation. A radical innovation, on the other hand, is often based on the use of new technologies and represents a product or process that has not existed in this form before. [25]

Summing up, this paper focuses on the product use phase of CPS and their product functions in forms of function models as well as product innovations.

3. STATE OF THE ART

To determine the need for further research regarding usage hypotheses validation, several existing approaches are summarized and reviewed. After the introduction of relevant fundamentals on cyber-physical machines and plants, function models and innovation, literature on approaches of the combination of these terms in forms of usage hypotheses will be evaluated in the following.

3.1. Research object and objectives

Existing approaches are evaluated regarding their examination of this paper's research object and objectives. The research object defines the context in which the usage hypotheses shall be embedded, whereas the research objective describes the research goal of the approach presented in this paper.

First of all, the research object of the presented approach are CPS due to their ability to continuously provide information on their usage. Since none of the evaluated existing approaches specifically considers the machinery and plant sector, all forms of cyber-physical products are focused in representation for machines and plants. Furthermore, through modeling the product in the use phase, the approach should focus on this specific part of the product life cycle. As mentioned before, customer needs are mainly fulfilled by product functions, which is why they provide an enormous potential for innovation. The description of product functions is therefore the third part of the paper's research object.

A key part of the proposed approach is the modeling of all relevant characteristics of product functions. In addition to this first research objective, the characteristics are to be modeled and described in order to support a validation of the usage hypothesis through the analysis of product usage data.

3.2. Critical analysis of existing approaches

[29] present a function model for technical systems which they divide into three sub-models: A conversion-oriented model, which focuses on the transformation of material, energy and information, a relationship-oriented model to identify weaknesses and conflicting objectives and a user-oriented model to represent interactions of different users with the system. These sub-models are designed to be used independently depending on the goal of the examination of product functions. Therefore, their model does not offer a holistic model including both user and technical description of the functions.

Another approach to model product functions is proposed by [30]. His characteristics-properties modeling approach is based on product characteristics, which are the physical features of the product, and properties, which describe the behavior of the product. While characteristics can be altered directly by the developer, properties cannot be directly specified. The connection between characteristics and properties is established through analysis and synthesis. Analysis is the determination of product behavior (properties) based on known characteristics. Synthesis on the other hand is the definition of characteristics based on required properties. This model does not consider different usage hypotheses, because it does not include the use phase of the product.

The Behavioral Design Approach by [31] includes the behavior of the product as well as the behavior of the user and his influence on the overall product behavior. Therefore, the interaction of the user with the product plays a key part in the model. He differentiates between manual and automatic functions. Automatic functions can be directly derived from the structure of the product, while manual functions are induced by the user. The approach focuses on the implementation of an IT-infrastructure to allow for a transfer of usage data to the product development. Modeling functions, their specifications or an overall usage hypothesis is not part of the approach.

Another approach focusing on the IT-Infrastructure is the Feedback Assistance System by [32]. The aim of the research is to identify potentials for product optimization through analysis of machine usage data. Statistical analysis of the data allows the identification of deviations between the assumed use of the component and the actual use. The model does not include the modeling of product functions through usage hypotheses.

[33] describe a model for the data-based support of product development. Their usage data-based weak point analysis of components during the use phase has the goal to find specific potentials for optimization. The focus of their work is a statistical model to identify design parameters that deteriorate at an above average pace during the use phase. Their approach is based on a function model that includes hierarchical ordering and relationship building between functions as well as performance features of these functions. The functions' specifications are not modeled during the development, though. Therefore, their proposed model does not support the validation of a usage hypothesis.

The approach which comes closest to the research object and objectives of this paper is the work by [34]. Their goal is the development of a method to draw conclusions concerning the human-machine interaction through analysis of product usage data and the data-based optimization of the product. Consisting of five steps, their method proposes to first aggregate existing knowledge regarding the product, the user und their interaction. After that, clear goals must be determined. The third step is the characterization of usage elements concerning the expected product usage. The usage elements are part of a usage profile. Each element can be characterized through usage elements states, is monitored by sensors and can be selected or adjusted by the user. Although their approach covers most of the mentioned criteria for research object and objectives, it does not include a functional description of the product.

Legend: Level of detail of examination ○→●

Authors	Object: Focus on cyber-physical products	Object: Focus on product usage phase	Object: Focus on product functions	Objectives: Description of assumed function specifications	Objectives: Validation of Usage Hypothesis
PONN & LINDEMANN	●	◑	●	◑	◑
WEBER	●	◔	◕	◔	◔
SUN	●	◑	◑	◔	◑
DIENST	◑	●	◔	◔	◔
HONGZHAN ET AL.	●	●	●	◔	◑
VOET ET AL.	●	◕	◔	◑	◕

Fig. 5. *Presentation and evaluation of reviewed literature*

The evaluation of the reviewed literature is summarized in figure 5 and the degree of fulfillment of the criteria is displayed. Most of the existing approaches can be used to model cyber-physical products and are focused towards the use phase. Some allow for the detailed description of product functions, while none are fully designed to define function specifications as part of the function model while developing the product. Determining the function specifications during the use phase is an essential part of formulating usage hypotheses. Therefore, none of the existing approaches allow the validation of usage hypotheses through comparing the function specifications and actual usage.

