Generic product model of air technology units – basis for the development of new, modular product families

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Abstract

Increasing product individualization demands flexible product families, for which modularization methods offer a promising approach. For practical application in developing modular product families of air technology units (e.g., air filtration and extraction units) in small and medium-sized enterprises, existing methods require adaptation. This paper presents a methodical approach for modularizing product families with a significant new development effort, building upon and refining existing minimum viable products. The foundation of this development is creating a generic product model describing interactions between product features, functions, effective principles, and components, structured as variety allocation model and multiple-domain matrix. The approach is employed in a case study.

Keywords

multiple-domain matrix, air technology, modularization, product structure, SME

 | DOI: 10.35199/dfx2025.10

1. Introduction and motivation

The increasing individualization of products establishes flexibility alongside time, costs, and quality as an important target parameter. Modularization offers a promising approach to address these challenges and create strategic competitive advantages. Small and medium-sized enterprises (SME) face particular challenges in the development of modular product families with small batch sizes. High initial modularization efforts and uncertain benefits, combined with limited resources and practical experience, create implementation barriers. Research on practical implementation experiences in SMEs remains limited [1]. Against this background, methodological approaches meeting SME-specific constraints become essential.

This article contributes to research on selecting and adapting existing modularization methods to SME constraints and their implementation in air technology applications. The term "air technology" encompasses air filtration and extraction units, as well as process air drying units. Customer requirements for these systems are highly individualized, varying in aspects such as filtered substances and air volume flow rates. In this paper, an approach for developing modular product families for air technology units in SMEs is presented, focusing on creating a generic product model that can be utilized for future projects.

2. Context of the research

The challenges of modularization are examined using the example of a product family for large equipment of air technology units with single and small batch production in the medium-sized company ULT AG. The development process of a product family is characterized by a high proportion of new development. Like the majority of development projects in practice, this development project can be classified as product generation development [2]. The product family builds on existing product generations and reference products [3]. The formulation and definition of necessary variance gains particular importance due to the significant new development efforts.

3. State of the art and research

The application of modularization methods requires a shift from individual product development toward comprehensive product family development [3]. Salvador describes five definitional perspectives of modularity: component commonality, component combinability, function binding, interface standardization and loose coupling [4]. Hackl refines these elements by distinguishing between properties and characteristics of modular product structures. She defines product family properties through common usage, combinability, and separability, while modules are characterized by oversizing, interface standardization, function binding, and decoupling [5]. These form important control variables in the development of the module structure.

Numerous methods exist for developing modular product families, ranging from customer-focused approaches such as modular function deployment (MFD) [6] to matrix-based approaches such as structural complexity management [7] and holistic approaches such as the integrated PKT-approach [3]. Krause and Ripperda conducted a systematic comparison of existing modularization methods based on self-selected criteria [8]. For practical application in SMEs, the following four criteria were identified as particularly relevant in the case study of the SME: product strategic modularization, product-related visualization, guidelines, and usability in corporate context. The integrated PKT-approach achieved the highest rating in these four relevant criteria [8]. The method provides four methodological building blocks for developing modular product families [3]:

- Product program planning

- Development of product programs with high commonality
- Variant-oriented product design
- Product lifecycle modularization

For defining the module structure, variant-oriented product design and product lifecycle modularization are relevant. These methods have already been successfully implemented in various companies, including SMEs [9, 10].

Silva and Santos describe the application of MFD in a SME that manufactures rigid inflatable boats. This company faced numerous challenges in applying the method. Being their first practical experience with modularization methods, the understanding of MFD terminology and concept was insufficient. To address this, interviews should be conducted to assess prior knowledge. Additionally, product experts focused on specific technical solutions rather than functions, leading to difficulties distinguishing between product properties and technical solutions. Consequently, connections between product properties and technical solutions were often inconsistent. This should be improved through multiple iterative passes for each process step. Apart from this challenging distinction, functional decomposition was also an obstacle. [1] They conclude: "Future work should focus on extending the use of modularization methods in SMEs from other industrial sectors. The struggle many Western SMEs face nowadays calls for more investigation on modularization methods." [1]

4. Research problem and objective

To introduce new product families to the market, it is advisable for companies to test market gaps with minimal development effort using a minimum viable product (MVP). During the development of an MVP, the basic structure is created, and potentially new technologies are implemented. At this stage, however, future use cases, functions, and operating principles are rarely fully defined. Design guidelines must be formulated for developing the MVP structure in order to efficiently incorporate additional requirements during subsequent modularization. This paper, however, focuses on developing a module structure with an existing MVP.

