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Development of Modular Product Families: Integration of Design for Variety and Modularization

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Abstract
This article presents a new approach to integrating design for variety and modularization, and evaluates the approach on the basis of a case study.

Keywords: Modularization, Platform-based development, Design for Variety

1 Introduction

In recent decades, European industry has seen a large number of competitors evolve as a result of the opening of borders and markets. This trend has been accelerated by advances in information technology, which provides new and cost-efficient distribution channels [1]. Additionally, lower transportation costs have reduced the importance of geographical proximity to the customer. The resulting global competition has created a buyer's market in many industries. In this market situation, customers expect their demands to be fulfilled at low cost.

To succeed in this environment, European mechanical engineering companies often aim for a differentiation strategy. Differentiation is usually achieved through manufacturing quality and satisfaction of diverse customer demand. However, satisfaction of customer demand results in rising product variety. This strategy therefore carries the risk of increasing cost disparities between cost leaders and differentiated companies. This means that at a certain level of cost divergence, differentiated products cannot induce customer loyalty [2]. To avoid this risk, cost-efficient ways of providing the external variety must be found (figure 1).

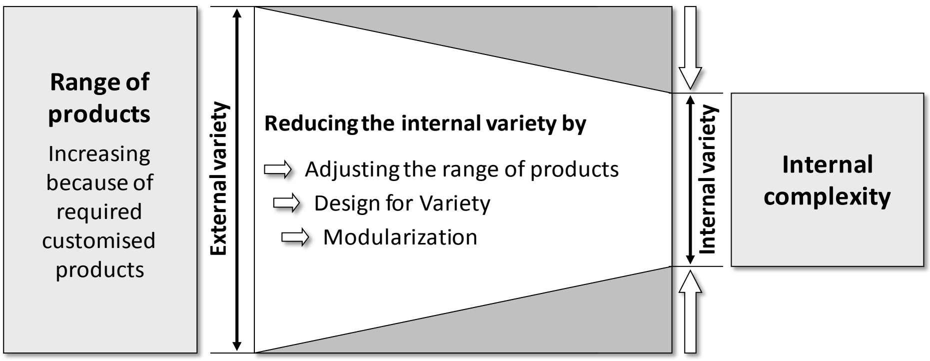

Figure 1. Motivation for Design for Variety and Modularization [3]

Other than consolidation of the product range, the development of modular product families is an effective way of improving the external/internal variety ratio. The communality and combinability of components are significant features of the modularity of a product family [4]. Achieving these goals requires a design for variety of components (communality) as well as a modularization of the product family (combinability). The following section of this article provides an overview of the basic design for variety and modularization approaches, followed by a description of our integrated approach for the development of modular product families.

2 State of technology

This section outlines the basic approaches to the development of modular product families. These are divided into design for variety approaches and approaches for the development of modular product structures.

2.1. Design for Variety

Basic principles of the *Design for Variety* approach according to Martin [5] are the key figures Generational Variety Index (GVI) and Coupling Index (CI). The GVI is an indicator of the amount of redesign required for a component to meet future requirements. The CI indicates the strength of coupling between the components in a product. Actions for platform development and component design are subsequently derived from the key figures.
Firchau [6] introduces a process for the *development of variety-optimized products* based on known approaches. In line with the VDI 2221, the process is divided into 7 phases. Firchau assigns individual steps involving known methods to these 7 phases. The result is a detailed process for the variety-optimized design of products. The proposed process is supplemented by design for variety guidelines.

2.2. Development of modular product structures

The *Method of Module Heuristics* according to Stone [7] allows the development of modular product architectures on the basis of function structures. Modules are identified by the three heuristics dominant flow, branching flow and conversion transmission. Subsequently, the proposed modules are combined into an overall solution.
Pimmler and Eppinger [8] subdivide their *Integration Analysis Methodology* into the three steps functional decomposition of the product into components, documentation of the interaction between the components and matrix-based clustering of the components into chunks. Their method is based on the Design Structure Matrix (DSM), which illustrates the relationships between components. Four different interaction types are considered: spatial, energy, information and materials. Module definition is achieved by clustering the components into chunks using permutation algorithms.
In his *Modular Product Development*, Göpfert [9] aims to combine modularization of product architecture with organizational structure. His approach is based on the visualization of the product’s functional and building structure in a diamond-shaped network diagram. The visualization is used to develop modules, which are mostly functionally and physically independent. Organizational units are then assigned to the modules.
Erixon [10] considers product-strategic aspects in his *Modular Function Deployment* method. This method is based on a Module Indication Matrix (MIM) which links the components of a product with so-called module drivers. Module drivers are reasons for defining modules from different phases of the product lifecycle. Erixon defines 12 general module drivers from the fields of design and development, variance, manufacturing, quality, purchase and after-sales. In the MIM, every component is weighted in a scale of 9, 3, 1 and 0 according to the importance of the driver for being a module. The components with a high overall score are candidates for modularization, meaning they can either be a module themselves or be the base

