UNIVERSITÄT DER BUNDESWEHR MÜNCHEN
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Application of algorithm-based validation tools for the validation of complex, multi-variant products

Felix Braun, M.Sc.

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Vorsitzender:		Univ.-Prof. Dr.-Ing. habil. Markus Klein
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Summary

Based on trends like mass-customization and the individualisation of mass products also in the vehicle manufacturing industry, multi-variant product portfolios are usually required to account for all the necessary variance. As this work is based on a research cooperation between university and a large commercial vehicle manufacturer, such types of a product portfolio are closely observed. In these types of product portfolios, large sets of Boolean portfolio rules are used to describe the product portfolio with all its variants. In the same time, numerous departments within engineering, sales and production work on these portfolio rules with different information flows and perspectives. Therefore, it is difficult to maintain a fully valid and consistent state of the portfolio over time. This is especially challenging, as advanced tools and algorithms are necessary to ensure validity, as the amount of rules and interdependencies is too large to be handled manually in complex product portfolios.

This research examines the different types of multi-variant product portfolio descriptions and its requirements regarding validity and consistency described in recent literature. Based on the definition of how validity is reached within a portfolio, existing approaches on how to ensure this validity over time are explained. Taking these findings into account, the current gap in research is identified: neither exists a concise definition of portfolio validity, nor is an integral approach or process presented to ensure validity in the practical application.

Therefore, this research proposes a concise definition of the requirements leading to validity within complex, multi-variant product portfolios. Based on these requirements, an integral approach, a procedural model, is proposed to achieve and maintain validity within complex, multi-variant product portfolios. This approach is explained in detail in the main section of this work.

This procedural model is implemented in a real-world industry example in the form of a case study jointly executed with the industry partner. In this case study, a fully valid state of the product portfolio, according to the predefined requirements, can be achieved. Hereby, both the applicability and the validity of the proposed procedural model are shown.

Finally, the main findings are outlined: a generic data model and documentation logic for complex, multi-variant product portfolios exist. On this basis, general requirements on the validity of a product portfolio definition can be stated. With the help of existing validation tools and algorithms, a procedural model can be used to guide and structure the validation process of the portfolio rules. When this process is being followed, a fully valid state of the product portfolio and its rules can be reached.

This work also helps the industry partner in the commercial vehicle industry to structure and perform its portfolio validation process as part of its daily business.

Zusammenfassung

Aufgrund von Trends wie der flexibilisierten und immer individualisierten Massenproduktion, auch in der Fahrzeugindustrie, kommen verstärkt multi-variante Produktportfolios zum Einsatz. Die vorliegende Arbeit beruht auf einer Forschungskooperation zwischen der Universität und einem großen Nutzfahrzeughersteller in der diese Art von Produktportfolios genau beschrieben wird. Hierbei wird eine große Anzahl boolescher Portfolioregeln verwendet um das Portfolio mit all seinen Varianten abzubilden. An diesem Portfolioregelwerk arbeiten gleichzeitig zahlreiche Abteilungen eines Unternehmens: in der Entwicklung, im Vertrieb oder der Produktion. Diese Abteilungen haben dabei ihre eigenen Perspektiven und Informationsflüsse. Daher ist es schwierig jederzeit ein vollständig valides und konsistentes Portfolio sicherzustellen. Dies ist besonders herausfordernd, da fortschrittliche Werkzeuge und Algorithmen zur Absicherung der Validität notwendig sind und die Menge an Regeln und Abhängigkeiten in einem komplexen Produktportfolio zu groß ist um manuell validiert zu werden.

Diese Arbeit untersucht die in der aktuellen Literatur beschriebenen verschiedenen Arten von multi-varianten Produktportfolio-Definitionen und deren Anforderungen hinsichtlich Validität und Konsistenz. Aufbauend auf der Definition von Validität werden bestehende Ansätze zur Absicherung von Validität vorgestellt. Aufbauend darauf wird die Lücke in der aktuellen Forschung dargestellt: weder existiert eine umfassende Definition von Portfoliovalidität, noch gibt es einen integrierten Ansatz oder Prozess wie die Validität in der praktischen Anwendung sichergestellt werden kann.

Daher stellt diese Arbeit eine ganzheitliche Definition der Anforderungen an Validität in komplexen, multi-varianten Produktportfolios vor. Aufbauend auf diesen Anforderungen wird ein integrierter Ansatz vorgeschlagen, ein Vorgehensmodell um die Validität in komplexen, multi-varianten Produktportfolios zu erreichen und zu erhalten. Dieser Ansatz ist im Hauptteil dieser Arbeit detailliert dargelegt.

Dieses Vorgehensmodell wird in einem realen Industriebeispiel in Form einer Case Study gemeinsam mit dem Industriepartner angewendet. Hierbei kann ein nach den Anforderungen vollständig valider Zustand des Produktportfolios erreicht werden. Damit wird sowohl die Anwendbarkeit als auch die Validität des vorgeschlagenen Vorgehensmodells gezeigt.

Schließlich werden die Kernergebnisse vorgestellt: aufbauend auf einer generischen Dokumentationslogik für komplexe, multi-variante Produktportfolios können generelle Anforderungen an die Validität von Produktportfolios identifiziert werden. Mit der Hilfe von bestehenden Validierungswerkzeuge und Algorithmen kann ein Vorgehensmodell angewendet werden um den

Validierungsprozess der Portfolioregeln zu strukturieren. Unter Einhaltung dieses Vorgehensmodells kann ein vollständig valider Zustand des Produktportfolios und seiner Regeln erreicht werden.

Zuletzt hilft diese Arbeit auch dem Industriepartner aus der Nutzfahrzeugindustrie um seinen Validierungsprozess in seinem Tagesgeschäft zu strukturieren.

Contents

List of abbreviations

A/C	Air-Conditioning
BCG-matrix	Boston Consulting Group matrix
BoM	Bill-of-Materials
CD	Compact Design (in terms of truck layouts)
CPM	Characteristics-properties modelling
DCT	Decomposition tree
DOC	Documentation
DRM	Design Research Methodology
DSM	Design Structure Matrix
EoP	End of Production
FA	First Aid Box
FODA	Feature-oriented domain analysis
FR	Functional requirements
HP	Horse Power
HVAC	Heating, Ventilation, Air-Conditioning
IoT	Internet of Things
IUR	Item Usage Rule
JSON	JavaScript Object Notation
KMAT	Short from German: “Konfigurierbares Material“
NPV	Net Present Value
OEM	Original Equipment Manufacturer
PDD	Property-driven development
PDM	Product Data Management
PDMA	Product Development and Management Association
PLM	Product Lifecycle Management
PP	Planning Period
R&D	Research and Development
ROI	Return on Invest
RW	Real world
SAP iPPE	SAP integrated Product- and Process-Engineering
SAP VC	SAP Variant Configuration
SAT	Satisfiability
SD	Spacious Design (in terms of truck layouts)
SE	Solution Element
SL	Side Marker Lights
SoP	Start of Production

SW	Spare Wheel
TB	Tire Inflation Bottle
Trafo	Transformation
W	Watt

1 Introduction: Focus of this research

1.1 Preface

Across various industries the trend towards mass customization, as first described by Stanley Davis in 1989 [1], has become common business practice [2]. Individually configured passenger cars, personal computers, individualised training shoes or muesli online configurations are examples of this development. To be able to offer these individual products for a maximum number of specific customer needs and various requirements, a vast number of product variants is required. This challenge is counteracted in industry by the introduction of product platforms and product modules being part of so-called product family architectures [3]. In product family architectures, functional elements, their interfaces as well as configuration mechanisms can be found.

The present approach to offering all possible variants to the customers is based on product configuration systems or short configurators [4]. In a first step all possible variants need to be documented, e.g. within a product family architecture. In a second step the configuration logic is set-up, including formalized rules describing which variants can be combined. It can then be used by the customer in a configuration process. The combination of variants into one final product is considered as a *configuration*. In a last step, customers can configure and order their individual product based on their specific preferences and needs.

From a customer or sales perspective, these products are considered as *configure-to-order* products. The final product is configured directly by the customer with the help of a product configurator that represents all product variants that are feasible. The specific product is then manufactured according to the specified configuration.

Within large, *multi-variant product portfolios* [5], extensive numbers of variants and resulting combinations of variants (i.e. configurations) can be possible. A key challenge, therefore, is to ensure the validity of the entire product portfolio. Inconsistencies between different variants and their configuration rules can occur, especially as many users from different departments (e.g. Sales, Engineering, Production) work on a product portfolio at the same time.

This research is going to deliver a contribution to handling validity and consistency in large, multi-variant product portfolios.

1.2 An industrial application: commercial vehicle engineering

In general, automotive industry is an industry sector with a huge range of product variants. A BMW 7 series for example can have up to 10^{17} possible configurations, based on the combination of variants [3]. This is due to different customer requirements regarding functions, differing market requirements or geographical requirements, e.g. concerning climate. A special niche in the entire automotive industry is the commercial vehicle industry. There, large sets of requirements due to highly specialized transport tasks and as a result, of specialized vehicle applications, can be found. Yet, often only low quantities of vehicles are sold in these niche applications [6]. In 2017 for example, 974.000 configurations of the vehicle type Volkswagen Golf have been distributed worldwide [7], whereas by MAN Truck & Bus, only 90.000 vehicle configurations were sold [8], taking all models, types, variants and even buses into account. Therefore, strategies to deal with large multi-variant product portfolios are extremely critical for business success in the commercial vehicle industry.

The background for this research is a cross-functional multi-year project with the commercial vehicle manufacturer MAN Truck & Bus SE. The focus of the project is the introduction of an entire PLM-/PDM ecosystem together with a generic bill of materials and a generic product structure. As these types of multi-variant product portfolios can become extensively complex, it is important to maintain validity and consistency for all parts of the product portfolio. At first, the scientific support for this project is focussing on many aspects around modularization techniques [6], the product information model [9] and variant planning [10]. In the later phases of this project, the scientific focus shifts towards the implementation and practical application of this portfolio model. In consequence, aspects regarding the validation and verification of complex, multi-variant product portfolios and its portfolio rules become more important.

Thus, this research is examining the requirements of product portfolios with regard to validity, outlining the current state of research on validation strategies, processes and tools and is going to provide scientific recommendations to deal with these types of product portfolios. This research has been carried out in a close collaboration between MAN Truck & Bus SE and the Universität der Bundeswehr München.

1.3 Problem description

Multi-variant product portfolios can consist of uncountable numbers of possible and feasible product configurations. An industrial example taken from MAN Truck & Bus SE shows over 30.000 different technical component variants resulting in over 10^{300} configurations being part of the entire truck product portfolio. Combinability within the portfolio is hereby described through different sets of Boolean rules, in this case consisting of over 50.000 singular rules.

