Model-Based Handling of Variability in Offer Management in Mechanical and Plant Engineering

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Abstract: This paper introduces a model-based approach for the offer phase in special-purpose machinery, focusing on simplifying customer requirements, rapid solution design, and cross-domain interaction. A developed flexible configuration enables an efficient workflow, even without specific expertise, managing variance and enabling in-depth customization. It serves as the basis for post-order planning and is demonstrated in collaboration with a special-purpose machine manufacturer of the furniture industry. The conclusion discusses future steps in utilizing artificial intelligence.

Keywords: Model-Based Engineering, Mechatronics, Variant Management, Offer Management, Special-Purpose Machinery

1 Introduction

Mechanical and plant engineering and construction is a key factor in Europe's competitiveness, with Germany accounting for almost half of the value added in this sector in the European Union. The German mechanical engineering industry is characterized by a high degree of vertical integration, which underscores its outstanding position in providing tailor-made solutions for individual customer requirements (VDMA, 2021). The offer phase is a critical phase in special-purpose machinery, From the early cost estimation to the development of the initial solution concept, there are many challenges to overcome. Changes in customer requirements lead to increased iterations in this phase, which reduces the time needed to complete the offer (Weiser et al., 2015). One of the main causes of these challenges is the increasing complexity of machine systems (Dumitrescu et al., 2021). Advances in automation, robotics and networking require increased collaboration and coordination between the various departments involved in the offer phase. The interactions between the development of the customer's product and the manufacturer's production system must be considered in an integrated manner (Disselkamp et al., 2024). The technical sales department, which is mainly responsible for this phase, often does not have all the expertise of the individual technical departments (Kleinaltenkamp, 1999). The offer phase in special-purpose machinery is characterized by high variability that needs to be successfully managed. This variability is a result of the variety and complexity of customer requirements, as well as the different solution concepts that are under consideration. The product range of companies is often divided into standard solutions, which can be ordered via a catalogue, and customer-specific solutions. Unlike standard products, customized solutions require engineering efforts specific to each order and are characterized by greater product complexity (VDI 2221 Part 2, 2019). Each customer has unique needs and specific technical requirements, customer requirements can vary widely. This requires structuring and documenting these diverse customer requirements to ensure that they are fully captured and correctly interpreted. On the other hand, variability is also related to the numerous solution concepts that are considered during the offer phase (Eberhardt-Motzelt, 2014). To achieve efficiency and cost savings, there is a desire to reuse proven approaches and technologies that have already been developed. The challenge is to integrate the variety of customer requirements and the simultaneous variety of possible solutions into a structured and efficient process in order to create optimal offers.

Systems Engineering (SE) is an appropriate approach to address these challenges and cope with increasing complexity of mechatronic systems (Dumitrescu et al., 2021; Wilke et al., 2023). According to the International Council on Systems Engineering (INCOSE), SE is defined as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts and scientific, technological, and management methods" (INCOSE, 2023). Model-Based Systems Engineering (MBSE) is a concrete method in which models serve as central tools for defining, analyzing, and documenting systems (Gausemeier et al., 2019). By using MBSE in the offer phase, common platforms can be created on which different departments can contribute their expertise and requirements. This not only avoids misunderstandings, but also ensures that solutions are continually improved.

This paper presents a model-based approach to address the mentioned challenges. The research emphasizes the importance of interdisciplinary collaboration in the development of a mechatronic system and the role of technical sales in this process. Section 2 introduces key terms for the topic. It presents the offer process, the challenges for technical sales, and the potential for MBSE in this area. The problem is summarized and research questions for this paper are presented in section 2.5. Section 3 gives an overview of the state of the art. In section 4, a flexible configuration model is presented that is intended to guarantee simplified and efficient work processing for technical sales (even without model-based expertise).

The model was validated together with a special-purpose machine manufacturer of the furniture industry. This procedure is presented in section 4.3. For this use case, the approach was set up in the MBSE tool iQUAVIS (cf. section 4.4). Finally, a conclusion and an outlook on future research steps are given (cf. section 5).

2 Offer management in special-purpose machinery

2.1 Classification of the design strategies in special-purpose machinery

There are two main categories of machine manufacturers in the special-purpose machinery industry: those that focus on Engineer-to-Order (ETO) for special-purpose machines and others that focus on Configure-to-Order (CTO) for series machines. Due to the unpredictability of customer requirements, machine manufacturers in high-wage countries tend to follow a **combined strategy** that integrates elements of both approaches (Brecher, 2011). Order processing in special-purpose machinery is largely based on **pre-planned standard variants** to efficiently meet frequently recurring customer requirements. This enables an optimized and cost-controlled production. However, a significant proportion of orders require **customer-specific adaptations or new developments**. 55% of all the orders received in the mechanical engineering sector requires adaptation design (Kurz et al., 2004). This flexible approach to specific customer needs is a key challenge that requires both technological innovation and close cooperation between customer and manufacturer.