The field of air technology lacks documented applications of modularization methods. In addition to the wide range of requirements for air technology units, which is the main reason for modularization, there are certain specific characteristics in developing a modular product family for these devices. These units are characterized by components that are arranged along the airflow in a similar sequence. It is crucial to ensure minimal loss in airflow. This background results in a rigidly predetermined spatial structure. Additionally, the enclosure dimensions of these devices can vary significantly with changing requirements, such as different filter sizes or quantities. However, customers demand minimal footprint and height for these units. This emphasizes the importance of distinguishing between different construction sizes. This context necessitates tailored methods with a specific focus that also meet the requirements for a new product development method.

Beckmann et al. conducted a survey with 12 participants from different industries and positions regarding their requirements for product development methods. The participants were the target group of the methods and were already familiar with them. The most important requirements were that the methods should integrate into existing work practices and be aligned with user conventions. Furthermore, they should be efficient and easy to apply, focusing on essentials [11, 12]. These requirements must be considered when adapting existing methods to the needs of an SME in the field of air technology.

The following research question is formulated:

- Which tools and methods can be applied to efficiently develop the structure and design of modular product families for air technology units in medium-sized companies?

5. Research methods

This paper is based on a single in-depth case study. The integrated PKT-approach was chosen as the appropriate method following the method comparison in Section 2. The selection and adaptation of suitable methods and tools from the methodical toolkit, as well as the choice of supplementary methods, were guided by the following requirements of the company:

- systematic capture of customer requirements
- weighting of product features from the customer's perspective
- support for variant-oriented product design (adjustment of the MVP)
- defining the module structure with a focus on product strategy aspects
- clear visualization for shared understanding and as a basis for discussion
- Support in decision-making between variants
- optimization of the module structure for production
- reuse of data for future development projects

The following section introduces the methods used for developing the modular product family, along with those already employed by the company. The latter are crucial to ensure seamless integration of the new product development methods into existing workflows.

5.1. Relevant methods of the integrated PKT-approach

As a foundation for modularization, variant-oriented product design is necessary to achieve an ideal product structure that systematically differentiates between standard and variant components, whereby each variant component functions as a carrier for a single distinguishing feature. This structural approach necessitates a one-to-one mapping between distinguishing features and their corresponding variant components while ensuring the decoupling of variant components to maintain system modularity. [13]

For variant-appropriate product design, the Variety Allocation Model (VAM) was developed in the integrated PKT-approach to represent external and internal variety. This serves to identify weaknesses in existing product structures, such as functional structures or chosen constructions that exhibit excessive internal variety. The description of the variety takes place at the four abstraction levels of product development with increasing specificity: product features, functions, effective principles, and components. With the help of the VAM, both the variety of elements at the individual levels and the causal relationships between elements of different levels can be visualized. This makes weaknesses visible in the form of deviations from the ideal image. The representation provides illustrative transparency on how decisions in early product development phases influence internal variety. [13]

The elements at the different levels are compiled using various methods. The identification of distinguishing features is conducted through the Tree of Variety (ToV). The relevance to customer purchase decisions, determined by their position in the ToV, as well as the number of variations of each element, is indicated using a bar chart. The functions level is captured using function structures. For the diversity of effective principles, a distinction is made between individual effect elements (e.g., width of the roller surface) and entire effective principles (e.g., number of deflection rollers). This distinction is illustrated by their position in the effective principles level. Components are identified through decomposition, with a particular focus on the orientation towards final assembly. This decomposition is documented in a Module Interface Graph (MIG). Developed by Blees, the MIG not only represents decomposition but also visualizes modular concepts. It sketches the approximate spatial arrangement and placement of components, as well as their spatial coupling, and the flow of materials, energy, and information. [14] In the integrated PKT-approach, visual differentiation is generally achieved through the use of frames and fillings for variant, optional, and standard components.