Other examples in literature show possible quantities of over 100.000 rules [4]. Within large organizations, numerous departments are working manually on these large sets of Boolean rules. Figure 1 below shows an exemplary organizational structure of an engineering company in which different departments deal with portfolio rules:

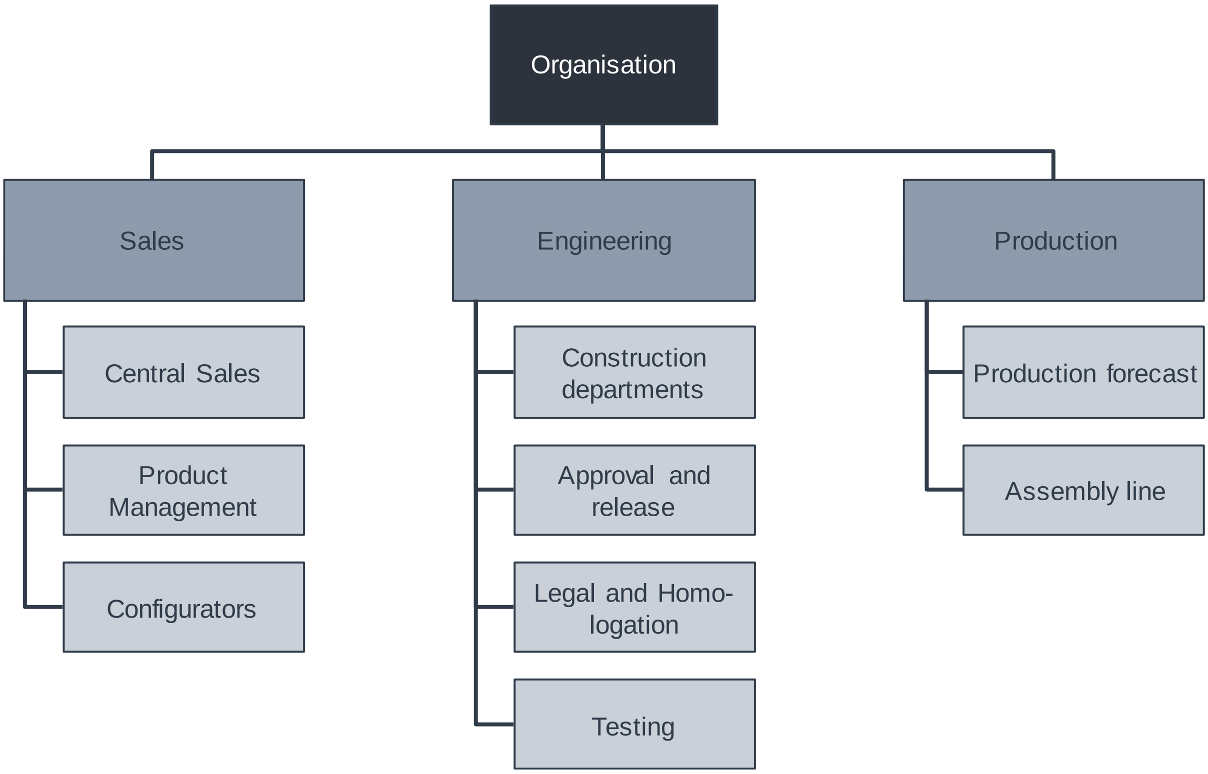


Figure 1: Exemplary organizational structure of an engineering company showing departments dealing with product portfolio rules

Within the *Sales* organisation, there are departments that are responsible for the sales configurators used to sell products to the end-customers, product management who decides upon new product features and options and central sales departments responsible for the sales documentation. In *Engineering*, there are departments that are responsible for the development of technical components, for the technical validation and release process of these components, for the compliance with legal requirements and for the technical approval of these solutions. And in *Production* there are departments focussing on production forecasts and capacity limitations, as well as assembly lines. All these different departments have their own work processes and routines, often with separate information flows. As they all work on the same product portfolio of a company, numerous errors can occur due to the large number of configurations, the manual processes and missing agreements within these departments. Some rules could contradict other rules; some product variants might never be *selectable* (i.e. a certain variant can be actively chosen by a customer in a sales configuration) or *incomplete configurations* (i.e. not every element of a sales configuration is described) could appear. All these inconsistencies lead to so-called *portfolio errors*, resulting in an *invalid* and *inconsistent* product portfolio description.

The product portfolio definition forms the basis for all tasks and processes dealing with any type of information about the products of a company. Therefore, it has to be *valid* and *free of portfolio-errors* at any point-in-time. Methodologies and tools need to be developed and processes need to be established to continuously monitor and ensure the correctness of the product portfolio definition. A process is necessary to check the product portfolio definition and its rules on errors, to find and solve any inconsistencies in the rule set and guarantee this state over time.

The key question this research answers is what requirements regarding validity exist and how these requirements can be met, i.e. which tools and processes are necessary to ensure the validity of all portfolio rules. Based on this high-level research question, core hypothesis and detailed research questions are stated in chapter 2.5, taking the current state of literature in this field into account.

As much research has been done already in the field of multi-variant product portfolios, some aspects will explicitly not be covered in this research. Neither will types and advantages of different portfolio models be part of this research nor will different modularization strategies be covered here. Also, no algorithmic guidance on a code-base level will be given, as the focus lies on the requirements and process-aspects of validation processes. A more detailed definition of the aspects not covered in this research is found in chapter 2.5, based on the hypothesis and research questions.

1.4 Objectives

As outlined in the problem description above, the aim of this research is to develop processes and methodologies to help users deal with large and complex product portfolio definitions.

The following objectives are addressed to meet this goal:

- Exploration of different product portfolio documentation models:
    - Identification of different documentation models described in science that can be used for large and complex product portfolios
    - Proof of their relevance based on their actual usage in the industrial practice
- Examination of requirements regarding the validity of product portfolios:
    - Identification of general requirements that can be used to classify information quality
    - Adaption of their meaning for the usage in combination with product portfolio definitions

- Explanation of existing methodologies to help achieve these requirements:
    - Outline of existing approaches to ensure validity of product portfolio definitions
    - Explanation of their shortcomings and optimisation needs
- Development of a procedural model to support users of large and complex product portfolio definitions:
    - Proposal of a procedural model that covers all relevant aspects of validity
    - Proof of how this procedural model can be used in the real-world application and evaluation of its benefits

The first goal, the exploration of product portfolio documentation models, creates a common structural basis for the tools and processes used in this research. With the second and third goal, the requirements for the solution are clarified and the shortcomings in the current state of the literature are evaluated. Thereby, the scientific contribution of this research is clarified. The fourth goal delivers a precise and easy to use proposal for a new procedural model that users can follow to ensure the validity of the product portfolio definitions they are working on.

Based on these goals, the potential users with regard to the scope of the solution can be defined. This research aims to provide a procedural model that can be executed by a broad set of users in the industrial practice. It is dedicated to supporting validation processes not only in the commercial vehicle or automotive industry, but also in other industry fields that have to deal with large and complex, multi-variant product portfolios. In these fields, the potential users do not only belong to Engineering divisions, but also to Sales or Production departments, as they can all be working on the product portfolio definition, especially in large corporations. Additionally, the solution developed as part of this research might also be helpful for users in related fields, e.g. information scientists or software developers. Furthermore, the theoretical basis of this research is dedicated to helping researchers to rely on a holistic documentation of portfolio validity and the challenges involved.

1.5 Thematic classification of the research

This research combines approaches from different fields of science as it uses product portfolio definitions common for engineering disciplines, validation tools and data quality criteria developed by information scientists and process frameworks originally setup by management sciences. The following Figure 2 shows the examined fields of science considered in combination with the contribution to scientific knowledge this research aims for.

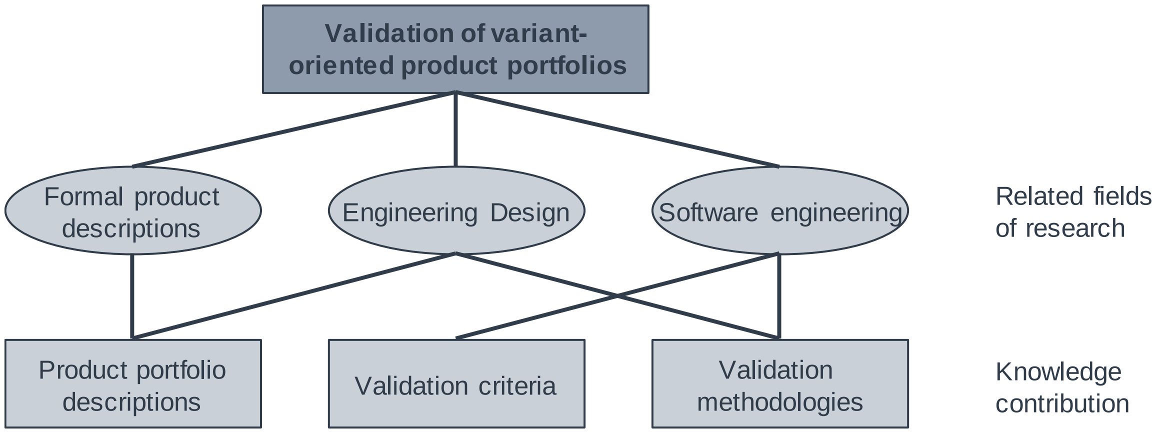


Figure 2: Related fields of science and knowledge contribution

Research about formal product descriptions delivers different approaches to how to structure and document complex, multi-variant product portfolios. Additionally, information about the usage of these formal descriptions in different industrial use cases is given. In return, this research provides a comprehensive overview of relevant product portfolio descriptions that are actually in use within the industrial practice.

The research field of Engineering Design provides insights into working with product portfolios and approaches to dealing with the aspects of validity as well as validation methodologies in multi-variant product portfolios. The knowledge contribution in this field is the evaluation of the existing validation methodologies, their shortcomings and the procedural model developed as a solution for this research.

The software engineering research provides examples and strategies on how to define and measure data quality and the algorithmic tools needed to compute validation tasks. In return, this research develops both precise use cases for the application of generic data quality dimensions and a comprehensive procedural model to optimize the application of validation algorithms.

1.6 Research methodology and background of the author

This research is meant to both develop an applicable solution to match the requirements in the industrial practice and to provide additional knowledge for the scientific community working in that field of theory. Therefore, the research methodology that this research follows is explained below.

The course of this research is approximated to the Design Research Methodology [11], as outlined in Figure 3 below.