2.2 Definition of the terminology of variance, variability and variants

There is a high degree of variance in the field of special-purpose machinery, as mentioned in the introduction. As part of the explanation of this challenge, we will first have a look at the terminology.

The terms variant, variability and variance are often used synonymously in the context of different product characteristics. In the following, the terms are defined and placed in relation to each other. The definition of **variants** based on the findings of FRANKE et al. states that a variant of a technical system must fulfill the same purpose and differ from the original technical system in at least one relationship or element (Franke, 2002). According to DIN 199, product variants are described as "objects of similar form or function with a generally high proportion of identical groups or parts" (DIN 199, 2000). Variant management as a whole is the active and comprehensive design of the product architecture and the variable technical characteristics of products and product portfolios (VDI 2221 Part 1, 2019). In the design context, a distinction is made between **variant, adaptation and new design**. A variant design is configured by combining different prefabricated modules. New principle solutions do not have to be considered in this process, as reference is made to known principles. A **customized design** is individually adapted to customer requirements. An existing product serves as the basis, which is adapted according to specific customer requirements or changed market conditions. Certain sub-functions can be completely redesigned. Investment goods are typical representatives of this type of design. In a new design, all aspects of the product are redesigned. New principle solutions are considered and the complete development process is carried out (VDI 2222 Blatt 1, 1997).

In general, variability is the ability of something to change. In the context of a company's product portfolio, variability explains the extent to which the products in the portfolio differ from one another. According to POHL and METZGER, a distinction is made between external and internal variability. **External variability** describes the customer's perception of all differentiated features and is expressed in the form of requirements. **Internal variability** describes the differences in the product with regard to technical solutions and development. It is not apparent to the customer. The focus is therefore on the requirements externally and the technical solutions internally. In this context, the terms **variance** and variability can be treated as synonyms and are defined identically. In order to be able to realize a concrete product, the variability or variance must be resolved and represented by a variant (Eigner et al., 2017). Variability, variance and variants are therefore directly related to each other. The totality of all variants of a product is represented by the variability or variance. The variants are the realizable characteristics of the variance or variability of the product.

2.3 Challenges of technical sales in the offer phase

The offer phase in the area of customized machines and industrial plant projects is addressed by the VDI standard "Offer management in the industrial goods business" (VDI 4504 Blatt 1, 2010). The abbreviation VDI stands for Verein Deutscher Ingenieure (Association of German Engineers), which uses scientific and practical expertise to define standards and recommendations in technical and scientific fields. VDI 4504 deals specifically with offer management in the field of industrial goods. It outlines the procedures for preparing, submitting, and tracking offers for complex and customized products and services. Regarding the VDI 4504, the offer process is divided into three main phases:

1. **Register & evaluate the inquiry:** In this phase, the customer's requirements are analyzed and a decision is made to prepare an offer. In addition, internal resources are evaluated.

2. **Prepare & present the offer:** In this phase, the offer is prepared according to the customer's requirements, including cost and price calculations, offer design, document preparation and final submission to the customer.

3. **Track the offer & evaluate:** The final stage of the offer management process is the review and monitoring of the proposal, including customer feedback and internal evaluations to identify areas for improvement.

In addition to the process description, the VDI also provides organizational tips for successful offer processing. Among other things, it is pointed out that an important prerequisite for optimal offer management is the existence or development of systems for structuring products, technical processes and services (classification and key systems, lists of characteristics, etc.) and customers (customer segments). A company should have a system for classifying and categorizing requests and offers. By archiving offers according to such criteria and attributes, a knowledge database is built up. For new requests, it is possible to quickly access comparable requests in the old database and use the previously created offer as a reference. This reduces the amount of search time and errors (VDI 4504 Blatt 1, 2010). However, **a concrete methodical implementation of these suggestions is not given**, so that it remains unclear how a company should proceed to establish such a knowledge base.

In 2007, the VDI Technical Committee "Operational Sales" conducted a survey on business-to-business projects to substantiate the VDI guideline 4504 on offer management in the industrial goods business. The 281 participants identified **several areas for improvement** (Schmidt, 2008): Improved IT support through CRM, ERP and product configurators, introduction of modular construction methods or modular systems, promoting transparency and communication (internally and externally), consistent information flow, improved calculation basis, and optimized access to the required information. For a more in-depth analysis, Fraunhofer Research Institute for Mechatronic Systems Design IEM conducted a **qualitative study on the challenges of technical sales in special-purpose machinery**. The study, described in detail in (Wilke et al., 2024b), surveyed fourteen special-purpose machinery companies. In summary, the most frequently cited challenge from the interview study was the challenge of multiple iterations, caused by customer changes and internal agreements, and changes during the offer phase. Other serious challenges for companies are a lack of prior technical knowledge and low data transparency on the customer side, as well as high external pressure to customize. From an internal perspective, the main challenge is a disagreement on the technical solution concept between specialist departments and technical sales, and a lack of internal communication. Assessing the cost-benefit ratio during the offer preparation process is also seen as a significant internal challenge. In addition, the interview study revealed that the most used method is the use of checklists and work instructions, and that many analyses, such as feasibility or risk analysis, are based only on the knowledge of the employees. Regarding the use of IT systems, it was found that companies mostly use unlinked text editors (e.g., Word, Excel) and have not yet adopted knowledge base systems or model-based approaches. It can therefore be assumed that the potential for improvement identified in the 2007 study has existed for several years but has not yet been sufficiently realized. The VDI process has to be adapted: Descriptions of methodologies and concepts to improve e.g. transparency and communication need to be added (Mundt et al., 2023).

