

Management of rule-based product-portfolios with high variance: a systematic literature review

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Abstract

This paper conducts a systematic literature review about the management of rule-based product-portfolios with high variance. This type of portfolio is particularly distinctive in the chosen use case of the German automotive industry since it satisfies the requirements of mass customization and modularization. However, the research field of variant- and complexity management is manifold and multidimensional. This paper systematically searches the databases Scopus and Web of Science using the PRISMA method and briefly summarizes the main contributions and comparing them by elaborated topics.

Keywords: product development, configuration management, mass customisation, variant management, automotive industry

1. Introduction

Offering mass customizable products is a tremendous benefit to meet diverse customer needs and requirements. However, enabling mass customizable products to customers is a huge driver of complexity, complexity induced costs and prolongs development times (Stich, 2007). Finding an optimal balance between variance-induced costs and the increased willingness to pay for a customised product by the consumer, is challenging venture. As a result, various methods have emerged to address this complexity for example by online configurators, modularization, and carry over parts. To describe this type of complex product, the documentation is based on additional constraints, known as rules (Herlyn, 1990). These rules can be of a technical, legal, or marketing driven character. With its countless configurable product variants, the German automotive industry is an exceptionally good example of rule-based product-portfolios with high variance. However, existing approaches are manifold and address different challenges along the product life cycle. For that reason, a systematic overview of literature in academia is needed to identify progression over the last decades as well as identify and describe potential research gaps.

The goal of this paper is to systematically search the two most common databases for scientific publications, Scopus and Web of Science, and elaborate existing approaches to managing of rule-based product-portfolios with high variance. To do so, in section 2 of this paper, the necessary background is presented to identify important key words for the search. Section 3 presents the used methodology and applied search string. Section 4 provides an analysis of the achieved results as well as an overview and a comparison of the found publications. In conclusion, the findings are discussed and presented.

Thereby, this paper contributes by answering the following research questions:

- What literature exists regarding rule-based product-portfolios with high variance and how can this literature be systematically reviewed?

- What existing approaches can be found in the literature for handling complexity and managing data-driven product documentation and how have they developed?

2. Background and related work

Ensuring precise and distinctive documentation is inevitable for successful designing a product and even more crucial when it comes to managing entire product-portfolios. Managing this type of portfolio is not only complex but also prone to errors due to dynamic changes in the product description. To ensure precise and distinctive documentation, the product description uses references to features-values of the corresponding product. If products differentiate in the manifestation of a feature-value or within a feature-class, often referred to as feature-family, variants are formed. If the number of unique product variants exceeds the number of part variants used, they are referred to as highly variant products (Herlyn, 1990). Therefore, the definition of variants in product development starts in the early phase in which features and corresponding constraints are defined. Implementation in series production is achieved through standardization and modularization of platform designs, which is prescribed as system architecture in VDI 2221 (VDI, 2019). If the combination of feature-values is dependent on predefined constraints, so-called rules, these are referred to as rule-based variance schemes (Herlyn, 1990). To describe these dependencies in the form of rules, prohibitions and restrictions are used, which can be converted into each other. As an efficient format for encoding, a Boolean notation with the standard operators and a Conjunctive Normal Form (CNF) has established industry wide.

To ensure feasibility along the entire product life cycle, the product structure can be converted into a Constraint Satisfaction Problem. This approach enables checking and efficiently validating the feasibility of every possible configuration (Sinz, 1997). In addition to satisfiability, consistency checking is a key factor in managing complexity (Braun et al., 2018). SAT solvers and data-driven knowledge-based decision support systems are therefore used from engineering through production and extending to after-sales.

The German automotive industry uses this particular product description and has played a key role in its development. Hence, it is chosen as the basis for this elaboration including not only passenger cars but also commercial vehicles and trucks.

3. Methodology

The systematic literature review is conducted following the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA), which consists of the four phases: (1) Identification, (2) Screening, (3) Eligibility, (4) Included (Page et al., 2021). Considered databases are limited to Scopus (S) and Web of Science (WoS) due to their strong search engine capabilities and reputation for excellent scientific standards.

Since this systematic literature review is part of a Descriptive Study of an ongoing PhD project, four control papers are known to be relevant for this topic and therefore included as mandatory check in the search. The four control papers are Greisel et al. (2013), Herlyn (2005), Braun et al. (2017) and Küchlin and Sinz (2000). Including these four control papers in the search methodologically increases the relevance of the found results in the review process. The integration and comparison with other review findings enables a systematic analysis of the found results in relation to previous relevant findings and thus represents a valuable addition to the evaluation of this research. The inclusion of mandatory control papers slightly biases the selection of search criteria, which is discussed and presented in the conclusion to ensure transparency.