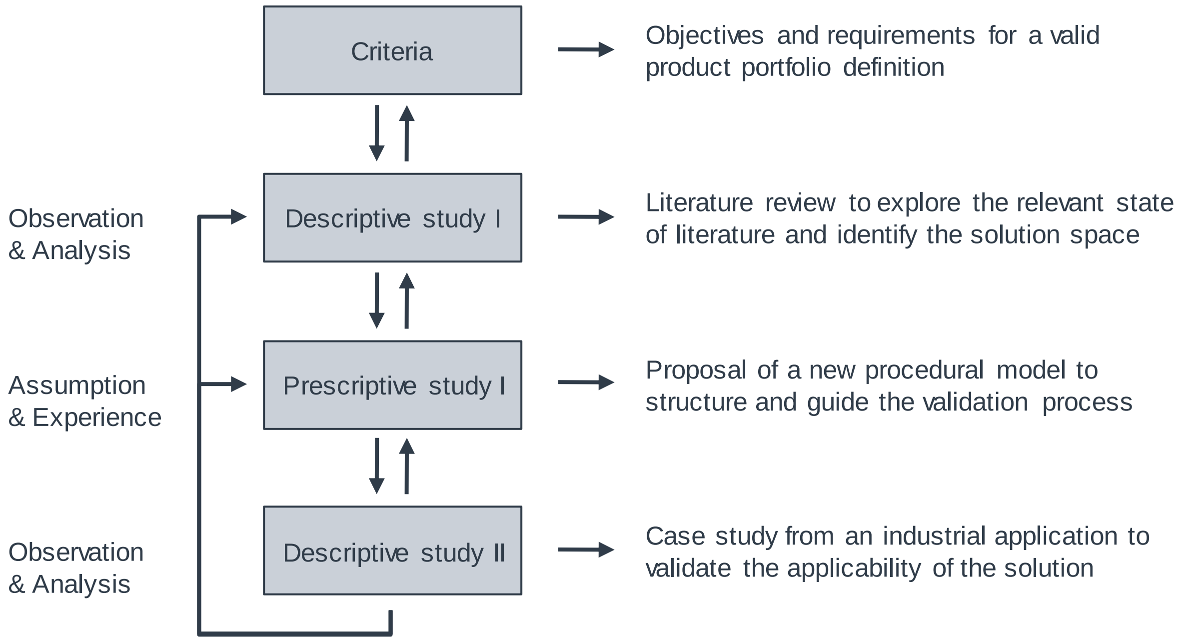


Figure 3: Design Research Methodology, adapted from Blessing & Chakrabarti [11], [12] as used to structure this research

In the first stage, the *criteria definition* stage, the aim and the focus of the research project is defined. Based on these criteria, the problem description is examined in detail in the *descriptive study I* with the aim to define the solution space for the support developed as part of the research. The *prescriptive study I* proposes a support (e.g. a methodology, a tool, a process) to solve the problem description as outlined before. This proposed support is than evaluated against a (real-life) problem case example to prove the efficiency of the developed solution as the main goal of the *descriptive study II*.

For this research, the design research methodology has been adapted resulting in a thorough literature review as part of the first descriptive study, a proposed solution representing the prescriptive study as well as a real-life case example from the industrial application representing the second descriptive study.

Although this research involves knowledge and experience from different fields of research, e.g. from engineering design in terms of product lifecycle management, from information science in terms of data quality criteria and validation algorithms and from business management sciences for process frameworks, the author has a background focussed mostly on engineering design. Yet, the integration of knowledge from different fields of science and its application for engineering design has been at the researcher's heart of interest in his past studies.

Before focussing on the topic of product portfolio definitions, the author was involved in a study on platform strategies and their monetary evaluation, in which both monetary criteria and their application for platform design were examined [13]. In this study, knowledge of different disciplines (engineering design and finance & accounting) was integrated into one solution, dedicated to an engineering application.

Furthermore, the author was dealing with the topic of customer acceptance of new products in Product Service Systems [14]. In a case study, the customer acceptance of electric vehicles in car-sharing was examined in Sweden compared with Germany. Here again, knowledge of different disciplines and fields of science (e.g. engineering design, marketing, innovation management) was integrated.

Most of this research originates from a collaboration project between the industry partner MAN Truck & Bus SE and the Universität der Bundeswehr München. In this set-up, the author was acting as both the lead researcher on sides of the university and as the project lead in the IT department being part of the MAN Truck & Bus SE IT department for Engineering.

1.7 Structure of this research

As explained in the previous section, this research follows the approach of the Design Research Methodology as introduced by Blessing & Charkabarti [11] with the key elements *descriptive study I* to explore the problem description in detail, the *prescriptive study I* to propose a solution to the problem and the *descriptive study II* to evaluate the proposed solution against a real-life example case. This structure is outlined in the following and visualized in Figure 4.

Chapter 1 - Introduction presents the current challenges in the industrial application, the scientific approach used in this research and outlines the problem description.

Chapter 2 - Related state of the art explores the current state of literature focussing on three aspects. First, how are product portfolios systematically described and what are they used for, second, what aspects are relevant regarding the validity of product portfolios and third, what kind of approaches already exist for the validation. Finally, these three fields of literature are set into context to derive implications from the current state of the art, i.e. identify the scientific contribution of this research. Based on this literature review, the key hypotheses and detailed research questions are stated that this research is answering.

Chapter 3 – Procedural model defines the requirements for the solution based on the findings from the state of the art and proposes a procedural model to structure the validation process as a solution.

Chapter 4 – Working with the procedural model explores the theoretical application of the procedural model with focus on the relations of the elements and the sequence of validation tasks as well as its integration into corporate core business processes.

Chapter 5 – A case study validates the applicability of the proposed solution, the procedural model, based on a real-world industry application in a case study. This chapter consists of a description of the case study itself, the actual application and the resulting observations and findings.

Chapter 6 summarises the results based on the case study and its findings, gives a brief reflection of the work of this research and concludes with an outlook on future research needs.

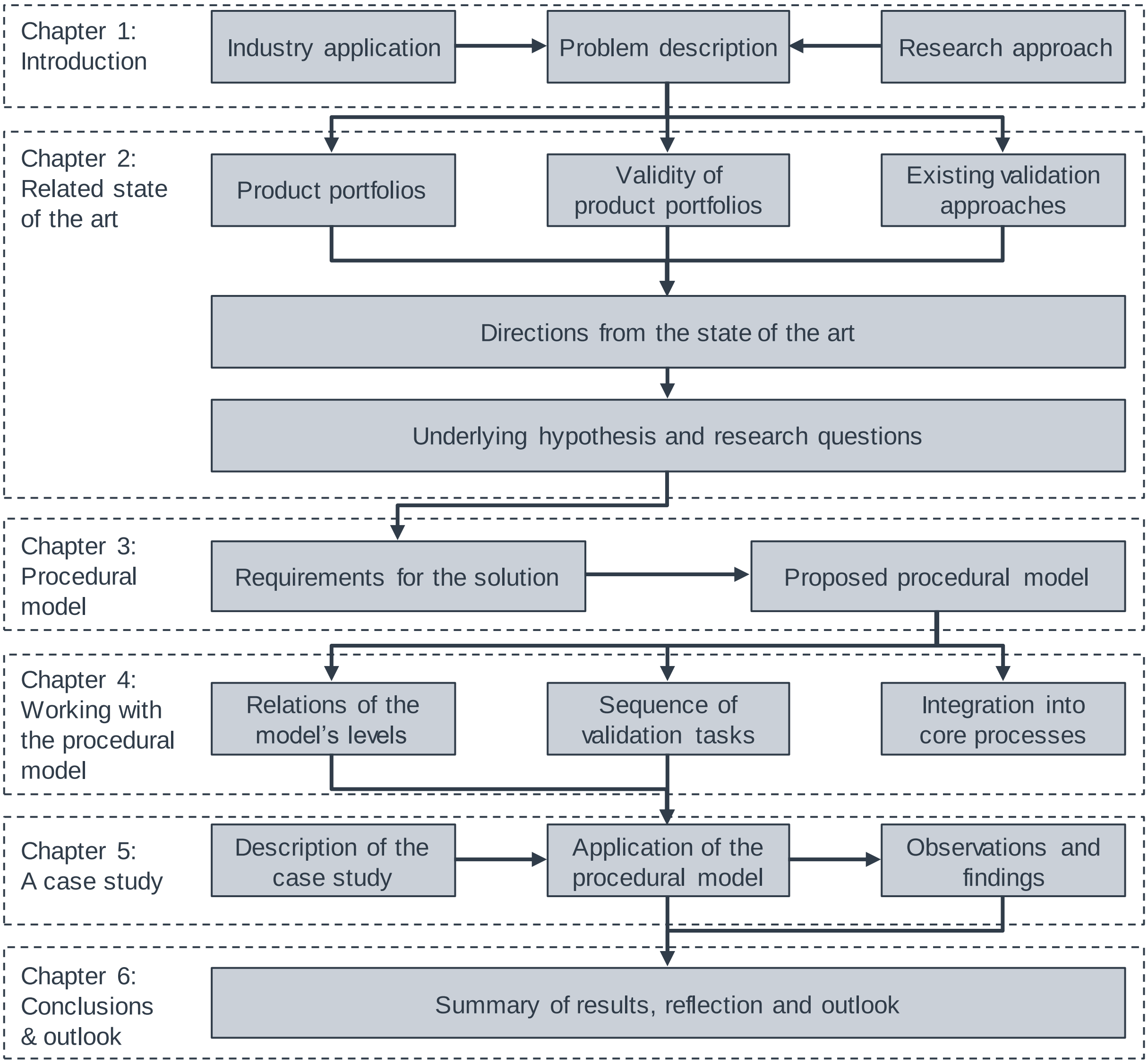


Figure 4: Structure of this research, inspired by Kreimeyer [15]

2 Related state of the art

For the definition of a comprehensive validation framework, literature from different research fields and sciences has to be examined and connected.