for a module. Additionally, components with similar module driver profiles can be identified and considered for integration into one module.

3 Our proposition

The previous section provided an overview of approaches for the development of modular product families. Design for variety approaches focus on the design of components and product structures in order to minimize internal variety. This results in component designs and product structures that succeed in reducing internal variety but do not meet the requirements of other stages within the lifecycle of a product (such as sourcing or manufacturing).
By contrast, modularization approaches examine the product structure in a much broader way. In particular, Erixon's module drivers point out the diverse requirements for the product structure derived from the lifecycle of a product. However, no modularization approach includes a design for variety of components. This is a disadvantage because minimized internal variety is a prerequisite for effective modularization. It enables the development of modular product structures which allow a simple configuration of diverse product variants.

In light of these observations, this paper proposes a consistent approach for the development of modular product families, combining the benefits of common design for variety and modularization approaches. This approach responds to the following questions:

- *How can design for variety and modularization be combined to form a consistent approach?*
- *Are the intended benefits achieved by an integrated approach, especially when compared to separate application of the two respective approaches?*

Our proposed method is based on the observation that sequential integration of these approaches brings considerable benefits. The aim of sequential integration is to modularize a product family on the basis of components created by using design for variety. We will examine this approach using the example of a design for variety method [11] and a method for the development of modular product structures [12] derived from previous research at our institute. The following section evaluates sequential integration on the basis of a case study.

4 Applying an integrated approach to the development of modular product families

The method will be applied to the example of a product family of spraying systems for herbicides which were the subject matter of the AIF-founded research project AUXESIA. A description of the family of spraying systems will be given before the integrated approach and its application can be described. We will then illustrate our method by running through the steps analysis of the existing product variety, design for variety and modularization, before describing the outcome of the method.

4.1. The MANKAR-Roll family

The MANKAR-Roll family by Mantis ULV spraying systems consists of Ultra Low Volume (ULV) Spraying Systems for herbicides in a wheelbarrow design. An example of such a spraying system is shown in figure 2. Spraying systems of this type are used for large in-row cultivations and public places. In contrast with other spraying systems, ULV technology allows an undiluted application of herbicide. This enables a much more efficient use of the herbicide and thus helps to protect the environment.
All MANKAR-Roll products consist of a mainframe, handle, wheel and spray hood. When sprayed, the undiluted herbicide passes through the components reservoir, pump, segment rotary nozzle and battery. The herbicide is stored in the reservoir, from where the pump presses it to the segment rotary nozzles and doses it in accordance with the distance it travels.

The segment rotary nozzles atomize the herbicide using rotation achieved by integrated electric motors. These motors derive their energy from the central battery.

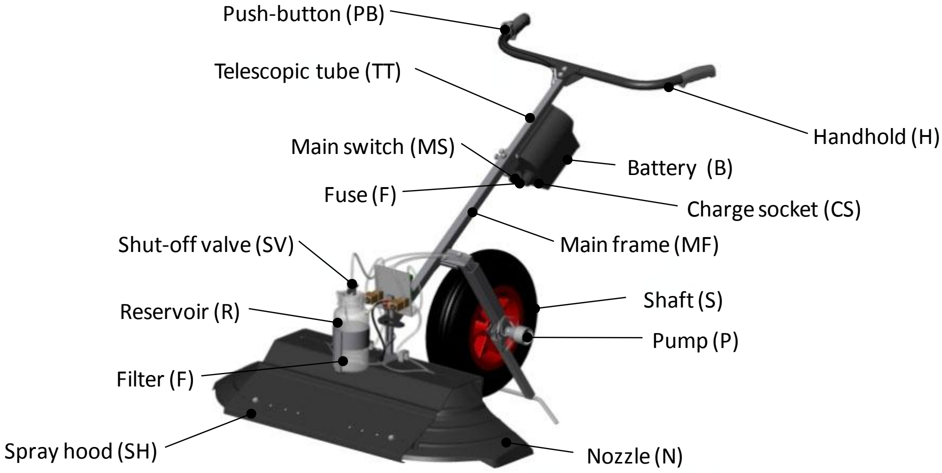

Figure 2: MANKAR-Roll spraying system for herbicide

Variety is achieved within the product family for example through varying spray widths. To fulfill various customer requirements, the product family covers a spraying area from 30cm up to 110cm. The spray width can be altered using different numbers of segment rotary nozzles, 6 different spray hoods and 3 variants of the pump.