2.4 Potentials of (Model-Based) Systems Engineering for the offer phase in special-purpose machinery

In three preliminary projects, SE potentials for the offer phase were identified with special-purpose machinery manufacturers in order to master the challenges of developing a mechatronic system. The paper (Wilke et al., 2023) summarizes the identified potential of using a model-based approach during the offer phase in special-purpose machinery. It shows how the challenges identified in literature and practice (cf. section 2.3) can be addressed by MBSE. Figure 1 shows an overview of the MBSE potentials and use cases for the offer phase (Wilke et al., 2023).

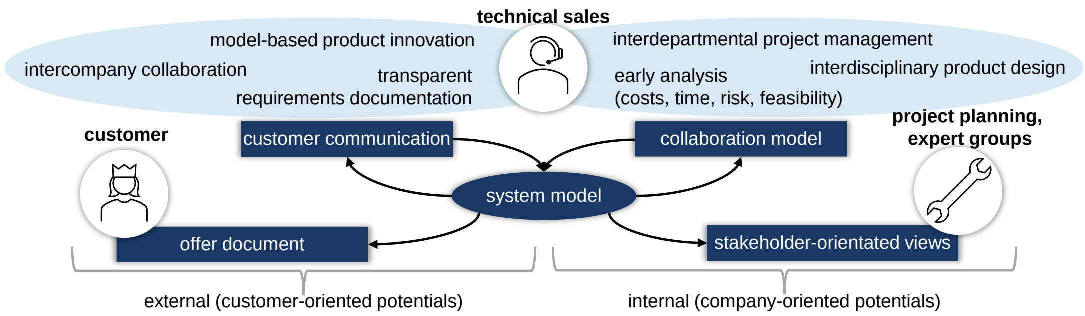

Figure 1. SE potentials (shown in light blue) and use cases (shown in dark blue) for the offer phase (Wilke et al., 2023)

SE promotes "model-based product innovations". This represents great potential for special-purpose machinery, as this industry is characterized by a high level of innovation. Due to the limited domain-specific experience of technical sales, innovative solutions are often lacking, especially regarding the increasing complexity of systems. Technical sales need support in terms of domain knowledge to meet these challenges. “Interdisciplinary product design” enables the integration of knowledge from different disciplines. The potential benefit "cross-company collaboration" describes communication and cooperation with the customer from the early development phase to the end of the product life cycle. “Transparent requirements documentation” is defined by the systematic and interdisciplinary collection, documentation and management of requirements. The requirements should be analyzed and understood with the involvement of the customer and their individual needs in order to be able to create a comprehensive offer. This should be designed in a cost-benefit manner for the offer phase. "Interdepartmental project management" requires interdisciplinary cooperation and transparent project planning. "Early analysis" aims to save costs and time by minimizing risks and increasing reliability. A system model, which is already built in the offer phase, offers clear advantages through central availability, formal clarity and complete representation with explicit relationships between elements (Eigner et al., 2014).

2.5 Interim conclusion and research questions

In summary, it can be said that the offer phase in special-purpose machinery is a highly complex process that is characterized by external and internal variance (cf. section 2.2). The technical sales department is facing the tensions between individualization and standardization. This leads to various challenges that the industry tries to solve with a specific design strategy (cf. section 2.1). Although there is a standardized offer process according to the VDI, there is a lack of concrete methodological support (see section 2.3). The MBSE approach shows potential for methodological support and addresses the challenges of developing a mechatronic system (cf. section 2.4). However, there is still a lack of specific support tailored to the needs of technical sales departments. This raises the first **research question**, *which approaches from the literature are suitable for managing the variability in the offer phase of special-purpose machinery for product design?* The second question is *how these approaches can be integrated into a model-based working method?* To evaluate the state of the art for suitability, **requirements** are defined based on the previous problem analysis and have been reflected with a user company:

A1) Structured approach: The approach must offer a structured procedure to be able to work in a structured manner despite high variability and to be able to filter out existing solution concepts as efficiently as possible.

A2) Include & document interdisciplinary aspects: Today’s products imply a deep integration of different disciplines, which is also expressed by the term “mechatronic”. The approach should be able to document and use interdisciplinary interdependencies, consider them for own work, but also for internal and external communication.

A3) Comprehensive requirements capture: The approach must enable efficient communication with the customer regarding requirements capture to ensure solutions that meet the customer's specific needs and technical challenges, resulting in high customer satisfaction and efficient production processes. Technical details that are important for the subsequent detailed design should also be documented and traceable.