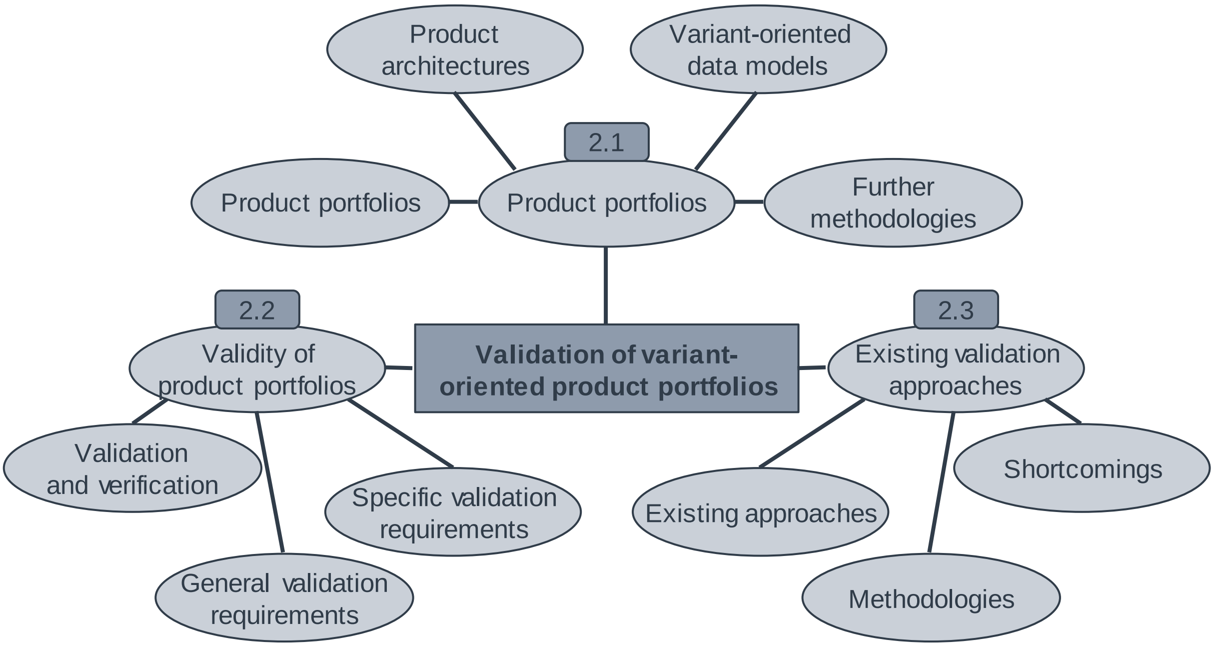


Figure 5: Main areas of literature covered in this research

The scope of this research covers three main areas of literature, as shown in Figure 5 above: research on product portfolios themselves, on the validity of product portfolios and on existing validation approaches. Within the first focus area, different types of product architectures and multi-variant data models are explained in detail. Additionally, further methodologies are outlined to define the borders of this research. As part of the second focus area, a general definition of the terms validation and verification is given. Based on these definitions found in literature, both the current state of research on general and specific validation requirements for product portfolios is explored. The third focus area concentrates on literature regarding existing approaches to validation. Both methodologies and approaches are analysed and their shortcomings as described in literature are outlined. Last, the implications of the related state of the art for this research are outlined to clearly lay out the scientific contribution this research aims for.

2.1 Product portfolios and product architecture in research and industry

Before discussing the validation and verification of products, the object under investigation needs to be clearly defined first. Therefore, in the following chapter the current state of literature regarding the relevant basics for multi-variant products are outlined. These basics are especially the *product portfolio* and the structure that this portfolio is documented in, i.e. the *product architecture*. In the following chapter, product portfolios and portfolio management are outlined in section 2.1.1. Following in section 2.1.2, product architectures and their components are explained. In the third section 2.1.3, the practical application of product architectures in science and industry is shown. Lastly, section 2.1.4 gives an outlook on further well-known methodologies and their shortcomings.

2.1.1 Product portfolios and portfolio management

Large manufacturing companies generally develop a variety of different products. Each product is tailored to fulfil a specific set of functions and to meet a certain customer demand. The sum of all products that one manufacturer is offering is also considered as the *product portfolio*. The product portfolio consists of both the existing products that have already been developed and the new product projects that are still in the phase of an R&D project, according to Cooper et al. [16], as depicted in Figure 6 below.

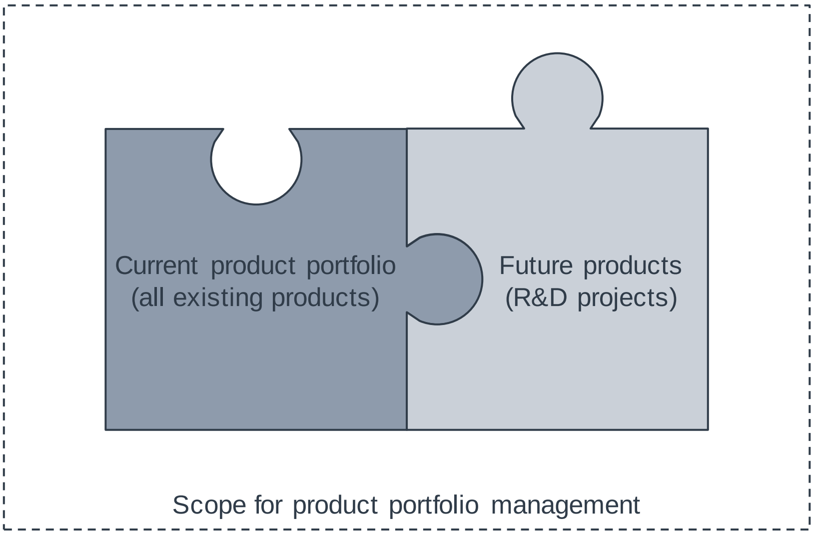


Figure 6: Scope for product portfolio management

When discussing the content and structure of product portfolios, most authors refer to the product architecture and product platform strategies, as described in chapter 2.1.2. Therefore, only few authors focus on the product portfolio itself. Yet a lot of research covers the way of how to manage product portfolios, as this is a fundamental aspect for a manufacturing company to persist over time. This area of research is covered from different perspectives, both from an economic and management point-of-view and from an engineering perspective. One of the first and most-cited approaches to manage product portfolios is the BCG-matrix developed by Henderson [17], as explained with Hambrick et al. [18]. Based on financial figures, it divides a product portfolio in a matrix with four quadrants along two axes: growth on the y-axis and market-share on the x-axis. For each of the four quadrants (stars, question marks, pets and cash cows), norm strategies on how to deal with the product have been developed. As different perspectives exist on the product portfolio within a company, a loss of information on the portfolio happens. A joint, rule-based product portfolio description helps to establish a general level of knowledge on the portfolio, also for portfolio management activities.

Especially at the beginning of the 1960s and 1970s, portfolio management was largely a highly mathematical process, involving optimization functions. Over time, a vast set of methodologies has been applied to meet portfolio management challenges. Cooper et al. [19] outline eight different domains of portfolio management, starting with financial models and financial indices, over probabilistic financial models, option pricing theory and strategic approaches, scoring models and checklists, analytical hierarchy approaches, behavioural approaches as well as mapping approaches or bubble diagrams. Five of them are used frequently based on their industry case study [16]:

- *Financial methods*: approaches such as Net Present Value (NPV), Return on Invest (ROI) or payback periods
- *Business strategy*: the prioritization of money for product development projects being in line with the business strategy
- *Bubble diagrams or portfolio maps*: approaches similar to the BCG-matrix, as described above
- *Scoring models*: the evaluation of product development projects with adding-up scores in different dimensions to form a ranking
- *Check lists*: the evaluation of product development projects along certain yes/no-criteria

To cover the entire product portfolio management process over time, a six-step approach was defined by the Product Development and Management Association [20], which incorporates changes in the portfolio induced through the development of new products, as shown in Figure 7 below:

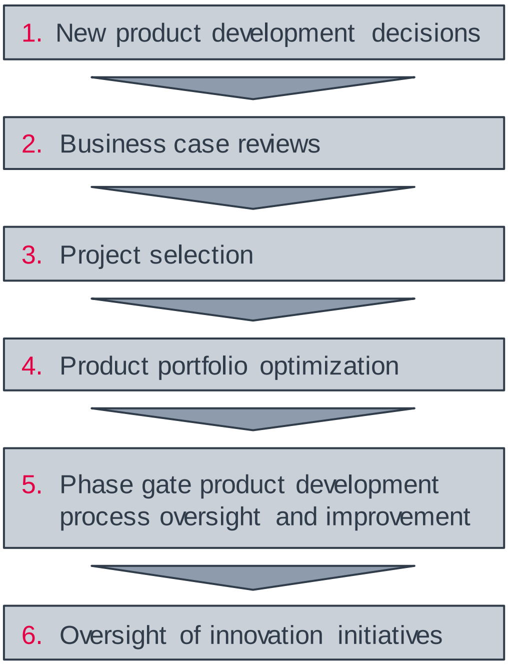


Figure 7: Managing product portfolios according to PDMA [20]

As outlined above, countless approaches based on numerous methodologies to manage product portfolios exist in the industrial application. For this research, the question of how to manage a product portfolio is not the primary focus. The validation of product portfolios does not solely depend on the way of managing a portfolio. Whereas portfolio management approaches deal with both the current and the future state of a product portfolio, the way of how to get from today's to tomorrow's portfolio is often not addressed. Nevertheless, it is an important aspect of how a product portfolio changes over time. Not only has the existing product portfolio to be validated, as shown in Figure 6 above, but also the future changes introduced through new product projects are of interest. Therefore, chapter 4.3 deals with the validation of future changes within a product portfolio and the integration into the product development processes.

2.1.2 Product architectures and their constituents

The term product architecture is widely used within engineering design, both in a scientific and an industrial context to refer to the structure of all elements in the product portfolio. A general definition of product architectures has been given by Ulrich [21], in which he defines product architectures as: "(1) the arrangement of *functional elements*; (2) the mapping from *functional elements* to *physical components*; (3) the specification of interfaces among interacting *physical components*". In Ulrich's view, product architectures consist of a usage-oriented perspective (i.e. "*functional elements*") and an engineering / product-oriented perspective ("*physical components*"). The connection between the functional elements and the components can either be a one-on-one-mapping, which means one functional element maps to exactly one physical component or a n-on-m-mapping, relating several functions to several components and the other way around [21].

An idealized modular product architecture consists of only one-on-one-mappings, so each component has a dedicated functionality and de-coupled interfaces between the components, i.e. components, which are independent from each other. Opposite to modular product architectures are integral product architectures, in which functional elements have a n-on-m-mapping to components with mostly coupled interfaces between the components.

Dahmus et al. [22] also rely on a functional decomposition to examine the functions relevant to the product and their relation to the components of the product.

Over the years, a lot of research has covered the different types of product architectures and especially the corresponding models. A comprehensive exploration of different models can be found for example with Fixson [23]. He divides product architectures in three groups according to the underlying architectural model: mathematical models, conceptual models and engineering models, as explained in Table 1 below.

Table 1: Types of product architecture models, according to Fixson [23]

Product architecture model	Characteristics
Mathematical models	Mathematical formulation of components and their interactions to provide a basis for optimization algorithms
Conceptual models	Models describing the degree and type of modularity to measure and improve modularity on product architectures
Engineering models	Indices-based models describing the combinability of components, often linked to representations in a Design Structure Matrix

Another extensive research on different types of product architecture models and product architecture analysis techniques is found with Deubzer [24]. In his work, generic elements of product architectures are described as Goals, Objects and Actions of a product architecture. Within the objects of a product architecture, Deubzer also differentiates *component domains* consisting of components, assemblies and interfaces and *property domains* consisting of properties and characteristics of the product variants.

Similar approaches to structuring elements within a certain domain is found in different scientific areas often defined as *system architectures*.