4.2. Analysis of the existing product variety

Applying the integrated approach, the first step is an analysis of the existing and proposed internal and external product variety. Therefore a feature tree is used as a model of external product variety (Figure 3 left).

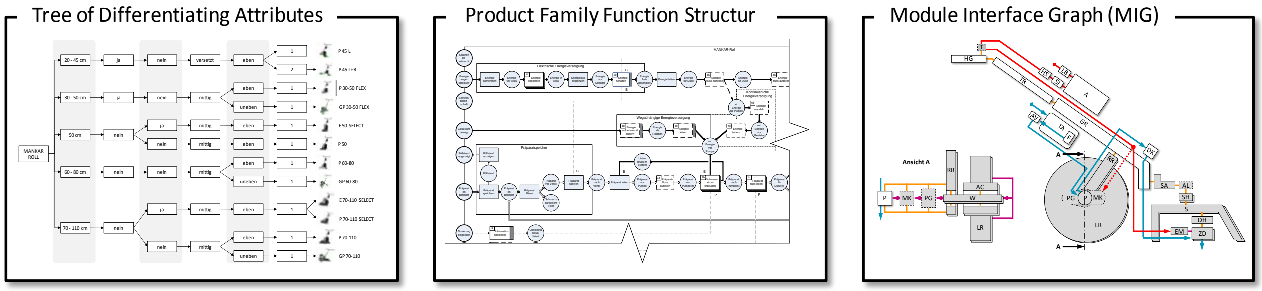

Figure 3: Partial models for the analysis of product variety

Internal variety can be analyzed through the overall function structure of the product family, sketches of variant working principles and the Module Interface Graph (MIG) [13]. The function structure of the product family (Figure 3 middle) is first drawn to capture the various functions. Then the working principles of the identified variant functions are sketched. In this way, the minimum necessary variance within the working principles can be identified. The MIG (Figure 3 right) provides a decomposed illustration of the product family. It visualizes the identified components of the product family, their couplings (structure, material, energy and information), their spatial arrangement and their variety.
Based on this analysis of internal and external variety, we will, in the following section, apply the design for variety method to the product family.

4.3. Design for variety in the MANKAR-Roll product family

Within an integrated approach, the aim of the design for variety method is to allow the development of a product family that achieves the desired external variety with a minimum of internal variety. This requires the development of new function structures, alternative working principles and component designs. This abstract objective can be applied to the product family design with the help of a reference model derived from previous research in this field [11]. This reference model describes design for variety within a product family on the basis of four simple characteristics. These are:

- Distinct differentiation between standard and variant components
- Reduction of the variant components to their variant elements
- 1-to-1 mapping of differentiating attributes and variant components
- Decoupling of variant components

This means the design for variety method must aim to achieve an approximation between the reference model and the design of the real product family. For this purpose, captured internal and external variety is summarized in the Variety Allocation Model (VAM). The VAM visualizes the variety at all levels of abstraction that are common in methodical product development (requirements, functions, working principles and components). Additionally, it illustrates the relationships between these levels.