A4) Rapid concept development: Technical sales must be able to quickly develop mechatronic concepts for an initial offer. For this purpose, basic solution concepts should be quickly accessible and adaptable in the form of an internal knowledge base. This assumes that a company has already found a way to structure basic concepts or product variants, known as e.g. a product breakdown structure. (It is not the focus of this paper to provide a procedure for this structuring.)

A5) Ability to collaborate across departments: In case of special requests, technical sales should be able to get quick internal feedback from the specialist departments. Interdepartmental collaboration in specialty engineering is important because it enables the integrated approach necessary to develop complex and customized machine solutions that maximize efficiency and creativity, minimize errors and costs, and ensure customer satisfaction.

A6) Model-based representation: The approach should be model-based to promote transparency of decisions and agreements (with customers/internally), to handle mechatronic complexity, and to enable seamless model-based post-development, i.e. detailed design.

3 State of the art

A keyword search, derived from the research questions, was used to evaluate the state of the art. Approaches from the fields of MBSE, configuration management and customization design were examined for their suitability. In order to expand the scope and provide a more comprehensive view of the research topic, the literature search was progressively expanded by reviewing the papers cited in the sources. The main approaches that fit our requirements are presented below.

3.1 Introduction of the approaches

In searching the literature for approaches to dealing with variance, we found approaches that deal with modeling product variants and product lines. A product line refers to a group of products that are based on a common construction kit to realize required functionalities (features) (Schmid, 2010). Products in a product line are normally built on a common basis and have variation points, whereby the construction kit provides various building blocks for configuration.

Figure 2 provides an overview of the interdisciplinary product line approach according to VOGEL-HEUSER et al. which is divided into four areas. The modeling of the solution space from the customer's perspective and the identification of variants for the features required by the customer are supported by a variability model from the customer's perspective. A variability model from the developer's perspective allows the composition of variants from discipline-specific building blocks. An allocation matrix enables the mapping between solution and problem space. The definition of adaptation requirements for building blocks to resolve feature interactions takes place in the adaptation space.

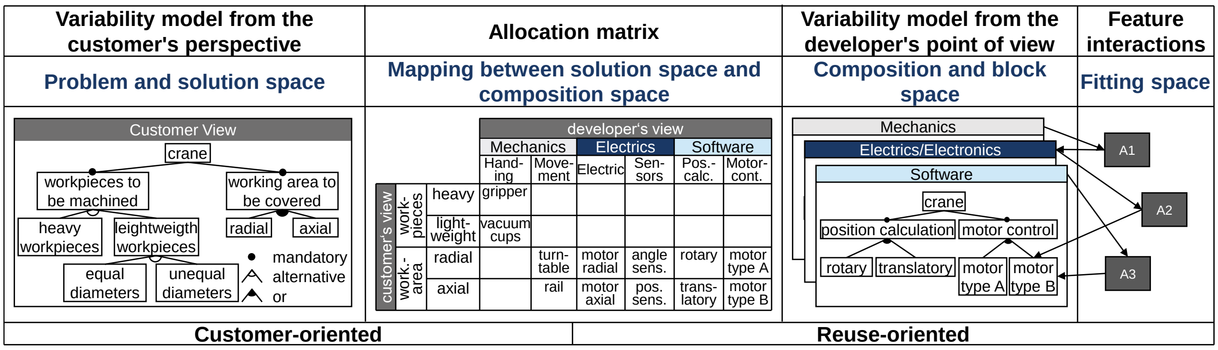

Figure 2. Overview of the interdisciplinary product line approach according to Vogel-Heuser (Vogel-Heuser et al., 2015)

KÜHN et al. (Kühn et al., 2014) have developed an model-based evaluation method that uses feature models to support decisions in the early stages of product development. The first step of the evaluation method is to list all the features of a system. Existing documents such as customer requirements lists or use cases can be used for this purpose. The second step is to identify optional features. It may not be possible to implement all features during product development, so alternatives are analyzed using the features documented in the first step. A hierarchical feature tree is created that clearly breaks down the features and shows possible relationships. In the third step, the specific dependencies between the features are analyzed in terms of technical feasibility. During the analysis, it may become apparent that some features are required to implement another feature and its system elements. Other features may complement each other in their function or may have opposing relationships and are therefore exclusive in their implementation. Once the dependency check is complete, the final step is to make a decision based on the previous findings.

Another MBSE approach, the VAMOS method by WEILKIENS, is a method for modeling variants with SysML (Weilkiens, 2016). It is based on the SYSMOD method and has been extended with concepts to represent variants in a manageable way. The extension consists of the three packages Core, Variations and Configurations, which build on each other. The product architecture of the Core package is modeled according to SYSMOD and extended by variation points that mark the variants. The core package contains all model elements that occur within the configurations and product variants. The variation package includes all variations. According to WEILKIENS, a variation is the set of all variants of a variation point. The configuration package shows the finally defined product variants, which are configured and formed from the core and variation elements.