Prior to the definition of the search string, it is important to emphasize that the field of research on variant management, complexity and configurations is already mature, extensive and manifold. For this particular reason, the intention of this paper is to narrow down the many findings to the most important and relevant contributions. Consequently, a restrictive search and a limitation to the two most influential databases was chosen. As a result, this paper does not claim to be exhaustive in its representation of the exclusive areas of research and contribution in this field.

To build the search string, relevant keywords are identified, and synonyms are found. The search is done in English and German language only ("LANGUAGE"). Besides English as the primary language of sciences, papers in the German language were accepted to allow a dedicated view on the chosen use case of the German automotive industry. For some words, wildcards ("*") are being used to generalize the results and make it more robust for example by including synonyms and homonyms. The search string is a combination of keyword search ("KEY") and article title ("TITLE"). The combination of the two achieved the best and most robust results. Furthermore, the search is limited to the subject areas ("SUBJAREA ") of "Engineering (ENGI)" and "Computer Science (COMP)" since these two are the areas of relevance and contribution of this work. To further limit the search results, only the document types ("DOCTYPE ") "Conference Paper (cp)", "Article (ar)" and "Review (re)" are considered.

Finally, the search string is build using AND and OR statements and tested for the results. The final query used in this systematic literature review is:

"(KEY (product AND boolean OR complex OR serial AND automo OR vehicles OR trucks) AND TITLE (product OR varian* AND complex* OR consiste* OR design OR development OR lifecycle OR engineering OR production OR knowledge OR seri*)) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "COMP")) AND (LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English") OR LIMIT-TO (LANGUAGE , "German"))"*

Using this query in the advanced search section of Scopus and Web of Sciences grants direct access and reproducibility to the considered results. In order not to misrepresent the results, no limit was set for the considered period of time. The search was last queried on 10th of November, 2023.

In the scope of this paper, no Snowball method was used in which the reference list of a finding or the citations to this same finding are used to identify additional papers which might be of interest. The Snowball method is more suitable for initial overviews due to its qualitative character and exponential growth in the number of papers to be analysed. Additionally, the Snowball method is dependent on the initial viewpoint from which it is started. Since the Snowball method is also not replicable because citations can constantly be added, a more definitive method has been chosen with the decision for a systematic literature review.

4. Results

The results of the systematic literature review are first analysed and subsequently examined by the PRISMA method. The papers analysed as eligible are finally included in a tabular overview and compared against 19 key topics. The PRISMA method is an evidence-based analysis used in systematic literature reviews and meta-analyses to screen findings of database searches to find and focus on relevant records (Page et al., 2021). The results consist of both qualitative and quantitative papers.

In the first step, 74 records match the systematic search on Scopus and 5 records are added by the same systematic search-query on Web of Science. After removing two duplicates that appeared in both databases, a total of 77 papers are identified. The number of citations vary from 0 to the highest of 257. The year of publication from the found matches ranges from 1992 to 2023 and vary from 0 to a maximum of 8 per year. Looking at the last 31 years, a slight upward trend in the number of publications on this topic can be observed. There have been at least two publications per year since 2012. The fact that there have been publications in this area of research for the past 31 years indicates two things. Firstly, the subject is mature and new research has the potential to build on existing efforts. Secondly, there has been a constant and continuous interest and relevance in the area of research. The fact that a total of no more than 77 publications were found is not an indication of a small field of research, but rather due to the carefully prepared query. A visualisation of the found documents over the past years is presented in Figure 1.

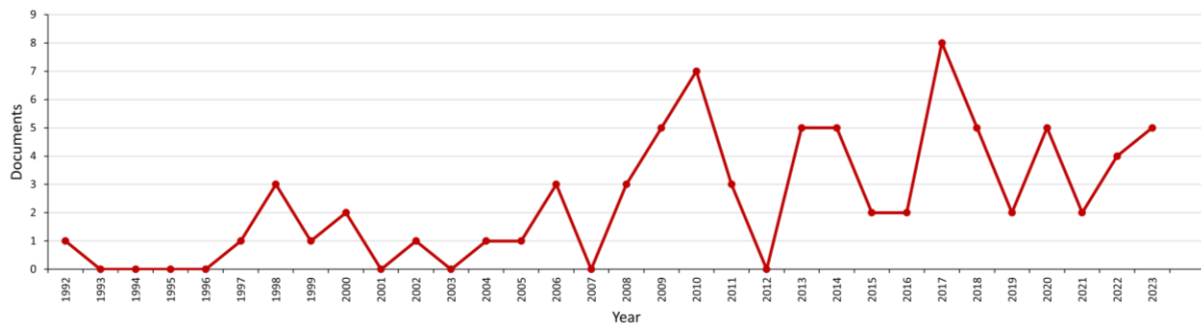


Figure 1. Found documents per year from 1992 to 2023

Nine authors have in total more than one contribution. The highest number of publications examined came from Kreimeyer, M. (n = 4) followed by Braun, F. (n = 3) and Albers, A. (n = 2).