Within information science, system architectures are used since long time to structure distributed information systems and their components [25]. Based on the use in information systems, the application of systems architecture has become important for the use in engineering-related disciplines as well. Especially within IoT (Internet-of-Things) and Cyber-Physical Systems consisting of both hardware and software elements, system architecture approaches are of use [26].

Despite the differentiation into modular and integral architectures or other types of product architectures which is not in the focus of this research, the dualism of *functional elements* and *physical components* is found with typical representations of product architectures in both the academic and industrial context. In this research, the validation of product architectures following a usage-oriented view ("what to do with the product", i.e. the *functional elements*) connected to a product-oriented perspective ("what components are relevant", i.e. the *physical components*) is examined. The detailed application of these kinds of product architectures is outlined in the following section 2.1.3 showing the relevance of these product architectures in the industrial application.

2.1.3 Multi-variant data models in science and industry for product architectures

A widely used model within the industrial application is the SAP iPPE standard (SAP integrated Product- and Process-Engineering) according to Blumöhr et al. [27] or Kreimeyer [10]. The SAP iPPE is usually implemented within the SAP Variant Configuration (SAP VC) software, as stated by Configit [28]. The main component is the so called "*variant product: configurable material KMAT*" *(short from German: Konfigurierbares Material)*. The main components of the variant product KMAT are outlined in Figure 8 below:

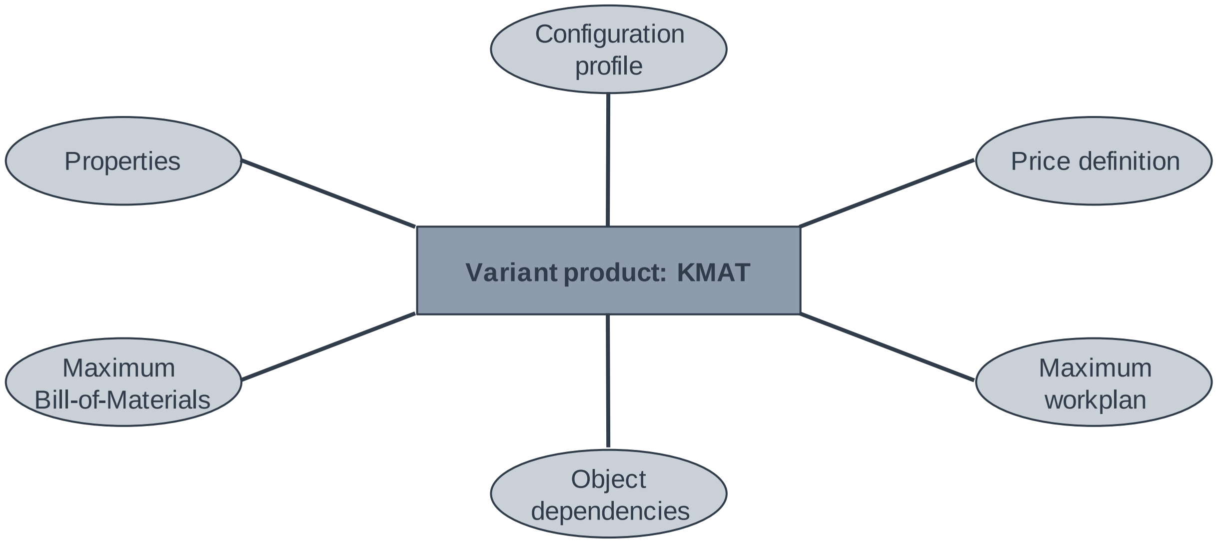


Figure 8: The variant product KMAT, as depicted in [29]

The variant product KMAT consists of six key elements [27], [29]. The *properties* contain all the elements that are used in the product configuration, i.e. all properties that can be selected within a configurator. For each property, a *configuration profile* must exist to define the application of the properties within a customer order. The *price definition* incorporates the prices for all product variants, in which the prices might depend on the combination of properties. The *maximum work plan* consists of all process steps that are relevant for the production process in the plant. The *Maximum Bill-of-Materials* contains all components that are part of the product portfolio. Both the maximum work plan and the maximum bill-of-Materials consist of all variants of components and process steps being part of the portfolio. For one dedicated customer order, these maximum structures need to be reduced to only the variants relevant for the actual product variant. Therefore, the *object dependencies* are vital. Here, all the dependencies on combinations of properties as well as components or process steps are stored. Furthermore, the selection conditions that link the Bill-of-Materials and Work plan to the selected properties in the configuration process are contained. Especially the maximum bill-of-materials is relevant from the engineering point-of-view, as here all physical components are documented. In consequence, the SAP iPPE data model can be used to document and configure products with large numbers of variants and numerous different elements within the Bill-of-Materials.

As the SAP iPPE data model is widely used within the industrial context [10], it can be found with large corporations, e.g. with BMW [30], which have built an entire product documentation ecosystem around the SAP iPPE-model, but also with smaller automotive suppliers, e.g. Karmann [31] and also outside the automotive business area, e.g. being used by a large steel group [32].

Structures similar to the SAP iPPE-model have been built up by various automotive OEMs dealing with complex products with large numbers of variants. Often these OEMs have developed their own software solutions or have adapted existing ones (i.e. not relying on SAP but in a similar structure) to form their tailored Product Data Management (PDM) systems. A Product Management (PDM) System is a software solution used to manage all product-related data, as describes with Mesihovic et al [33].

A detailed examination on different product architectures in the industrial application, is carried out by Tidstam & Malmqvist [34]. Here, examples taken from Volvo and their PDM-system *KOLA*, Scania with the product configuration system *SPECTRA* as well as Mercedes with the *SMARAGD* PLM-system are illustrated. All these different PDM-systems are often highly customized variants of generic PDM software that are tailored to meet the specific processes and information flows of the respective company. Still, the underlying structures can be generalized in a framework, according to Tidstam & Malmqvist [34], as shown in Figure 9 below.

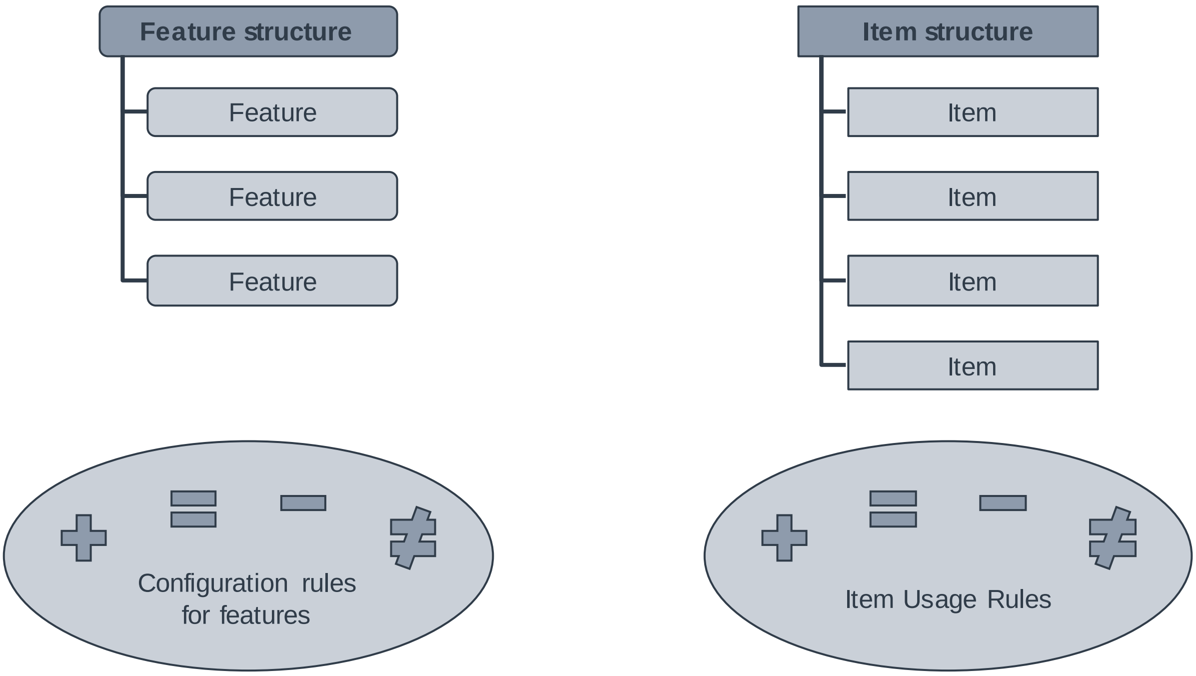


Figure 9: A generalized framework of product architectures, according to Tidstam & Malmqvist [34]

First, a *Feature structure* is defined consisting of different features. The features are the properties of the product that a customer chooses when configuring a final product. It is similar to the properties described within the SAP iPPE. A similar structure is described as the *Item structure,* which consists of the components that the product is built of. These components are named items, as they can be both hardware and software, as well as documentation components. This item structure can be directly linked to the Maximum Bill-of-Materials and the Maximum work plan in the SAP iPPE model. Second, two sets of configuration rules have been identified. The *Configuration rules for features* are used to define the relations between the features in the feature structure. Here, the constraints between different variants within the product portfolio are documented. The *Item Usage Rules* are the second set of rules. They are relevant to identify the correct items within the item structure, based on the configuration of features. For example, these rules can be used to identify the unique Bill-of-Materials based on a general Bill-of-Materials (i.e. the Maximum Bill-of-Materials). The Configuration rules as well as the Item Usage Rules are again represented by the Object dependencies within the SAP iPPE model.

Another application of these *configuration rules* can be found in the agricultural vehicle manufacturing. For instance John Deere, a manufacturer of large tractors and agricultural equipment, relies on numerous sets of configuration rules to define the combinability of functions and respective components in their portfolio [35].

Furthermore, for Mercedes-Benz passenger cars, a very similar portfolio structure is described in detail, closely linked to their bill-of-materials system *DIALOG* involving different types of rules (constructability check rules, parts selection rules) and features (equipment codes) as well as items (parts) [36].

Figure 10 below shows the communality between the findings of Tidstam & Malmqvist [34] and the SAP iPPE model [29], as described above.