The next approach (Schulte et al., 2016) focuses on an orthogonal variability model (OVM), which aims to create a variability model that is decoupled from a system model. When considering a product line, variation points (VP) are assigned to all areas that are flexible. The variants associated with the variation points indicate exactly how the aspects differ. The dependencies and possible combinations of VPs and variants are also considered in the model. To obtain a complete product, a variant must be selected. In the context of the research project mecPro² this approach is extended by some aspects. Variables represent exactly one different value between elements. They are linked to a VP and an element in the system model and pass on their value to the system model. This is done by adding a connection from the solution-neutral space to the solution-defining space. In this way, variants can be directly linked to solution elements. Additional notations and a binding time are also introduced to incorporate the product life cycle.

The approach according to BURSAC, a product modeling framework, helps developers to synthesize and analyze modular products with MBSE (Bursac, 2016). A reference product model is created using previous products and product lines. It contains a knowledge base about the used components and their information as well as product structures. This provides a direct indication of which components are commonly used across product lines. This information is used to create a modular reference model. The repeatable part is distinguished from the individualized part of the products. The matches are stored with as much background information as possible. The reference product model therefore contains all the necessary components to model the product. The modular reference model contains only the repeatable, interchangeable components. The models are linked and should be compatible with each other. The next step is to create the modular model from the modular reference model by classifying each component. This allows reuse of previously modeled components, analysis of component variants, and reduction of internal diversity across multiple product lines. The reference product model and the modular reference model serve as the basis for new product models. Additional newly developed subsystems can be integrated to address the customer-specific concept.

The synchronized configuration and adaptation (cf. Figure 3) according to SCHUH et al. is performed using a system model based on SysML. The configuration with the customer is realized by the sales department. The individual requirements are assigned to the appropriate interdisciplinary team depending on their category. In this way, the necessary development effort can be roughly determined during the planning phase. By transforming the configuration model from the feature space of the external variance to the internal variance, discipline-specific configuration models are automatically created. These are transferred to the respective planning systems via standardized interfaces and used to control the internal configurators. Preconfigured, consistent project data is thus available as a basis for customer-specific adaptations, which are then individually adapted by supporting a model-based development process.

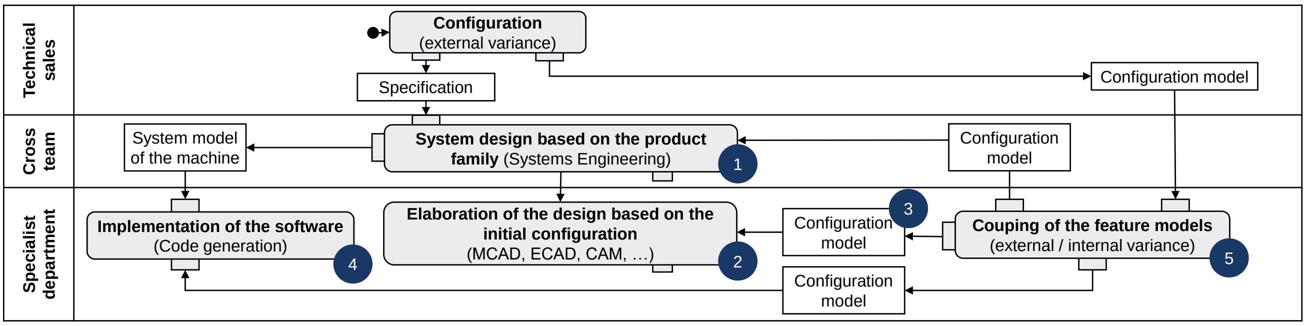

Figure 3. Configuration model according to SCHUH et al. (Brecher, 2011, p. 234)

3.2 Evaluation of the approaches

Using the rating scale shown in Figure 4, the state of the art was jointly evaluated by the authors based on the previously defined requirements. It is considered whether the requirements are fully, partially, or not at fulfilled.

Rating scale: ○ = not fulfilled ◑ = partially fulfilled ● = fulfilled

Considered approaches	R1	R2	R3	R4	R5	R6
Interdisciplinary product line approach according to Vogel-Heuser et al.	●	◑	○	◑	◑	○
Approaches to model-based variant management (VAMOS) according to Weilkiens	◑	○	○	●	○	●
Feature models supporting trade-off decisions according to Kühn et al.	●	○	●	◑	○	◑
mecPro2: Model-based configuration management (MBCM)	○	◑	◑	●	○	●
MBSE to support modular development for product generation according to Bursac	●	●	◑	●	○	●
Synchronized configuration and adaptation according to Schuh et al.	●	●	◑	●	◑	●

Requirements (R):

- R1 Structured process
- R2 Option for customized documentation
- R3 Complete recording of requirements and documentation of technical details
- R4 Rapid concept development
- R5 Opportunity for cross-domain collaboration
- R6 Model-based mapping