The connection lines within the VAM represent specific causal relationships between hierarchical levels, where distinguishing features induce functional variance, functions necessitate corresponding effective principles for their realization, and components encompass the respective effective principles required for implementation. After capturing all elements in the VAM, alternative variant-oriented solution concepts are sought for the individual levels. [13]

5.2. Multiple-Domain-Matrix

In addition to the graphical representation in the VAM, a Multiple-Domain Matrix (MDM) is useful for systematic linking [15]. This allows elements within the VAM to be interconnected across individual levels. As a result, implicit knowledge can be systematically and comprehensively captured, making it valuable for future development projects. Küchenhof et al. present a matrix-based approach to evaluate the impact of generational variety on product family structures. The developed matrix connects trends, features, functions, effective principles, and components [16].

5.3. List of main features according to Pahl/Beitz

In the development of a modular product family with significant new development efforts, there is no existing variance of distinguishing features. Therefore, the requirements are recorded in the form of a list of main features (“Hauptmerkmalliste”) according to Pahl/Beitz, as is standard practice in the company. [17]

5.4. Modular function deployment / quality function deployment

The gathered requirements must be transformed into distinguishing features. The quality function deployment (QFD) matrix is well-suited for this purpose and is also used in the first phase of MFD to clarify product design specifications [6]. This matrix enables the translation of customer desires into product features, which form the top level of the VAM. Customer requirements are very individualized and not uniform, and they are collected through market analyses, sales and service experiences, and dealer insights. Technical features, on the other hand, are measurable. QFD helps determine the technical significance of product features by weighting customer requirements and evaluating them in the relationship matrix, which reflects the strength of a product feature's influence on customer requirements. Product features with high values are particularly relevant to customers [18]. Silva and Santos describe using this approach to translate 21 "customer values" into 48 "product properties." [1]

6. Implementation of the methods to the use case

The methods presented were integrated into the existing development process. The development of the modular product family follows the process outlined in Figure 1 [cf. 3].

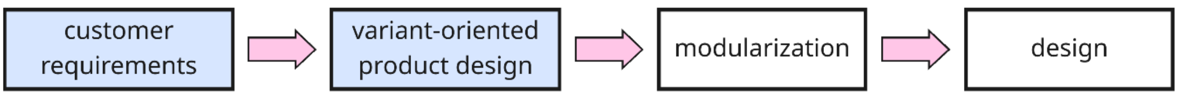

Figure 1: process for the development of modular air technology units

The process steps highlighted in blue in this figure (analysis of customer requirements and variant-oriented product design) are the focus of this paper. These steps prepare for the subsequent definition of the module structure. For these two steps, an adapted approach is presented in Figure 2, which meets the company's requirements.

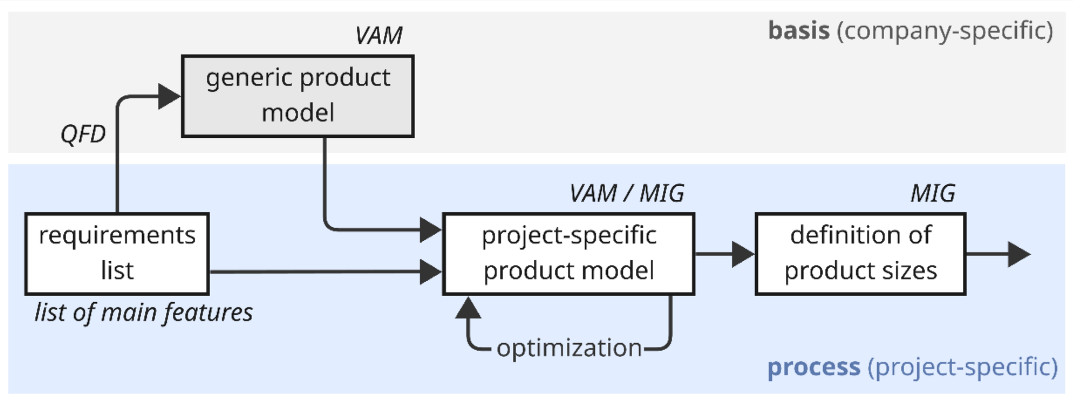

Figure 2: process model for variant-oriented product design of air filtration units

The approach builds on the methods and tools of the integrated PKT-approach developed by the Hamburg University of Technology, as well as the clarification phase of product design specifications in the MFD. The procedure and its implementation are explained in more detail in the following steps. Selected methods from the integrated PKT-approach are applied in collaborative workshops to achieve variant-oriented product design and modularization.