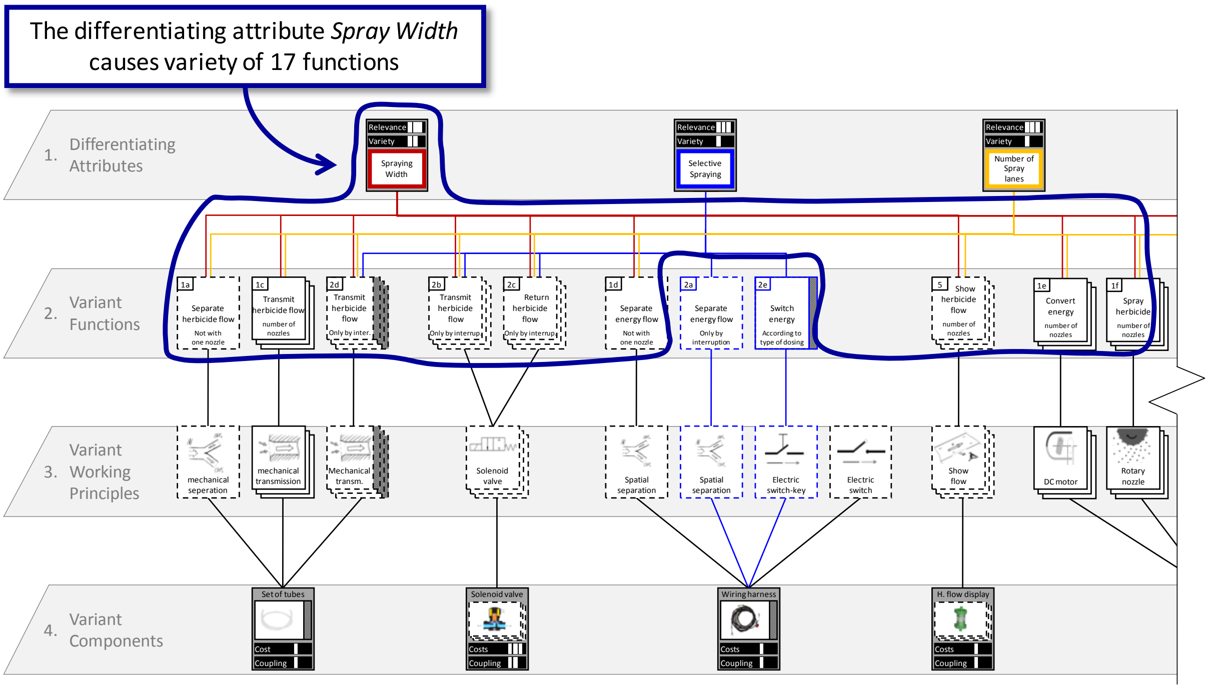

Figure 4. Applying the Variety Allocation Model (VAM) to the existing product family

At the first level, the model summarizes the differentiating attributes of the product family (Figure 4). At the second level, the model lists variant functions. The relationships between these levels show which differentiating attribute causes the variety of a function. This same concept is transferable to the levels of working principles and components.

On the one hand, the VAM is used in the design for variety method to identify priorities regarding the design of functions, working principles and components. On the other hand, it is used to evaluate the degree of fulfillment of the four characteristics of the reference model. The model thus enables a search and selection of alternative solutions within the design for variety method.

The following is an example of how the VAM operates in relation to the design of the functional structure of the MANKAR-Roll product family. Priorities for the design of the function structure can be identified in the VAM by counting the number of functions affected

by one differentiating attribute. If an extraordinary number of functions are affected, reducing this quantity will be a priority when designing the function structure. In the VAM of the existing product family, the differentiating attribute *Spray Width* (see figure 4 top left) causes the variance of 17 functions. By contrast, the differentiating attribute *Selective Spraying* affects 5 functions (Figure 4 top middle). Consequently, reducing the number of functions affected by *Spray Width* is a priority when designing the function structure.
The design for variety method facilitates the subsequent creative process of finding solutions through procedures, abstract solutions and design for variety guidelines [3]. One result of this creative process is visualized in the VAM of the final concept (see figure 5). Here, we see that the *Spray Width* affects only 2 functions, 2 working principles and 2 components (see figure 5 on the left). Compared with the original state, the result is far closer to the criterion of 1-to-1-mapping between the differentiating attribute and the variant components.