4. RESULTS

The existing approaches described above as well as the introduction in the first chapter reveal the need for a systematic description of usage hypotheses in order to evaluate them by analyzing product usage data for the targeted identification of innovation potential. Therefore, the main research question of the overall approach, which contains the description of usage hypotheses as first step, can be formulated as follows:

"How can product usage data systematically be analyzed to identify innovation potential regarding product functions and to deduce measures in order to continuously improve those product functions?"

The overall approach consists of four steps. The first step focuses on the identification of those product functions which provide the greatest innovation potential as well as on the systematic description of their assumed characteristics during the use phase. The output of this step therefore formulates the usage hypothesis of the product. Based on this usage hypothesis, the second step elaborates which product usage data can be used to validate the assumptions from product development and how these data must be recorded and processed. In the third step, the usage hypothesis is validated by comparing the recorded product usage data with the assumptions on product function characteristics. Deviations between product usage hypothesis and real product usage data are identified and classified in the fourth step. The goal is to derive measures for function-based further development of the product as outcome of the whole approach.

The four steps of the overall approach are summarized in figure 6.

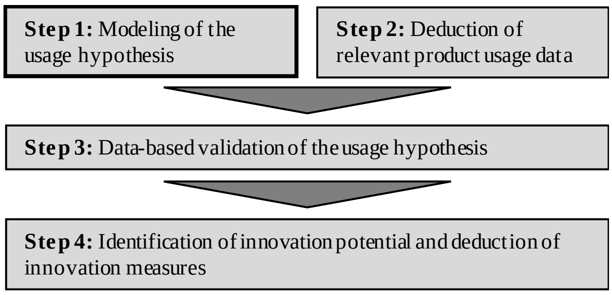

Fig. 6. *Overall approach for the identification of innovation potential*

Due to the limited space available, this paper will focus on the first step of the overall approach. The overall objective of this step is the modeling of the usage hypothesis in order to provide the basis for the identification of innovation potential through the analysis of product usage data. In figure 6, the first step is therefore highlighted. According to the description above, the research question of this step can be formulated as follows:

"How can the initial usage hypothesis of a product be described holistically?"

The approach for the modeling of usage hypotheses will be examined in detail in the following.

4.1. Determination of relevant product functions

The usage hypothesis should summarize all assumptions from development about product functions and their characteristics during the product use phase so that the assumptions can subsequently be validated data-based.

In doing so, due to the mass of information on functions and their characteristics, not all of them should be considered equally. Before modeling the usage hypothesis, the relevant product functions for the identification of innovation potential are therefore determined.

The first step is thus the determination of relevant product functions that need to be considered in the modeling of the usage hypothesis. For this purpose, functions should be derived from product requirements. Product requirements can be either qualitative, normative, technological or functional requirements. Since functional requirements define the benefit for the customer, they are focused in this approach. [35] In order to focus on the most relevant requirements and to derive those product functions which presumably offer the greatest innovation potential, the so-called unique selling proposition (USP, often also known as unique selling point) was identified as a suitable filter. According to [36], who is regarded as the founder of the USP concept, a USP is defined as a specific benefit that the product provides and thus encourages the customer to buy it. Furthermore, his concept of USP is relying on the assumption that, in the same industry, the technological advance would build distinctive functional advantages for a product, and such distinctive advantages could not be matched by competitors in a given time period. The criterion resulting from the definition of USP for prioritizing product requirements is therefore the question “Which functional requirements do we serve better than the competition?” In this way, those requirements are identified which serve to differentiate the product from those of competitors. Once these requirements have been identified, they are translated into those main functions that serve to fulfill them. This procedure is summarized in figure 7.