6.1. Transformation of customer requirements into weighted product features

The requirements list was created in the form of a list of main features, based on market analyses, distributor surveys, and feedback from sales and service, as is standard practice in the company. In the VAM according to Kipp, distinguishing features are recorded using the Tree of Variety (ToV). This is not present in the development of modular product families with a high proportion of new development. The variance of product features must first be established. Therefore, product features are developed and weighted using QFD based on the captured requirements. In this application case, it was necessary to iteratively supplement the distinguishing features during the creation of the generic model and determining their weighting.

Additionally, it was noted that requirements not only determine product features but also partially restrict the variance of effective principles and components. This must be considered when creating the project-specific product model at a later stage.

6.2. Generic product model

The generic product model is created using the VAM, based on expert knowledge. Possible variations of the individual elements were collected during this process. Delineating between the different levels when creating the VAM was challenging. The terms for the individual levels should be defined precisely beforehand.

Product feature: The distinction between properties and characteristics in the literature is unclear. According to Lindemann in VDI 2221, characteristics are defined as "a feature of a system whose manifestation causes it to be perceived as a property" [19, 20]. Weber offers another definition, also used by Krause, where properties cannot be directly influenced by the developer, are not quantifiable, and reflect the customer's perception. In contrast, characteristics are directly influenced by the developer and are quantifiable [3, 21]. Here, it is noted that in practical implementation, a strict separation between properties and characteristics according to the last definition is not feasible. Nevertheless, the top level is referred to as product features.

Function: Defined in VDI 2221 as the general and intended relationship between the input and output of a system to accomplish a task [20].

Effective principle: According to VDI 2221, these are understood as solution principles incorporating the employed physical effect, as well as geometric and material features. They describe effective geometries, movements, and materials. In practical implementation, these were used quite freely to describe various possibilities for realizing functions. [20]

Components: Understood as the smallest unit considered, which can be used individually for assemblies or parts. [3]

When constructing the VAM, it was found that building the generic product model from the "bottom up," from the perspective of possible components, and expanding it iteratively is helpful. With a high proportion of new development, traditional decomposition is not feasible. Therefore, a schematic model of a generic product was created, assigning the functions of individual components. These were transferred to the VAM, and additional elements were subsequently added. Creating a functional structure was unnecessary, as the spatial sequence of individual components is more relevant for air technology units. During VAM creation, product features with strong influence on many components were identified and extracted from the original structure. These features were mirrored with their functions and effective principles and arranged at the bottom of the VAM. This highlighted their cross-cutting significance and kept the structure clear and organized. In the case study, 26 distinguishing features, 30 functions, 40 effective principles, and 44 components were identified based on the first test project. A simplified section of the model is presented in figure 3 for confidentiality reasons. Since air technology units exhibit a rigid spatial structure, the VAM was organized around modules (e.g., filter chamber, intake) based on this sequence. Parallel to the VAM creation, possible variations of individual elements should be documented, as these cannot be represented in the VAM.

Subsequently, the VAM of the generic product model can be derived as a MDM. This can be expanded through future projects, allowing the generic product model to serve as a repository of experiential knowledge. Additionally, it can be enhanced by linking elements within a single level, which is not possible within the VAM. It should be noted that the elements are not variant in every product; this depends on the specific project and will be assessed in the next step.