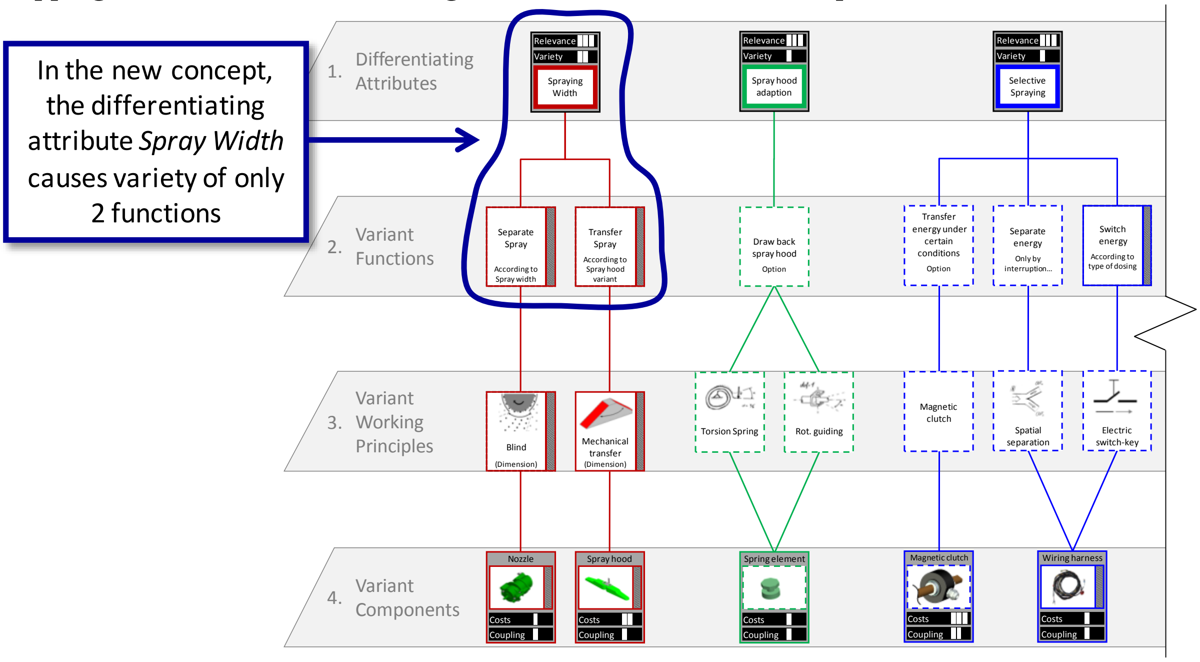

Figure 5. Applying the Variety Allocation Model (VAM) to the final concept

The final step in this design for variety methodology is the selection of one concept. The VAMs of the concepts are used to analyze to which extent the concepts meet the criteria of the reference model. Based on this analysis, a weighted point evaluation is carried out.
The result of the design for variety is a new set of components which achieve full external variety efficiently. In the case of the MANKAR-Roll family for example, the 1-to-1-mapping between differentiating attributes and components has nearly been achieved (Figure 5).

4.4. Lifecycle modularization of the MANKAR-Roll product family

Lifecycle modularization of the components takes place on the basis of the design for variety of the components [12]. This approach addresses a separate development of product structures in line with the product's life phases consisting in purchase, production, distribution, use and recycling/disposal. The modularization carried out is also consistent with the whole product life. The basic advantage of this approach is the adaptability of the product structures to the different life phases. This makes it possible to highlight clashes between different perspectives and facilitates the search for solutions.
Actual modularization is achieved through an extension of the module driver concept developed by Erixon [10]. As is shown in Figure 6, the module drivers have been assigned to different product life phases. The greatest advantage of the module driver concept is its adaptability to various corporate strategies. A disadvantage, however, is that the module drivers only provide very general guidelines for module deployment. For this reason, the

module drivers are further substantiated by product-specific module driver specifications. In the case of the spraying device, the technical specification of the module driver is substantiated, e.g. by the module driver specification *Terrain*.

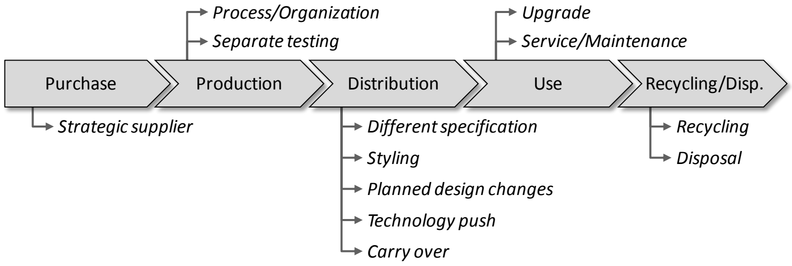

Figure 6. Allocating module drivers to product life phases

The development of modules is based on network diagrams, each of which applies to one particular product life phase. In the network diagrams, the product's components are linked to the module driver specifications of the particular product life phase. The aim of each network plan is to group the components that relate to one of the module driver specifications into one module. For instance, in Figure 7, components relating to the driver specification *Terrain* have been grouped into a module.