Figure 4. Assessment of the state of the art based on the defined requirements

3.3 Conclusion on the state of the art

In summary, to answer the first research question, none of the current state-of-the-art approaches fully satisfies all requirements. The VOGEL-HEUSER approach introduces valuable organizational insights into problem and solution spaces, as well as a distinct adaptation space. KÜHN et al. focuse on the early phase of concept development, and, like VOGEL-HEUSER and SCHUH, it uses feature models. By considering relationships and dependencies, KÜHN's approach reveals interdependencies between different variants, which could be very interesting for managing both internal and external variance. However, the scope for customization is limited. None of these three approaches explicitly supports early-stage collaboration and communication. In addition, ease of use for salespeople, preferably without complex modeling, is a critical factor. Here, the methodologies of WEILKIENS, SCHUH and SCHULTE require careful reflection. In addition, these approaches emphasize long-term variant management. Regarding customer-oriented customization, only SCHUH addresses this issue. BURSAC's approach also tends towards the long-term development of an internal construction kit, without a specific focus on documenting customer requirements. In conclusion, there is a need for an approach that fully documents all requirements (system and customer) and boundary conditions in the problem space. At the same time, it should allow mapping to preliminary solution concepts. A detailed mapping to domain-specific information may not be efficient during the offer phase. However, it should allow for comprehensive documentation of all important domain information and the ability to filter for domain-specific details. This ensures that technical sales can receive domain-specific feedback on a proposed solution concept. The approaches of VOGEL-HEUSER and KÜHN are primarily favored for further concept development.

4 Model-based offer management

As part of a transfer project, a flexible configuration model was developed for efficient offer processing. The following sections present the procedure, the methodological concept, and the modeling concept in application.

4.1 Procedure for concept development in the context of a transfer project

To meet the challenges of insufficiently documented customer requirements and complex customized designs, Priess, Horstmann & Co. Maschinenbau GmbH & Co. KG has set itself the goal of overcoming these challenges with MBSE. The company specializes in drilling and assembly systems for the furniture industry for processing fronts, side panels, shelves and carcasses and is classified as a special machine manufacturer with a focus on customized designs. The company has to deal with an incredible number of possible solutions because each customer's needs are different. Within the scope of a research transfer project, the modeling language and method CONSENS was selected for the creation of a model-based offer management. It is a consistent approach to the holistic and interdisciplinary description of mechatronic systems for the creation of the system model in the concept phase. The acronym is defined as CONceptual design Specification technique for the ENgineering of complex systems (Gausemeier et al., 2019) and represents a model-based approach that is easy to learn and intuitive (Kaiser, 2014) for people without much model-based knowledge, e.g. in technical sales (Wilke et al., 2023). As part of a project, the following procedure was used to develop the concept for model-based offer management for the company:

1. **Process and design analysis**: A detailed analysis of the company's design approach was carried out, focusing on the categorization of machine builders into ETO and CTO. The realization that a combination of both approaches is used in practice formed the basis for the further procedure. The variance in this case is expressed in the company's many different solution concepts, but above all in the variety of options that can be requested by the customer, e.g: Should a complete carcase be produced, should the machine also produce tall cabinets, or should only shelves be processed? In addition, unknown customer requirements may also arise which must be discussed.
2. **Development of the CONSENS models**: CONSENS models were created to identify standard features and understand the model-based approach. This allowed a systematic approach to the complexity of order processing.
3. **Feature model for the problem space**: By going through various customer situations and analyzing the CONSENS models, a feature model for the problem space was created. Typical questions asked by the technical sales department were considered, and typical customer requests were documented and clustered. Exclusion relationships according to KÜHN were used to eliminate questions that were excluded by a previous answer.
4. **Conceptualization in the solution space**: The concept creation process was reviewed and a list of key product types and families was created. It was determined that the technical sales department proceeds from the rough concept to the adapted concept after the requirements have been captured. Options and alternatives were considered and dependencies, especially in the problem area, were identified.
5. **First demonstrator in the tool**: To illustrate and validate the developed concept, a first demonstrator was built in the MBSE tool iQUAVIS (cf. section 4.3). This allowed a tangible representation and evaluation of the concept implementation. Further dependencies between the elements were added.
6. **Current extensions**: The information is constantly being expanded to refine and adapt it to current needs.

4.2 Methodical concept of the flexible model-based configuration model

Figure 5 shows an overview of the methodical concept. It is divided into two areas: the problem space for documenting & filtering requirements and the solution space for deriving a suitable solution concept. The goal for the problem space is to systematically elicit the customer's requirements, understand their origin and dependencies, and have a basis for communication - both internally and externally. The solution space is the area where engineers define the solution at a system level, handle the dependencies between solution elements, and use this information again for communication and collaboration. Both aspects are considered in context of interdisciplinary dependencies which are modeled on the system level.