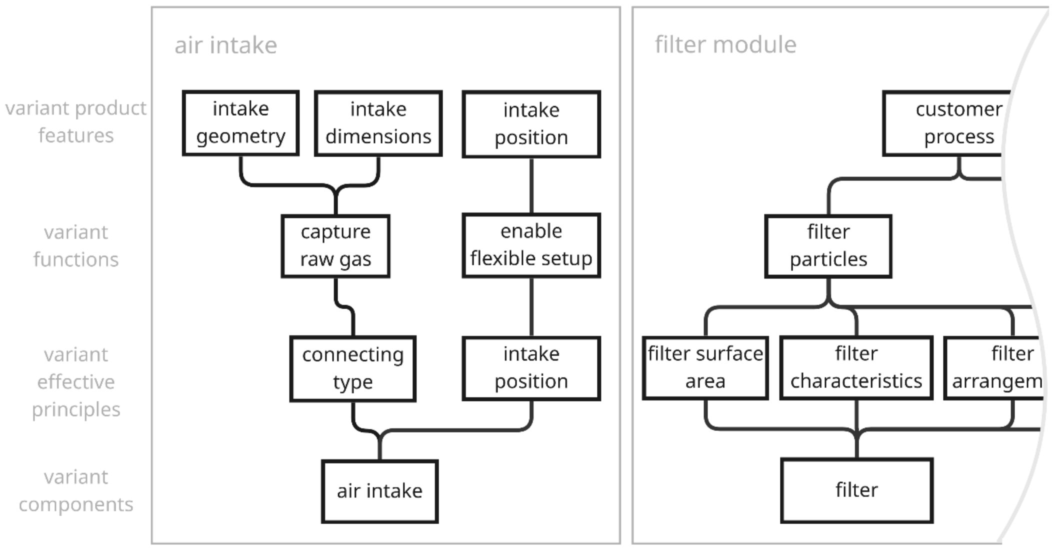

Figure 3: section of generic product model of air technology units (simplified)

The generic product model, as a project-neutral data basis, is applicable for use in future modularization projects. This allows for a reduction in effort for individual projects.

6.3. Project-specific product model

The generic product model is now transformed into a project-specific product model. This requires adapting the model to the respective project. First, the elements of the generic product model are constrained by the project-specific requirements. As a result, some elements or part of the variants of elements may be omitted. The remaining elements in the VAM are adjusted to fit the existing module structure of the MVP, thus altering the initially "ideal" structure of the generic product model. Subsequently, the elements are marked as variant, optional, or standard in the current project status using color and borders. It is expected that a high degree of variance might be present at the start of development. The project-specific product model for an air technology unit is depicted in a simplified manner in figure 4.

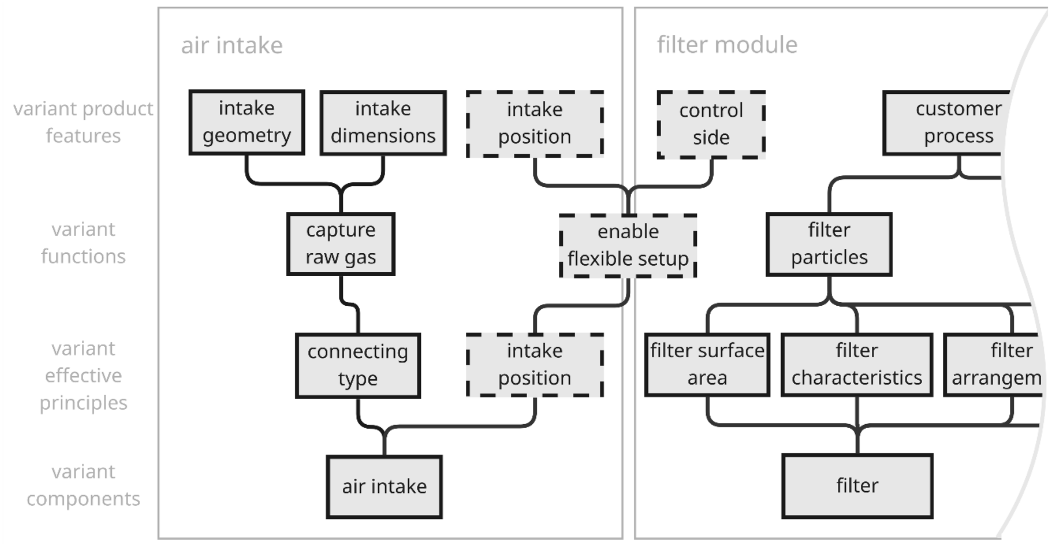

Figure 4: section of project-specific product model of an air technology unit (simplified)