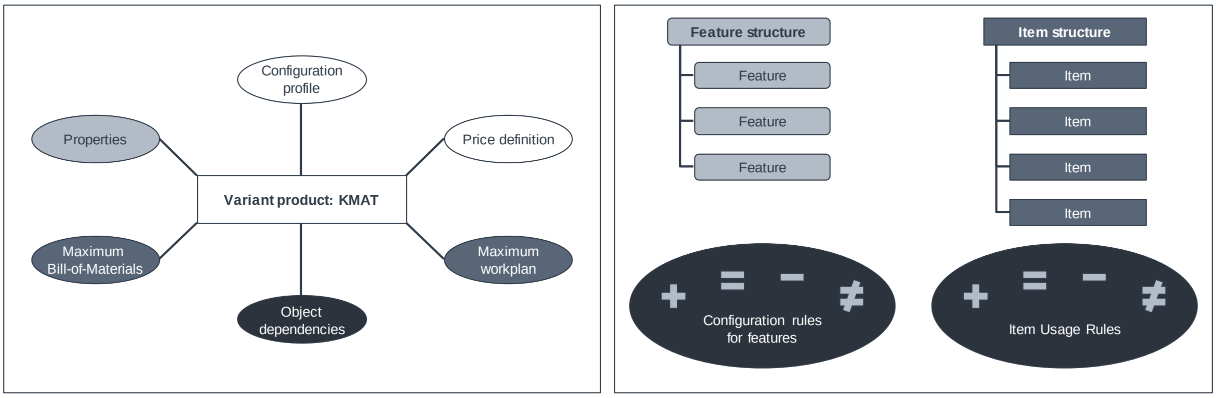


Figure 10: Communality between SAP iPPE model and the generalized framework observed for the automotive industry. The same colour of objects indicates similar elements.

In a more generalized view, especially the “feature structure and configuration rules”-part of this type of product architecture can be described as a rule-based configuration system according to Faltings & Weigel [37]. A rule representing any portfolio knowledge consists of an *IF* and a *THEN* part, representing the *condition* and the *consequence*. Based on logical deduction, these rules can be directly interpreted. If the condition is *TRUE*, then the consequence can be directly concluded.

$$IF\ (condition)\ \Rightarrow THEN\ (consequence)$$

Within the industrial application, in most cases relations and constraints between portfolio objects are rather complex. This is due to both large variances within the product portfolios based on broad customer demands and large sets of, sometimes contradicting, requirements that these products have to fulfil, e.g. legal, technological or sales requirements. This complexity results in rules with many conditions and consequences. Therefore, Boolean operators are used within configuration rules to allow for complex rules. The most important operators are outlined in Table 2 below.

Table 2: Boolean operators used within configuration rules

Symbol (alternative)	Boolean operator	Meaning in context
∧ (alt. + ; &)	AND	Logical conjunction of two conditions
∨ (alt. /)	OR	Logical disjunction of two conditions
¬ (alt. - ; !)	NOT	Logical negation of one condition
$<$	LESS-THAN	Numerical comparison of two conditions
$>$	GREATER-THAN	Numerical comparison of two conditions
⇒ (alt. →)	CONSEQUENCE	Material implication relating the condition to the consequence of a rule

With the help of these Boolean operators, configuration rules can be written with any desired complexity when using multi-level, nested conditions. In the industrial application, very long then-consequences for configuration rules for features, as well as long and complex if-conditions for item usage rules can occur with over 100 different influences within one rule. Examples can be found in the case study taken from the commercial vehicle industry in chapter 5.

Especially for very complex and interlinked product portfolios, these types of product architectures as outlined above, are used. These product family architectures can also be described as *multi-variant product portfolios* according to Kissel [38].

Classifying the elements of multi-variant product portfolios

One key aspect to be covered when discussing multi-variant product portfolios is the correct terms and terminologies for the elements of the product portfolio definition. As outlined above, these elements are named either *properties* within the SAP iPPE model or *features* within the generalized framework of Tidstam & Malmqvist. Within the academic discussion, the terms *property*, *characteristic* and *feature* need to be defined clearly to avoid confusion when relating to one or the other term.

A rather recent definition is the PCM and PDD approach, the *characteristics-properties modelling (CPM)* and *property-driven development (PDD)* as described by Weber [39].

Weber [39], [40] defines characteristics and properties as follows:

- The *characteristics* describe the structure, shape and material consistency of a product ("Struktur und Gestalt", "Beschaffenheit"). They can be directly influenced or determined by the designer (e.g. material, shape, dimensions, etc.)
- The *properties* describe the product's behaviour (e.g. weight, safety and reliability, aesthetic properties, but also things like "manufacturability", "assemblablability", "testability", "environmental friendliness" and "cost"). They cannot be directly influenced by the designer

On this basis, Weber [39] defines the *analysis* process as "*determining/ predicting the product's properties (behaviour) from known / given characteristics*" and the *synthesis* process as "*determining/assigning the product's characteristics from given/required properties.*"

For this research, a common definition and terminology for the objects describing the product portfolio from a customer's perspective is required. Weber [39] states that for customers, it is the properties that are especially relevant as they are chosen according to the customers' requirements. Yet, in the context of commercial vehicles, customers can choose both properties of a vehicle (e.g. a certain height, comfort level, etc.) and characteristics (e.g. colour of the cabin, size of the gas tank, etc.). Consequently, Weber's differentiation between properties and characteristics is not sufficient for this purpose.

Based on his work, Eilmus [41] , [42] , [43] has extended Weber's definition and introduced the terminus *customer-required differentiating properties*. In her view, customer-required differentiating properties are all elements that differentiate product variants from a customer's point-of-view. These differentiating properties can be expressed both directly through technical characteristics and properties [41]. This definition has also been applied by other authors in the last years, e.g. with Bahns [44].

A broader agreement is found in literature when examining the terms applied to for the physical product view on the portfolio. Pimmler & Eppinger [45] describe this as the *physical elements or physical components* of a product. With Zagel [46], these objects are defined as *product components (variants)*. Kreimeyer et al [9] refer to them simply as *components* and *component variants*. In the SAP iPPE model the objects are named *components*, whereas Tidstam & Malmqvist refer to them as *items* in their generalized framework.

For this research, all customer-chosen objects defining the product portfolio will be entitled as customer-required differentiating (product) properties, or short *customer-required properties*. In their original categorisation according to Weber [39], they can be both properties and characteristics. The physical representations of actual parts, as seen from the engineering / construction point-of-view are defined as *components and component variants* in this research.

2.1.4 Further methodologies to structure products and their shortcomings

As outlined before in chapter 1.3, large quantities of Boolean rules involving ten-thousands of elements and leading to 10^{300} possible combinations can be present in the industrial application. Product portfolio methods to handle these types of complex, multi-variant portfolios need to be capable of dealing with such large and complex dependencies. Therefore, some widely used and easy-to-understand portfolio description methods have shortcomings when dealing with large product definitions. In the following section, the most commonly known classes of product architectures are briefly outlined. Also their shortcomings in the application for large and complex product-portfolios are displayed.

A widely-used methodology, especially for the integration and decomposition of systems, is the *Design Structure Matrix (DSM)* [47], as depicted in Figure 11 below.

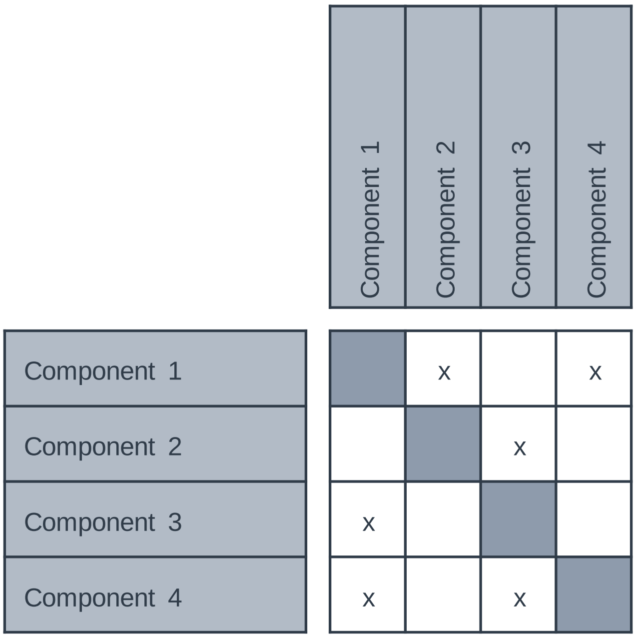


Figure 11: A Design Structure Matrix (DSM), according to Browning [47]

Within a Design Structure Matrix for example the relationship between components can be documented [47]. Pimmler & Eppinger [45] use large DSMs to break larger systems down into subsystems. On this basis algorithmic tools can help to cluster information stored within DSMs. Although the size of a DSM is not limited to any extent from a theoretical point-of-view, in the industrial application limitations have been found. Browning shows that the size of DSMs is practically limited to around 50 - 100 elements so that it can still be read on one page. For the practical application in larger product portfolios (commercial vehicle portfolios can consist of ten-thousands of elements, as outlined in chapter 1.2), the division into large quantities of smaller DSMs is required. As a consequence of this decomposition, the smaller DSMs often become inconsistent and contradictory [47]. In addition, another shortcoming is identified by Blees [48]: he criticizes the lack of transparency when using algorithmic tools for transforming DSMs.

Graph-based representations of product portfolios have been shown in the form of variant trees or *decomposition trees (DCT)*, as outlined by Jiao & Tseng [49]. According to them, a product decomposition tree depicts the *functional requirements (FR)* and their dependencies with "*and*" relating to other functional requirements and "*or*" nodes relating to the function variants as shown in Figure 12 below.

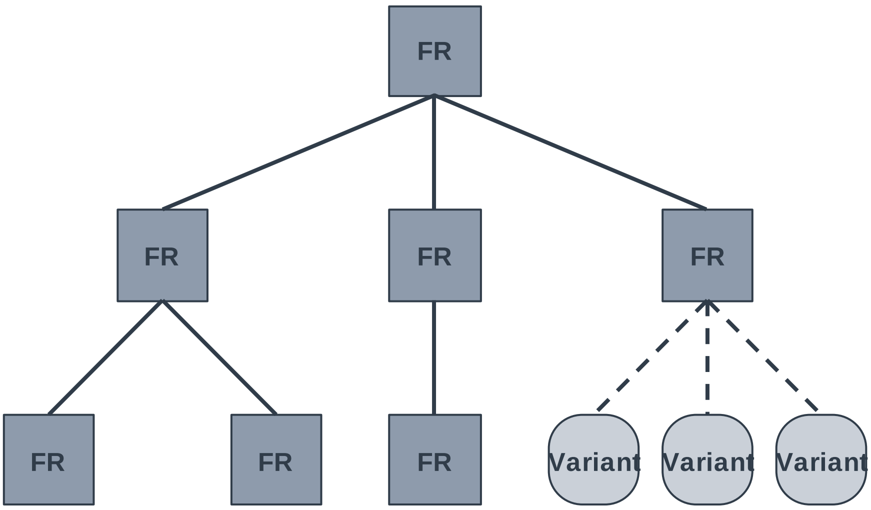


Figure 12: A decomposition tree, according to Jia & Tseng [49]

Variant trees work well for a rather limited observation field within entire product portfolios, as they can be easily understood and read, also by non-expert users. Yet, when it comes to large and complex product portfolios, e.g. ones with hundreds-of thousands of objects (i.e. functional requirements) and their combinations, manual readability is no longer possible. Therefore, variant trees are not suitable when assessing the validity of entire product portfolio definitions.