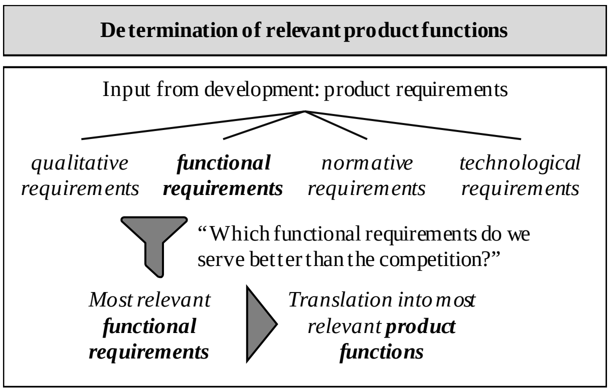

Fig. 7: *Determination of relevant product functions*

4.2. Modeling of relevant product functions as usage hypothesis

After the previous determination of the most relevant product functions, the next step is to describe the hypothetical state of the functions and their characteristics during product usage. The state of the functions in this context should mean the way those functions behave due to the specific way of use. For this purpose, each main function is subdivided into further sub-functions until the sub-functions can be described by one of the generally applicable functions (see chapter 2). The approach then provides a selection of descriptive characteristics for each generally applicable function. For example, the generally applicable function “conduct material” can be described by the characteristic “volume flow” in the unit [m^3/s]. In this way, the user of the approach is provided with a selection of predefined general characteristics by which the functions of his usage hypothesis are defined. For illustration, figure 8 shows an extract of the determined characteristics for the input/output variables energy, material and signal in combination with the generally applicable functions change, conduct and store.

	change	conduct	store
Energy	increase of torque, force, electricity, potential [%]	force [N] electricity [A] electric potential [V] resistance [Ω]	capacity [Ah] position energy [J]
Material	increase of geometric dimensions [mm] [%] increase of pressure [Pa][%]	volume flow [m³/s] volume [m³] flow duration [min]	storage capacity [m³]
Signal	change of signal amplitude [%] change of signal frequency [%]	transfer rate [kbit/s] transfer speed [m/s]	storage capacity [kbit]

Fig. 8: *Definition of generic characteristics for generally applicable functions*

In order to further detail this, the next step describes the assumed status of these characteristics during use phase. For this purpose, both the possible range and the assumed average value are defined.

In the example below, the hypothetical range of the characteristic “volume flow” goes from 0.2 to 1.8 m^3/s with the assumed average value in use of the product being 1.5 m^3/s (see figure 9).

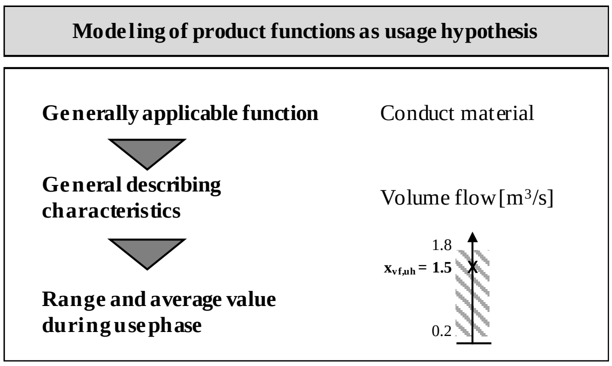

Fig. 9. *Modeling of product functions as usage hypothesis*

In this way, the function structure derived from the most important requirements in the first step, i.e. main functions and their sub-functions, is detailed by characteristics and their assumed range and status in usage.

The last step of the description of usage hypotheses is the recombination of all relevant functions in one overall model. As described before, a model always represents an approximation of reality with regard to a specific purpose and therefore separates essential aspects from unessential aspects (see chapter 2). In this case, the overall model of the usage hypothesis contains all identified relevant main functions, broken down to those sub-functions that can be combined with one of the generally applicable functions and their generic describing characteristics. It depicts the specific usage hypothesis for the whole product in focusing on its greatest innovation potential.

As shown in figure 6, this model is subsequently validated through the analysis of product usage data in order to derive innovation potential out of identified derivations between usage hypothesis and real product usage.

5. SUMMARY AND FURTHER RESEARCH

In this paper, an approach was presented to model the assumptions on product usage in a function-based usage hypothesis. This usage hypothesis represents the first partial model of an overall procedure for identifying innovation potential through the analysis of product usage data. After a short introduction and motivation of the topic, relevant fundamentals were presented. From the subsequent presentation and evaluation of existing approaches, the need for models of usage hypotheses was derived. In the following, the research approach was described in detail in two steps. The first step serves to derive relevant functions from the filtering of functional product requirements. In the next step, the relevant functions are broken down into sub-functions until they can be described by a generally applicable function. To describe the functions in more detail, generic characteristics have been developed for these generally applicable functions. These characteristics are described in their theoretically possible range as well as in their assumed average value in use.

Further research will consist in elaborating the next partial models. In this context, it will be investigated how relevant product usage data can be derived from the usage hypothesis. The analysis of deviations between the usage hypothesis and the real product usage is to be systematized in such a way that particular innovation potential can be derived and generic measures can be given to exploit this potential.

6. ACKNOWLEDGEMENT

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CORRESPONDENCE

Annika Becker
RWTH Aachen University
Faculty of Mechanical Engineering,
Campus Boulevard 30
52074 Aachen, Germany
a.becker@wzl.rwth-aachen.de