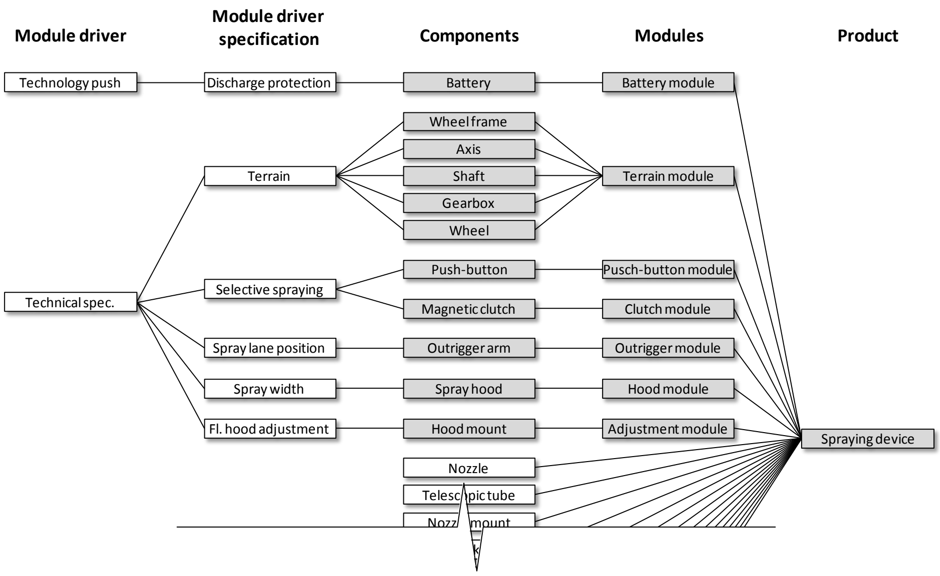

Figure 7. Modularization network diagram for the distribution phase

The particular product structures are then pulled together into a structure representing the entire product life (Figure 8). The starting point for the alignment of the different product structures is the distribution perspective. The aim is to compile the product's standard components within the product platform (see the highlighted frame in Figure 8) and to differentiate the variant modules. To achieve a modularization that is consistent throughout the life of the product, the product structure of the distribution phase is then aligned with the upstream and downstream product structures. For instance, in the case of the spraying device, the components flow control, spray hood, nozzle mount and nozzle can be purchased as a module from a supplier prior to the in-house assembly of the motor. In the distribution phase, the module can be used to create product variants with different spray widths. During the use phase the electric motor, which undergoes considerable wear, can be detached for maintenance reasons. Ultimately, the module can be broken down into synthetic and electrical waste.

As is illustrated in figure 8, this in turn allows a visualization of the detailed interface design of the modular product structure. The starting point is the left side of the model. Purchased modules can first be designed as integral constructions. In the subsequent assembly process, non-detachable connection types can be used. Easily detachable connection types do, however, have to be employed if the module must remain removable during the use phase. For recycling and disposal, destructive detachment of modules is an entirely feasible option.