The found documents are published international in 20 different countries, 4 documents are not clearly assigned to a country and remained undefined. The countries with the most published documents are Germany, followed by China and the United States. The ten largest contributors are visualised in Figure 2 (left). The majority of publications (67.5%) are Conference Papers, Articles make up the second largest share (28.6%) and Reviews account for only 3.9% of the examined literature. The documents by type of publication are visualized in Figure 2 (right).

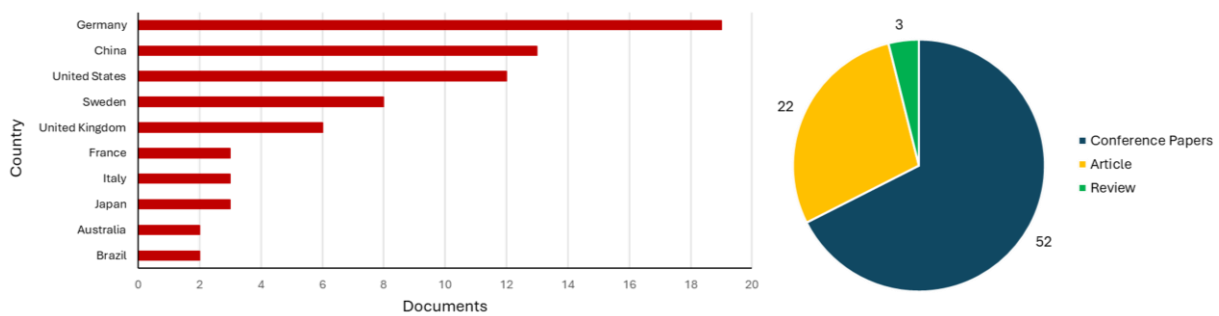


Figure 2. Found documents by country or territory (left) and by type (right)

In the second step, the 77 papers are screened for relevance by first reading the abstract, keywords and, if relevant, followed by reading the full text. Papers without open access or restricted access are automatically excluded from further consideration.

In the third step, only 35 papers are found eligible. Criteria for exclusion are irrelevant industries, focus on a specific algorithm, focus on presenting a given case study or too little consideration of the product development process.

Fourth, 22 papers are finally included in a systematic overview and subsequent comparison. These contributions are found to be extraordinary relevant and related to the research area described in section 2 of this work. Referred papers are presented in a brief tabular overview in section 4.1 and thereafter compared to one another in section 4.2.

4.1. Overview

The final considered papers are briefly summarised in the following Table 1 by their database source (DB: Scopus (S) or Web of Science (WoS)), names of the authors, year of publication, title and the analysed industry, if any. According to the above search string, considered industries are mainly the automotive industry, commercial vehicle industry as well as the truck industry. However, one publication applies not only to automotive but expands considered industries by the aircraft and powerplant industry.

Table 1. Overview of the final papers in descending order from year of publication