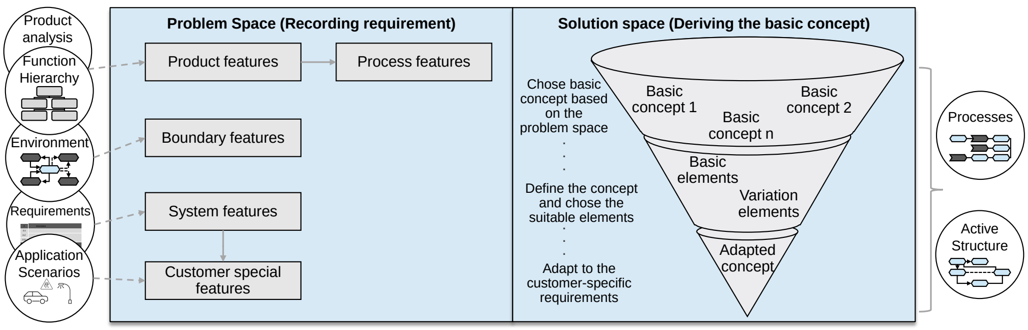

Figure 5. Configuration model for technical sales for use in the offer phase in linkage with the CONSENS partial models

At the left side of the concept, this is where the configuration and subsequent customization takes place as part of a customer order. This **problem space** is divided into four main feature areas: the product features (i.e., the features to be realized for the customer; in the case of a production line, similar to the processes to be realized), the boundary conditions, the machine/system features, and the special customer requirements. With respect to the state of the art, the adaptation space according to VOGEL-HEUSER et al. can be used in the area of special requests. At this point, the concept offers flexibility to document new customer requirements. The technical sales department asks its standard questions during the customer interaction, checks if the relevant requirements are already stored in the problem space, and adds individual requirements as an alternative. By selecting standard requirements and adding custom requirements, the **feature model of the external variance** is configured. Process characteristics can be derived from product characteristics. A product analysis can be performed for this purpose. Furthermore, CONSENS models such as environment diagrams, requirements and application scenarios can be used for the problem analysis. In this respect, the concept is designed as a flexible model, i.e. technical sales can either work purely at the configuration level (i.e. he selects from the previous, typically occurring requirements) or switch to a model-based approach for detailed analysis. In the case of special customer requirements, for example, more detailed considerations can be made by implementing the "application scenarios" sub-model. Specific information relevant to subsequent design can also be documented during the selection process. Since this paper focuses on the flexible configurator, reference is made to the paper (Wilke et al., 2024a) in which the individual submodels of CONSENS were evaluated with technical salespeople regarding their suitability for the offer phase.

Once the problem space has been agreed with the customer, the technical sales department can search the **solution space** for a suitable basic concept based on their experience. For this purpose, all essential basic concepts are documented in the solution space as a knowledge space. This means a certain amount of initial effort for the company to document the most important basic solutions for the configurator. Suitable concepts are selected for the current customer project. Alternatively, an automatic filtering can be used at this point by using existing dependencies between the problem space and the solution space. This allows continuous filtering. However, the usefulness of this logical storage must be questioned, especially in special machine construction, because it can become very complex. The selected solution concepts can then be adapted to customer requirements. The CONSENS models “processes” and “active structure” can be used for further elaboration. To explain the configuration concept in more detail, the modeling concept is demonstrated in the following.

4.3 Modeling concept & use case presentation of a special-purpose machinery company in the furniture industry

In the problem and solution space, the concept offers not only the possibility of documentation, but also of limiting variance and enabling collaboration. By storing relations (exclude & mandatory relations), which define different selection options (similar to the concept of a configurator, also used in the approach of KÜHN et al.), the technical sales department can perform the offer processing in an efficient and structured way. Figure 6 shows an extract from the application demonstrator. The four feature areas have been detailed in the problem space for the company Priess & Horstmann. The arrows show that mandatory or exclude relationships are stored. Individual relationships to the problem space are also already stored. Configuration is done using a simplified tree editor with checkboxes (called variant filter, Figure 6, right).