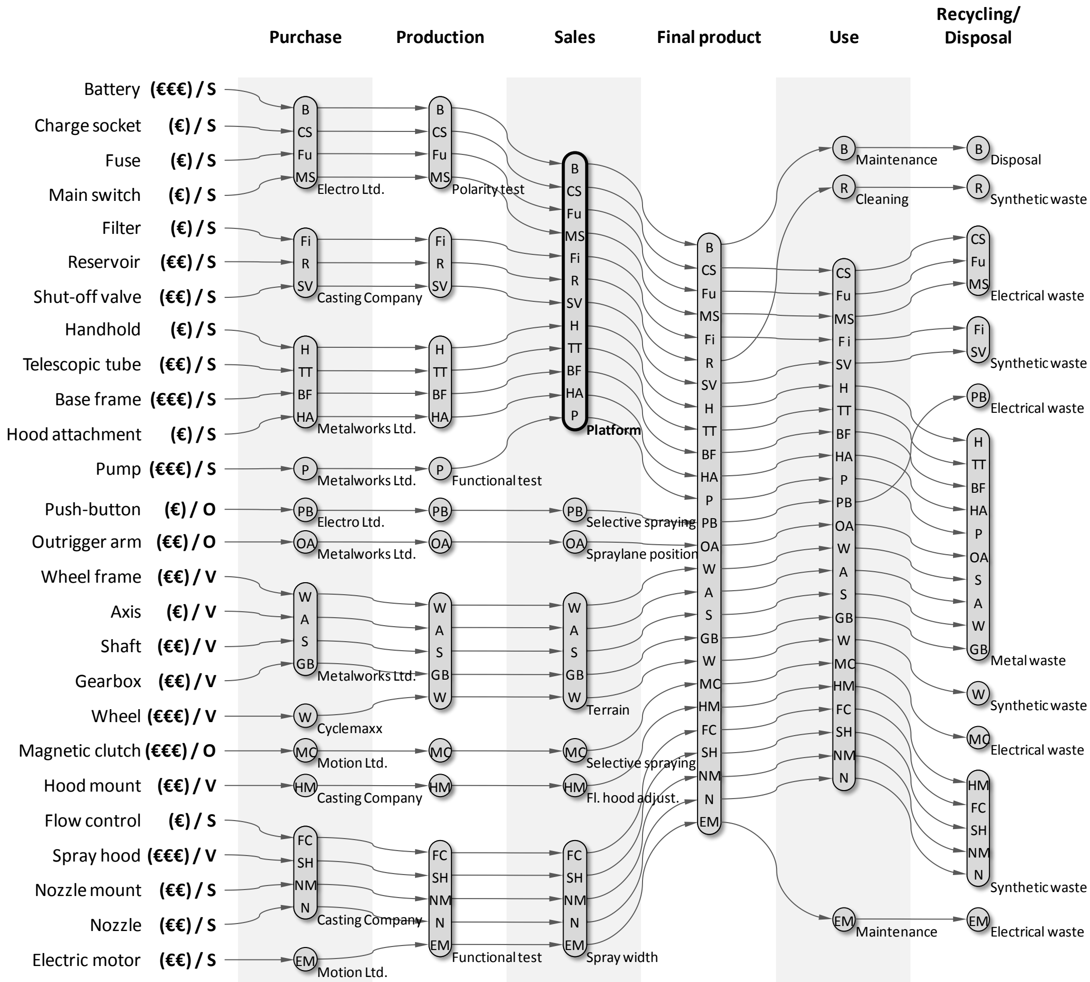

Figure 8. Modularization of the spraying device over the course of the product life

4.5. Analysis of the case study results

In this section, we will evaluate the success of the methodology applied in our case study by analyzing the resulting product concept. The criteria used for the evaluation are the preservation of external variety and the reduction of internal variety of the product family, the configurability of modules and the adjustment of the product structure to the entire product lifecycle.

4.5.1. Preservation of external variety

The new concept completely preserves the variety of the existing product family, including the differentiating attributes and their specifications. Our project partner also confirmed that customer perception of variety remains unchanged.

4.5.2. Reduction of internal variety

Due to the increasing number of standardized parts, the whole product family can be produced using approximately 39% less components. This assessment is based on the same product decomposition. Additionally, the modularization of components allows the 32 existing product variants to be assembled on the basis of one generic product and 10 variant modules (Figure 9). To date, the product family has been made up of 46 different components. Our approach can therefore achieve a considerable reduction of internal complexity in all departments of the company.