DB:	Authors:	Year:	Title:	Industry:
S	Franze, Neumann	1997	Design for environmental compatibility of automobiles - New life-cycle management tools in the BMW product development process	Automotive
S	Franklin, Hunt	1998	Can a universal screening methodology be devised for LCAs of complex products?	Automotive
S	Kobayashi et al.	1998	Life cycle analysis of a complex product, application of ISO 14040 to a complete car	Automotive
S	Bracht, Holtze	1999	Data mining for better parts-requirement forecasting. New approaches to planning with wide variation in series production	Automotive
S	Küchlin, Sinz	2000	Proving consistency assertions for automotive product data management	Automotive
S	Persson	2004	Managing the Modularization of Complex Products	Automotive
S	Herlyn	2005	Individual owner's manual for serial products with many variants	Vehicles
WoS	Persson, Ahlstrom	2006	Managerial issues in modularising complex products	Automotive
S	Thiel et al.	2008	Software product lines in automotive systems engineering	Automotive
S	Van Eikema Hommesb25	2009	Comparison and application of metrics that define the components modularity in complex products	Vehicle
S	Bittner et al.	2010	A case study on tool-supported multi-level requirements management in complex product families	-
S	Raza, Harrison	2011	Ontological knowledge-based system for product, process and resource relationships in automotive industry	Automotive
S	Andersson et al.	2011	Towards configuration support for collaborative simulator development: A product line approach in model-based systems engineering	Automotive, Aircraft, Power Plant
S	Greisel et al.	2013	Design for adaptability in multi-variant product families	Truck
S	Johansson et al.	2016	Multi-variant Truck Production - Product Variety and its Impact on Production Quality in Manual Assembly	Truck
S	Braun et al.	2017	Challenges in the validation of the variant description of complex products	Commercial Vehicle
S	Braun et al.	2018	Procedural model to ensure consistency and validity of complex, variant-oriented product portfolios	Commercial Vehicle
S	Albers et al.	2018	Customer-oriented product development: supporting the development of the complete vehicle through the systematic use of engineering generations	Vehicle
S	Frischen et al.	2019	Consistent controlling of variants with the aid of the rule-based complex bill of materials	Automotive
S	Li et al.	2021	Modularization for the complex product considering the design change requirements	-
S	Yamamura et al.	2022	Forecasting New Product Demand Using Domain Knowledge and Machine Learning: A proposed method uses machine learning and an expert's domain knowledge to enhance the accuracy of new product predictions	Automotive
S	Mehlstäubli et al.	2023	Methodical Approach to Cluster Configurations of Product Variants of Complex Product Portfolios	Commercial Vehicle

DB: Databases, S: Scopus, WoS: Web of Science

4.2. Comparison

For a simple classification into categories, the following 19 topics have been identified and are used for a systematic comparison in Table 2: Environmental Impact, Use of Tools, Life Cycle Assessment (LCA), Bill-of-Material (BOM), Parts, Forecasting, Consistency, Satisfiability (SAT), Modularisation, Variant-Management, Complexity, Software, (Model-based) Systems Engineering, Product Line Approach, Knowledge-based Approach, PLM/PDM Systems, Assembly Quality, Product Generation Development (PGE) and Machine Learning Methods. The derived topics represent concepts, methods and proposed solutions for the management of complex and high-variant products from the examined publications. The assignment of one or more identified topics to a specific publication is a simplification and has not always been conclusive. Nevertheless, care has been taken to correctly assign the core statement of a publication to one or more categories. The identified topics are selected based on repeatedly used keywords from the examined publications. To understand the basis of this comparison, a brief definition or context for each topic is briefly provided accordingly. Environmental Impact describes the topic of holistic life cycle considerations with specific interest in sustainable and environmental factors. Use of Tools describes the category centred around specific tools and their application whether as software or methodological. Life Cycle Assessment (LCA) is closely related to Environmental Impact since it analyses the potential environmental impacts of a product or service during their life cycle but focuses more on the assessment of the product itself. Bill-of-Material (BOM) is a topic well known as list of parts that go into a specific product or product variant, again closely related to the next category Parts that is focused solely on requirements for parts when it comes to production. Forecasting is about making predictions about the future and deriving statistical statements. Satisfiability (SAT) is about theorem proving and finding an answer to a given single Boolean function while Consistency is about satisfying a whole set of configurations as a whole. Modularisation is an approach for dividing components into standardized modules in order to offer customization which is a subject of the overall topic of Variant-Management. Complexity is the topic that summarizes challenges and possible solutions to be considered as a system due to dependencies common in many advanced products. Software comprises programs and information systems that run on a computer and are supplemented by hardware. (Model-based) Systems Engineering is a recent approach to mastering complexity through the central aspect of modelled behaviour which is extended in the Product Line Approach to understand a set of product variants as a modular system of reused components. The topic of Knowledge-based approaches focuses on a priori knowledge as a central element of a decision-making process. PLM/PDM Systems refer to tools managing all stages of life cycle and generated data. Product Generations (PGE) is an approach established by [Albers \[2018\]](#) for the management of products with more than one product life cycle generation. The most recent approaches of Machine Learning algorithms are part of Artificial Intelligence and are able to recognize patterns in data distributions and are used to enhance data analysis.

When identifying and describing the topics, as well as assigning them to individual relevant papers, it was found that the topics described are very closely correlated. Some of the specific topics are subsets of superordinate topics and vice versa, such as the example with BOM and Parts. The thematic proximity of the topics to each other reflects the restrictive nature of the query used and indicates that the findings should be considered in their entirety. The use of less specific topics is not recommended as this results in less diversity of topics and poorer differentiability. The comparison aimed to include only a handful of related papers for each of the topics. A correspondingly specific approach was used when selecting the topics. The topic Complexity is an exception, as it was chosen as a central focus in seven papers and could not be meaningfully subdivided into more specific subtopics. The topics Parts, Variant Management, Software, Assembly Quality and Product Generations were each only included once and thus represent small topics. However, they were not included in neighboring topics in order not to distort the results. The papers by [Herlyn \[2005\]](#) and [Johansson et al. \[2016\]](#) are exceptions, as they are not only assigned to a single topic, neither could this topic be assigned to any other paper.