A similar methodology often described is the *feature-oriented domain analysis (FODA)*. The FODA model consists of graphical symbols and relations between these symbols forming a configuration tree, as explained in detail by Pohjalainen [50]. Figure 13 below shows an exemplary FODA model for the engine power of a truck engine:

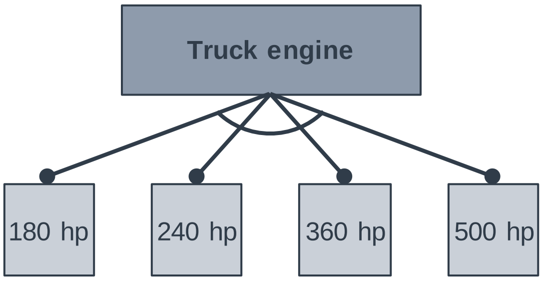


Figure 13: A simplified FODA model for truck engine power

Within the relations, both mandatory and optional choices can be labelled. Also, or-features can be distinguished. Due to the visual representation of constraints and interdependencies, this approach works well for the graphical analysis of systems. Yet, due to the lack of automation and FODA being carried out on a manual or semi-automatically level [51], it causes difficulties when being applied to larger and complex systems like multi-variant product portfolios. This is mostly due to large numbers of variants (product portfolios with ten-thousands of elements) as well as to the changes induced during product development activities, as described by Bühne et al [52].

2.2 Validation and verification of product portfolios

The product portfolio and product architecture as examined in the previous chapter form the structural basis for the validation and verification of multi-variant product portfolios. In this chapter, the current state of literature on the validation of product portfolios is outlined. First, in section 2.2.1 the aims, the context and the differences in validation and verification are discussed. Second, in section 2.2.2 general requirements for the validity of data sets are examined. Third, in section 2.2.3 the specific requirements regarding the validity of multi-variant product portfolios are derived on this basis.

2.2.1 Differentiating validation and verification

For the development and production of engineered systems in the manufacturing industry, a large range of complex entities is covered according to Engel [53]. This is, for instance, a mix of technologies, products as well as services, people and machines. Therefore, the verification, validation and testing of engineered systems is a critical link for ensuring error-free and high-quality products [53]. Also, according to Albers et al. [54], *validation* and *verification* are the central activities within the development process. Yet both termini, *validation* and *verification*, are difficult to differentiate and often confusion about the exact definition exists. This section gives an overview of the most common definitions and outlines the interpretation relevant for the context of this research.

In the IEEE community, the terms validation and verification are defined for both hardware as well as software systems in the IEEE 610.12-1990 standard [55]:

- *"Verification*: The process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase"
- *"Validation*: The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements"

The U.S. Department of Defence, Modelling and Simulation Office defines both terms related to the application in modelling and simulation contexts [56], [57]:

- *"Verification*: The process of determining that a model implementation and its associated data accurately represent the developer's conceptual description and specifications"
- *"Validation*: The process of determining the degree to which a simulation model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model"

Gonzales & Barr [58] define their own view on verification and validation in the context of intelligent systems. For them, intelligent systems are "any models of a real-world practice" [58].

- *"Verification*: Is the process of ensuring that the intelligent system 1) conforms to specifications, and 2) its knowledge base is consistent and complete within itself"
- *"Validation*: Is the process of ensuring that the output of the intelligent system is equivalent to those of human experts when given the same input"

In the Western European research area, the VDI-definitions of verification and validation are also popular as used within the engineering context [59]:

- *"Verification*: The review whether a realization (e.g. a software program) matches the specification (in this case: the algorithmic description)"
- *"Validation*: The assessment whether the product is suitable for its intended use, or rather whether it delivers the expected value. Here, the expectations of the technical experts and users are included"

The DIN EN ISO 9000 [60] relies on similar definitions for both verification and validation:

- *"Verification*: Review through providing objective evidence that predefined requirements are met"
- *"Validation*: Review through providing objective evidence that the requirements for a specifically intended use or a specifically intended application are met"

As outlined above, a large range of definitions of both termini exists and only the most relevant sources are covered here. Nevertheless, commonalities between the different definitions can be found and applied for this research.

Verification is generally described as the review whether the process or product was executed right, i.e. whether the requirements for the process / product are met, with no regard to their usefulness or applicability. It can be interpreted as “have we done it right?”

Validation is, opposite to the above definition, generally described as the review whether the process / product is suitable for the intended use, i.e. whether the fulfilled requirements also help to apply the process / product in the right way. It can be interpreted as “have we done the right thing?”

This view also helps to identify the right terminus for the focus of this research. When discussing the validity of multi-variant product portfolios in this context, the aim is to ensure that the product portfolio and its data is documented in a way that subsequent actions, e.g. engineering, production and sales processes, can be executed based on that data. Here, the intended usage is, for example, to be able to configure all products that are in the portfolio, to be able to build all these products and have an unambiguous Bill-of-Materials for any product and to ensure the correctness over time.

As the aim of this research is to develop a methodology to ensure that the product portfolio can be used properly, i.e. the portfolio is documented *right*, the process examined in this research must be considered as a *validation process*. Therefore, the following research focusses on the perspective of *validation* only, the *verification* process is out of scope as verification would mean to focus not on the data structure but on the real-world comparison as in crash tests or physical testing of products on a test track.

The cross check can be provided by describing what a verification would be in the context of multi-variant product portfolios: Verification is defined as to review whether the product portfolio was built in the right way. Therefore, the test would be to check the virtually documented product portfolio against the real world portfolio and compare whether all physically possible combinations of parts are also considered in the product portfolio definition. Yet no check on plausibility would be executed, so if errors existed in the physical product portfolio, verification would request the same errors to be found in the virtual product portfolio definition.

2.2.2 General requirements for the validity of data sets

To describe a validation process for multi-variant product portfolios, a clear definition of validity in this context has to be agreed on first. Therefore, this section outlines requirements for the validity of data sets in general. Here, definitions used within the information science to assess the general quality of any data sets are discussed.

One broad definition of the quality of data sets used by many authors is given by Wand & Wang [61]. In their work, they outline four main, intrinsic data quality dimensions: *Completeness*, *Unambiguity*, *Meaningfulness* and *Correctness*. These four dimensions can be derived from different sources of deficiencies of virtual system representations of the real world, as shown in Figure 14 below. The left-hand side symbolizes the data representation in the physical, real world (RW), the right-hand side symbolizes its representation as data (i.e. documentation (DOC)).

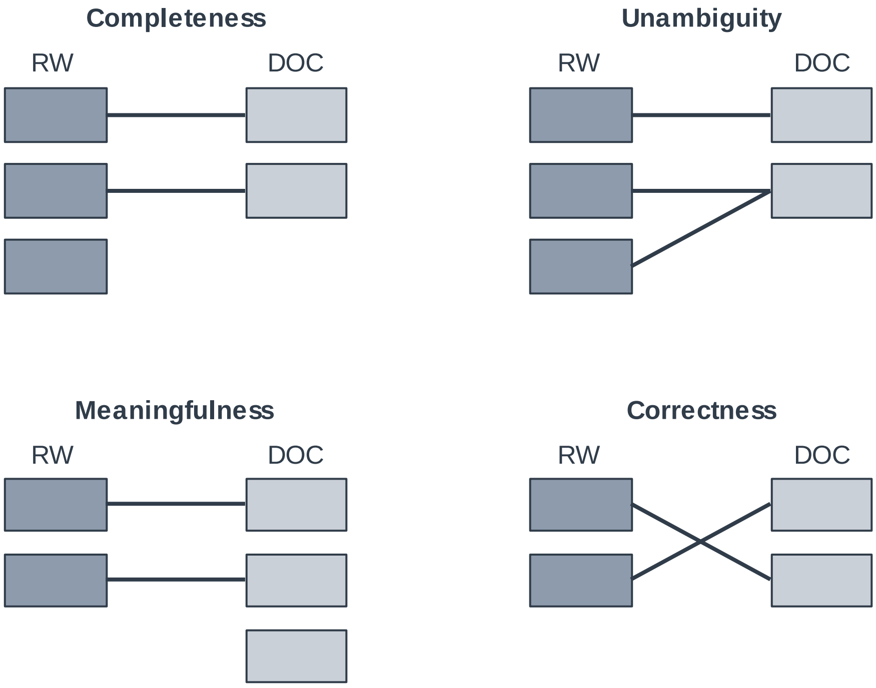


Figure 14: Four intrinsic data quality dimensions, adapted from Wand & Wang [61]

- *Completeness*, as shown in Figure 14 in the top left-hand corner, stands for the complete representation of all elements of the real-world (RW) within the data set (DOC). It has to be ensured that within the data set, no element of the real world is left out
- *Unambiguity*, as shown in Figure 14 in the top right-hand corner, stands for the mapping of not more than one element of the real world into the data set. It has to be ensured that the relation between the data set and the real world can be interpreted in both directions only in the same way
- *Meaningfulness*, as shown in Figure 14 in the bottom left-hand corner, stands for the accurate correlation between the data set and the real world. It has to be ensured that all data within the data set have a meaning

- *Correctness*, as shown in Figure 14 in the bottom right-hand corner , stand for the correct representation of the real world into the data sets. It has to be ensured that the data within the data set are correct, i.e. reliable and can be counted on

These intrinsic data quality dimensions have been reformulated and generalized by Wand & Wang [61] to form their generic data quality dimensions, as outlined in Table 3 below.

Table 3: Generic data quality dimensions based on Wand & Wang [61]

Generic data quality dimension	Definition
Completeness	No loss of information about the real world in the data set occurs
Unambiguity	No data within the data set can be interpreted in more than one way
Meaningfulness	No data within the data set can be interpreted in more than one way
Correctness	No data within the data set are based on an incorrect representation from the real world

Another definition of data quality dimensions was developed by Askham et al [62] consisting of six core data quality dimensions outlined in Table 4 below.

Table 4: Six core data quality dimensions, adapted from Askham et al [62]

Core data quality dimension	Definition
Completeness	The data set is 100 % complete compared to the scope it should cover
Uniqueness	Data within the data set are stored only once, no data is recorded twice
Timeliness	Data within the data set represent the real world from the required point in time
Validity	Data within the data set are valid in terms of conformity to the syntax (format, time, range)
Accuracy	Data within the data set accurately and precisely describe the real world
Consistency	Data within the data set have no differences when being compared to the definition

These six core data quality dimensions have to be selected, refined and adapted to the business process and purpose they are relevant for. The selection and adaption should be based on the "business context, requirements, level of risk, etc." according to Askham et al [62].

Another broad definition of data quality is given by Oberkampf et al [63] and Reitmeier & Paetzold [64] in extension of the Work of Wand & Wang [61] who structure data quality criteria in four different categories, as shown in Table 5 below.