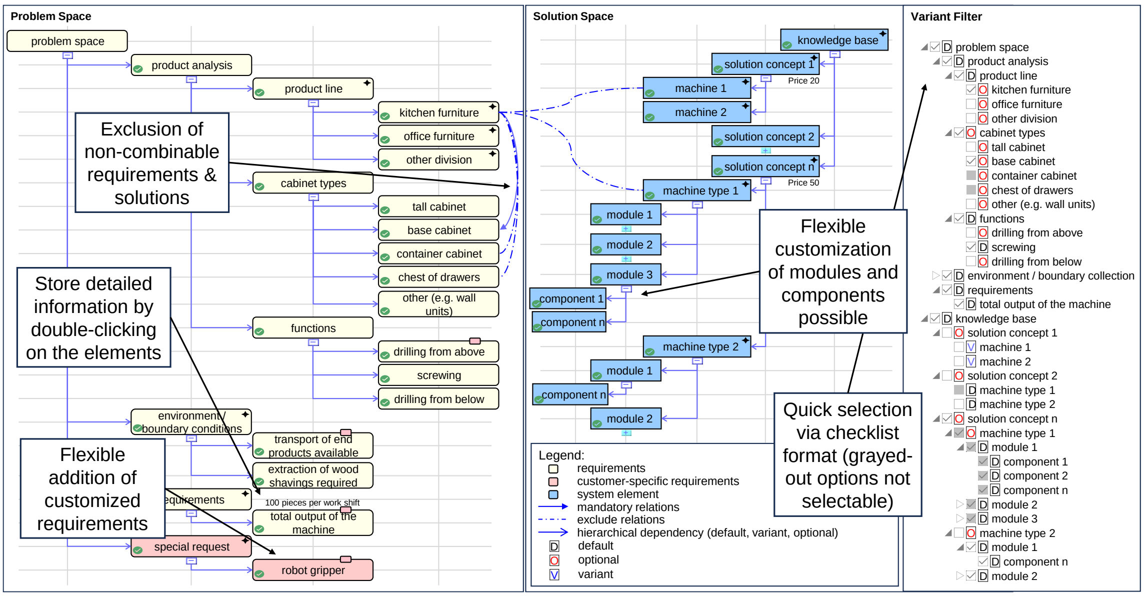

Figure 6. Configuration demonstrator in the transfer project with the MBSE software iQUAVIS

Similar to a checklist, the options required by the customer can be selected one by one. If an option is selected (e.g. kitchen furniture), which is linked to other options, further response options are filtered and cannot be selected (cf. Figure 6, grayed out, e.g. container cabinet, which belongs to the office furniture category). Customer specific requirements can be stored in the "special requests" area. These are directly visible internally. Special features that are important for the later design can be documented directly when creating the requirements. For example, the "Drilling" function can be used to specify whether drilling is to be performed from above or below. In this case, this is an important standard requirement for the company and has been stored as a standard requirement element.

Figure 7 shows that it is also possible to switch from the tree view to a domain-specific view. A tabular view allows the technical sales department to get feedback from other domains (represented by the two columns on the right).

	Requirements		Feedback mechanical construction	Feedback electrical construction
	Name	Details		
17	requirements	total output of the machine	With the required performance, we would propose solution concept 2 and add a further module which we will model for you in an active structure.	
18	special requests	robot gripper	The robot gripper could be attached to module 2 so that it does not cause any further interference.	We need the customer to provide us with the specific product details for the robot gripper so that we can assess the implementation.

Figure 7. Collaboration options during the offer phase

Furthermore, it is possible to enrich and derive an offer document from the information collected in the model. This was tested in a previous transfer project (Wilke et al., 2023) and allows an efficient way of working within a software tool.

5 Conclusion and outlook

The offer phase in special-purpose machinery is a complex process characterized by external and internal variance. A comprehensive literature review was carried out to investigate approaches that can handle variability. This paper has shown how technical sales can use a simplified configuration model to filter quickly and systematically within the external and internal variance. This provides the following improvements, which were highlighted by the user company as significant advantages: The customer's requirements are recorded in an efficient and structured manner. Moreover, the concept provides room for documentation and cross-functional discussion of special adaptations. By mapping the recorded requirements with the internal knowledge base, a similar solution concept can be found quickly, which can be adapted to the open customer-specific requirements. This will be the basis for future price comparisons of different solution concepts. However, it is based on a model-based approach that can be used to perform initial analysis for customization. For the development of mechatronic systems, the use of MBSE is an approach to master domain-specific complexity. Using MBSE in the early concept phase provides an efficient reuse for the subsequent detailed design.

However, there were challenges that arose during the creation of the configurator with the company. Converting the implicit knowledge of technical sales into explicit knowledge was a challenging task and required precise analysis and identification of relevant elements. Salespeople with years of experience quickly made subconscious decisions about a solution concept that needed to be identified for the configurator. The links between the problem space and the solution space were particularly difficult for technical sales, as these links cannot be predicted for special designs. Currently, the company sees value in having separate models for filtering. From a research perspective, integrating the two models could lead to better results. In addition, a process model for internal collaboration and clear responsibilities for maintaining the configuration model are critical to ensuring its effectiveness.

A special focus of future research is the optimization of the offer processing using artificial intelligence (AI). The focus will be on analyzing how AI can help identify solution patterns and provide technical sales with well-founded suggestions for similar solution concepts. The goal is to identify typical requirement patterns in requests and link them to corresponding solution concepts that have proven to be particularly successful in combination. The goal is not only to look at individual requirements in isolation, but also to identify the relationships and interactions between different requirements. In this way, not only standardized, but also highly customized solution concepts can be generated. By integrating AI into the offer process, we aim to establish a data-driven approach that allows us to draw on proven and successful solutions. Another focus is the creation of recommendation systems for technical sales with AI. These systems should not only provide sales staff with automated solution suggestions, but also make the reasons and background for these recommendations transparent. In this way, the sales department can better understand the proposed concepts and, if necessary, adapt or extend them. This outlook for future research work illustrates the potential of AI not only to automate repetitive tasks, but also to support and optimize complex decision-making processes in technical sales.

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