Table 2. Comparison of identified topics in descending order from year of publication

	Environmental Impact	Use of Tools	Life Cycle Assessment (LCA)	Bill-of-Material (BOM)	Parts	Forecasting	Consistency	Satisfiability (SAT)	Modularisation	Variant-Management	Complexity	Software	(Model-based) Systems Engineering	Product Line Approach	Knowledge-based Approach	PLM/PDM Systems	Assembly Quality	Product Generations (PGE)	Machine Learning Methods
Franze, Neumann [1997]	•	•																	
Franklin, Hunt [1998]			•	•															
Kobayashi et al. [1998]	•		•																
Bracht, Holtze [1999]					•	•													
Küchlin, Sinz [2000]							•	•											
Persson [2004]									•										
Herlyn [2005]										•									
Persson, Ahlstrom [2006]									•		•								
Thiel et al. [2008]											•	•	•						
Van E. Hommes [2009]									•		•								
Bittner et al [2010]		•									•		•						
Raza, Harrison [2011]														•	•				
Andersson et al. [2011]												•	•						
Greisel et al. [2013]									•										
Johansson et al. [2016]																	•		
Braun et al. [2017]								•			•					•			
Braun et al. [2018]							•	•			•								
Albers et al. [2018]												•						•	
Frischen et al. [2019]				•			•	•											
Li et al. [2021]									•		•								
Yamamura et al. [2022]						•								•					•
Mehlstäubl et al. [2023]											•								•

•: Match of the addressed topic in column with publication in row

5. Conclusion

In conclusion, a systematic overview of existing literature on the management of rule-based product-portfolios with high variance from Scopus and Web of Science databases was reviewed and compiled. The review and compilation process narrowed down the overview to 22 main contributions, which in turn were compared with each other based on 19 identified topics. Most of the papers are centered around the automotive and neighbouring industries, which was deliberately achieved through integration in the query. Within these limitations, two trends have been identified and one coherent cluster of linked publications has been recognized as such.

The first trend relates to the number of publications, which has developed slightly positive over the last 31 years. This indicates an existing and increasing scientific interest in the field of research and acknowledges its relevance. The second trend relates to the evolution of concepts, methods and proposed solutions considered over the same period of time. The comparison in Table 2 shows a slight but recognizable transition from life cycle assessment and parts prediction to more holistic considerations

such as Model-Based Systems Engineering, knowledge-based approaches and finally the use of data intense Machine Learning techniques. A presumed outlier is the consideration of environmental impact, which has not been addressed as a core topic since 1998 but is very relevant against the background of current ongoing discussions.

The connected research by Braun, Mehlstäubl, Kreimeyer and Paetzold was identified as the only coherent cluster. Their publications account for a total of 4 out of the 22 examined publications, all of which relate to the commercial vehicle/truck industry and are found to be relevant. Identifying this cluster of connected work will be a suitable starting point for the Snowball method in order to find even more relevant and connected work in future research. Further questions arise as to whether the used methods in the commercial vehicle industry can be generalized to the passenger car industry and vice versa. Considering unanswered research questions of the whole field will impact the remaining research gap which is still remarkable after 31 years of examined research.

The main contribution of this paper is to review and acknowledge existing work and building a systematically foundation of related work. This includes methods for literature review, databases, articles, authors, topics and similarities in between the areas of research and contribution. A particular benefit of the presented work is based on the search query which condenses a manifold and multifaceted field into a reasonable number of relevant contributions. Since the initial field of variant management, complexity and configurations is already extensively investigated, limitations have to be made to consider a dedicated use case. Due to these limitations, the contribution focuses on the described use case of the German automotive industry and the answering of the formulated research questions. The use of control papers increased the relevance of the review and provided valuable references to further research. As a result, the search bias needs to be considered as another limitation of the results.

In order to meet the continuing high demand of mass customizable products under further increasing complexity due to intensified requirements, further research is necessary. This includes the use of emerging machine learning techniques as well as knowledge-based decision support systems to simplify complex product-portfolios without violating constraints or losing customizability. Knowledge-based and data-driven decision support comprises emerging Machine Learning techniques such as Recommender Systems, Association Rule Mining and Bayesian Networks to model customer behaviour on complex product configuration to make the best decisions in the early stages of product development.

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