Subsequently, strategies to optimize product structures within the VAM are applied to achieve variant-oriented product design with the most ideal structure possible. It is important to ensure that as few connection lines as possible cross module boundaries, so that each module effectively fulfills a specific set of product features. Concurrently, decisions on limiting the variants of elements should be made to determine which internal variance is truly necessary and should be implemented within the product family. Estimating complexity costs and evaluating customer relevance (in terms of QFD) can help assess how much element variants contribute to fulfilling customer requirements. These decisions should be made in workshop settings with representatives from different lifecycle phases. The VAM serves as a useful and illustrative discussion basis to understand the impacts of decisions. Geometric decision impacts can be further clarified through the Module Interface Graph (MIG). This process enables iterative optimization of the product structure.

6.4. Definition of product sizes

For large-sized air technology units, specific product features significantly impact enclosure dimensions. Since enclosures represent significant costs due to tightness and stability requirements, reducing the enclosure dimensions is crucial. Therefore, determining size levels is particularly important, as it conflicts with commonality. Components that heavily influence the overall size are highlighted in red in the VAM. The decision on size levels is then made iteratively in workshops using the MIG. The MIG is created for all size levels, and the range of options for elements within each size is restricted (e.g., limiting the number of possible filters in smaller sizes). Representing this limitation in the VAM is challenging, so creating a VAM for each size level is advisable. The color coding for elements should be further adjusted for individual components, ensuring sizes are scaled only as much as necessary, not as much as possible.

The result is a product structure concept with defined graduated product sizes. The goal is to scale as few components/modules as possible across the size levels. Components that can be used as standard parts in all sizes are marked in green in the VAM. The developed product structure later serves as the basis for creating the variant bill of materials. Structured recording of product features, functions, effective principles, and components is helpful here. The concept forms a foundation for modularization, which is not further focused on in this paper, as the emphasis is on production-ready implementation.

7. Results and discussion

As Silva and Santos also reported, distinguishing terminology was initially a problem in the case study, which was improved through clarification and examples. The described approach provides a systematic collection of customer requirements and weighting of product features from the customer's perspective, focusing on design from product-strategic aspects. It builds on the design of the MVP. Clear visualizations in the form of the VAM and MIG create a shared knowledge base and a discussion platform, which supports decisions between variants. This laid the groundwork for concrete module definition, which from the company's standpoint should promote production-ready design. The VAM method has the drawback that dependencies within the level are difficult to represent. Therefore, the method was expanded with a MDM. A foundation was established for reusing data for future development projects; however, it still requires manual input and evaluation. A digitization of the approach with consistent data in the VAM and MDM models is intended. Enhancing the connection lines between elements with rules would be beneficial.

8. Summary and outlook

This paper presents an adapted methodical approach for developing modular product families of air technology units in SMEs. This approach was implemented in a medium-sized enterprise as part of a case study. It combines established methods from the integrated PKT-approach of the Hamburg University of Technology with QFD and MDM. The process begins with the systematic transformation of customer requirements into weighted product features. Subsequently, a generic product model is created using the VAM, which, along with the MDM, serves as a reusable knowledge base. This can reduce the initial effort required for development in new projects. Project-specific adaptation occurs through iterative workshops with interdisciplinary teams, followed by defining size stages for the product family. Visualization using the VAM and MIG of the integrated PKT-approach proved to be a helpful tool for joint decision-making.

The proposed methodical approach demonstrates potential for transfer to analogous products such as water filtration systems, heat exchangers, and HVAC systems. These product categories are similarly characterized by sequential component arrangement along fluid flow paths, scalable construction sizes, pressure loss optimization requirements, and spatial constraints at customer installations.

The developed method is suitable for application in SMEs. Future development of the approach aims to digitize the methodology, with a software-supported implementation ensuring consistency between the different representations and reducing the effort required for changes. Expanding the generic knowledge base with a concrete description of restrictions would be beneficial. Fundamental design guidelines should be established for developing MVPs of air technology units to reduce the effort for variant-oriented design and modularization.

Acknowledgement

This project is co funded by the European Union and co financed from tax revenues on the basis of the budget adopted by the Saxon State Parliament.

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