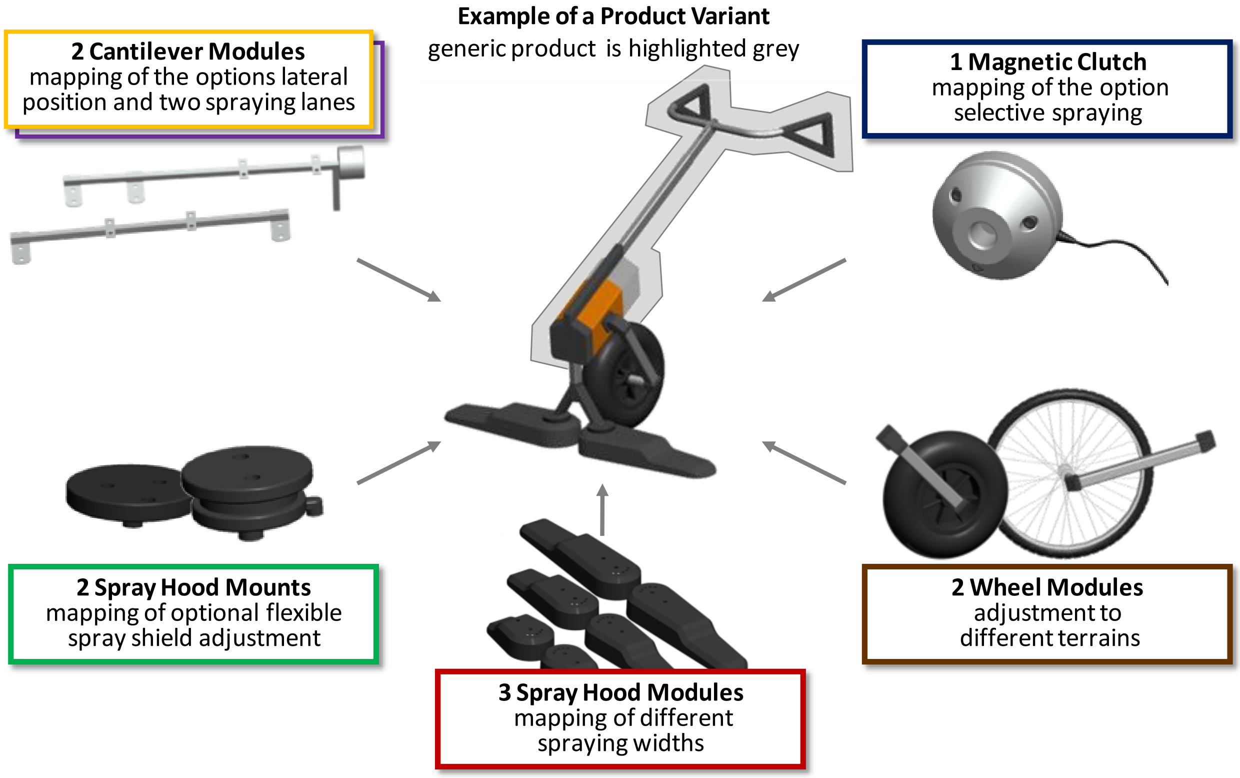

Figure 9: Developing product families from a variant module distribution perspective

4.5.3. Configurability of the product family

The nearly achieved 1-to-1 mapping between differentiating attributes and modules (Figure 9) facilitates the development of simple and unambiguous guidelines for the selection of variant modules. In addition, the simplicity of the module interfaces allows the customer to assemble the product himself. The combination of these aspects allows the product to be configured directly by the customer, thus facilitating the implementation of postponement strategies.

4.5.4. Adjustment of the product structure to the whole product lifecycle

In the pre-assembly process, 12 modules purchased from 5 suppliers are grouped into 10 assembly modules. The generic product and 6 different variant modules are delivered to distributors. These modules are sufficient to create the entire product family. Final assembly is carried out by the customer, locally. During the use phase, the reservoir can be separated for cleaning. As the battery and electric motor are subject to wear, they are provided as a replaceable module. Finally, the product can be disassembled into 10 disposal modules. Each of these modules belongs to 1 of 4 different material groups. The product structure is thus adapted to the requirements of the entire product lifecycle.

5 Conclusion and evaluation of our combined methodology

This paper points towards a possible way of combining design for variety and modularization methods within a single consistent methodology, and therefore responds to the first of the two fundamental questions which we pinpointed as the driving factors behind our research. In the first step, the actual product is analyzed, as is required for both methods. Subsequently however, the two methods are applied sequentially.

To evaluate the benefit of this approach in light of our second fundamental question, we applied both methods separately (not described in this paper) and then applied them sequentially.

When we carried out modularization separately, it became obvious that a grouping of components into modules is hardly possible due to the heterogeneity within the existing product family. Only minor changes could be made to the product structure. Individual application of the design for variety method simplifies the mapping between the differentiating attributes and the components and increases the number of standard parts within the product. However, the resulting product structure does not sufficiently meet the requirements of all stages within the product lifecycle.

Using the integrated methodology, it became possible to create a modularization that matches the requirements that flow from the distribution perspective. This is possible because a 1-to-1-mapping between differentiating attributes and variant components can be achieved when using the design for variety method. In addition, the generic product and numerous modules can be adapted to other stages in the product lifecycle like purchase and production.

In our case study, we developed a product structure which meets the requirements of all product life stages by using our integrated approach. This result could not be achieved by the separate application of the two methods in this specific case. Our ongoing research will focus on validating these results through additional case studies using the integrated Methodology for the Development of Modular Product Families.

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