Table 5: Data quality categories, accord. to Oberkampf et al. [63], Reitmeier & Paetzold [64]

Data quality category	Data quality attribute
Intrinsic Information Quality	Believability
	Accuracy
	Objectivity
	Reputation
Contextual Information Quality	Value-added
	Relevancy
	Timeliness
	Completeness
	Amount of data
Representational Information Quality	Interpretability
	Ease of understanding
	Consistent representation
	Concise representation
Accessibility Information Quality	Accessibility
	Access security

Wand & Wang have clearly derived their data quality dimensions from the types of deficiencies that can occur when representing real world behaviour within data sets. Their findings are then generalized to form general data quality dimensions that can be transformed and applied to specific environments and data types. In contrast to them, Askham et al have only postulated their six core data quality dimensions with no regard to their background or impact on the data set. With Oberkampf et al. and Reitmeier & Paetzold, a holistic overview on different aspects of data quality and a clear classification into categories is given. Yet, their work is more directed to the application in the context of simulation data quality in which all aspects of data quality play an important role.

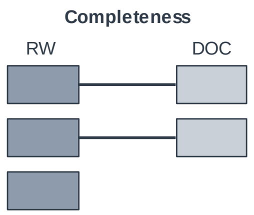
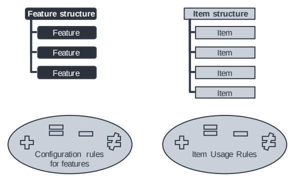
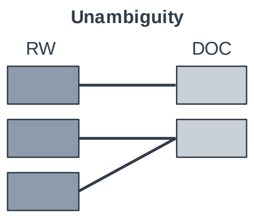
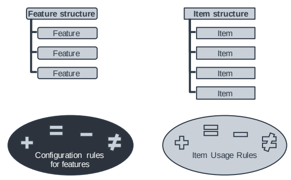
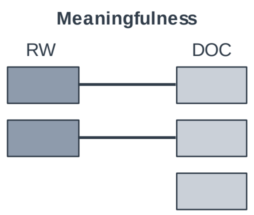
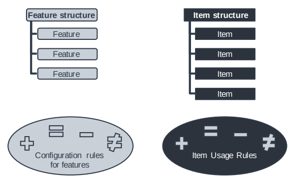
For this research, the focus is on the validity aspect of data in terms of an accurate and correct representation of real-world data. Therefore, the comprehensive approach formulated by Wand

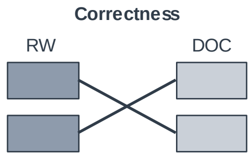
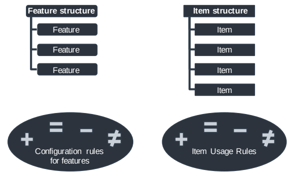
& Wang with the four generic data quality dimensions will be refined and adapted to define validity in terms of multi-variant product portfolios in the following section 0.

2.2.3 Specific requirements for a valid multi-variant product portfolio

As outlined before, generic data quality dimensions have to be adapted for the usage with multi-variant product portfolios and their representation within Product Data Management systems. In Table 6 below, the four generic data quality dimensions *Completeness*, *Unambiguity*, *Meaningfulness* and *Correctness* are related to a multi-variant product portfolio representation as outlined in chapter 2.1.

Table 6: Adaption of the specific data quality requirements for product portfolios

Data quality dimension	Generalized definition	Adapted definition for multi-variant product portfolios	Related elements in the product architecture framework
	No loss of information about the real world in the data set occurs	All existing features of the products have to be present in the data set, i.e. need to be selectable in a configuration	 Focus on features
	No data within the data set can be interpreted in more than one way	No configuration or item usage rule must contradict any other rule	 Focus on configuration rules for features
	No data within the data set can be interpreted in more than one way	For every complete configuration of properties, a unique Bill-of-Materials exists	 Focus on items and item usage rules

	No data within the data set are based on an incorrect representation from the real world	Any possible configuration within the portfolio has to be buildable in the end	 Focus on all objects in the product portfolio

The first data quality dimension *Completeness* is fulfilled in terms of multi-variant product portfolios when all elements of the real world, i.e. all different features that customers can order, are also present within the product portfolio. This can be validated by checking that every feature within the portfolio can also be selected within a configuration. As described in Table 6 above, the relevant objects in the product portfolio are here the *features*.

The second data quality dimension *Unambiguity* is fulfilled in terms of multi-variant product portfolios when no configuration rule contradicts any other configuration rule that is documented. Here, the relevant objects in the portfolio are the *configuration rules for features*.

The third data quality dimension *Meaningfulness* is fulfilled in terms of multi-variant product portfolios when a unique mapping of the configuration elements, i.e. the features, onto the components in the Bill-of-Materials, i.e. the items, is possible. Therefore, the relevant portfolio objects are the *items* as well as the *item usage rules* that influence the selection of items.

The fourth data quality dimension Correctness is fulfilled in terms of multi-variant product portfolios when any configuration based on features including the configuration rules for features is correct in the real world, i.e. buildable in the actual product manufacturing. Therefore, all elements of the product portfolio framework, *features*, *configuration rules for features*, *items* and *item usage rules* have to work together properly.

Hence, validity of an entire multi-variant product portfolio is reached when all these four adapted quality dimensions are met, which means if the portfolio definition is complete, unambiguous, meaningful and correct.

2.3 Existing approaches for the validation in multi-variant product portfolios

The topic of validation in multi-variant product portfolios is not a very new one, as exhaustive research for example on the validation of rule-based Bill-of-Materials was carried out by Sinz [65] already in 2003. Still various challenges exist in the real-world application of methodologies and tools to support the validation process, for instance, “no algorithms for supporting the automated analysis of IURs [item usage rules] have been presented" according to Voronov [66]. Therefore, the following chapter outlines existing approaches to the validation of multi-variant product portfolios and explains their shortcomings and challenges.

Especially concerning automotive product configuration data, Sinz [65] has first described validation approaches by checking both *static* and *dynamic validation criteria*. Additional to these two categories, conditions exist that are independent from the actual product. These are logical structural conditions that are relevant for the portfolio definition itself, e.g. all parts have to occur in at least one product possible to construct or within every object category, exactly one object has to be selected for a valid configuration [65]. These general constraints have more the significance of premises or axioms.

Static validation criteria describe criteria that refer to any state of a product portfolio in time, which means they are independent from the time perspective. Contrary to these, dynamic validation criteria include the evolution of a product portfolio over time, e.g. regarding product changes in its life cycle.

For this research, especially the static consistency criteria are of interest. With respect to these, Sinz [65] identified four different criteria, as outlined in Table 7 below:

Table 7: Static validation criteria according to Sinz [65]

Static validation criteria	Definition
No unselectable codes	All features within the feature structure have to be selectable in at least one product configuration
Consistency of order execution	The resulting Bill-of-Materials must not be influenced by the sequence of which features are selected, nor can the content of the BoM be changed when executing the item usage rules
No redundant parts	Within the Bill-of-Materials no items must be present that cannot be used in any possible configuration of features
Ambiguities in the Bill-of-Materials	Within the Bill-of-Materials, no items (i.e. components) can be combined that are not combinable in the (physical) real world

Especially within the commercial vehicle industry, product life cycles can easily last for a longer period of time, even for over 15 years. Therefore, the behaviour of a multi-variant product portfolio over time is of special interest. To integrate the time perspective, Sinz has also defined dynamic validation criteria [65]:

Table 8: Dynamic validation criteria, according to Sinz [65]

Dynamic validation criteria	Definition
Exchange of items (components)	Allow for the one-on-one replacement of certain items with ensuring the distinguishability of items
Product introduction and discontinuation	When certain features are introduced or discontinued, the relevant items of the BoM also need to be present or discontinued
Production relocation	When the production regarding certain items is relocated, the items might change and also have effects on surrounding items in the product portfolio

Based on these static and dynamic criteria, a first validation system was developed and implemented in the industrial use with Mercedes-Benz Cars (former DaimlerChryslerAG). In Sinz' work, different aspects regarding validity are covered, mostly from a mathematical point-of-view. Yet some challenges remain: Although the validation criteria cover a lot of aspects, a holistic framework defining and ensuring all aspects of validity in multi-variant product portfolios is missing. Also, in terms of the actual application, not many details are given on the algorithmic tools, as well as the actual process that product engineers have to go through to achieve validity. Nevertheless, Sinz' work is one of the first contributions to a practical application including SAT-solving algorithms [65].

Walter et al. (2017) have built upon Sinz' work and focus their efforts towards the correct mapping of a configuration in the features structure onto the items structure, which results in the Bill-of-Materials. Regarding the derivation of a valid Bill-of-Materials, they formulate three main requirements to test the validity [67], as outlined in Table 9 below:

Table 9: BoM validation criteria, according to Walter et al (2017) [67]

BoM validation criteria	Definition
Test on redundant parts	Identification of any items in the items structure that cannot be integrated in any configuration of features
Test on overlap error double hit)	Identification of any items in the items structure that cannot be uniquely differentiated within the Bill-of-Materials
Incomplete position (no hit)	Identification of any possible configuration of features in which no item can be selected for a certain section within the Bill-of-Materials

As outlined above, Walter et al. (2017) closely cover the valid Bill-of-Materials perspective, yet do not take a holistic approach covering all aspects of validity, also regarding the features structure and the configuration rules for features.

Earlier on, Walter et al (2013) [68] have introduced MaxSAT-algorithms especially to give recommendations for restoring invalid configurations in a collaboration with the German automotive OEM BMW. As a side-topic they also focus on dealing with configuration errors. They outline three different validation tasks similar to the ones described above, as shown in Table 10 below:

Table 10: Configuration error types according to Walter et al (2013) [68]

Configuration error types	Definition
Validation of partial configuration	Test whether the selection of features is not violating any configuration rules for features
Forced component	Identification of any items in the items structure that have to be used in any configuration of features
Redundant component	Identification of any items in the items structure that cannot be integrated in any configuration of features

As stated above, the focus of Walter et al (2013) is mainly on the error-handling within a configuration whereby they see four possible applications:

- *Maximization of chosen components*: Identification of the subset of valid feature configurations within an invalid feature configuration
- *Maximization of priorities*: Identification of a subset of valid feature configurations within an invalid feature configuration taking into account the priorities assigned to the items
- *Reconfiguration*: Identification of a similar, valid feature configuration taking into account the assigned priorities
- *Minimization of costs*: Identification of an alternative feature configuration with minimum cost, regarding a self-defined cost function

Within Walter et al (2013)’s contribution, validation tasks are only covered as a side topic and are therefore not further examined here. Yet their application of MaxSAT-algorithms provides an interesting application as within the configuration process the restoring of valid configurations is one of the key activities.

Parallel research on the validation of product architectures has been carried out jointly by Tidstam et al [69] and Voronov et al [66], [70].

In their work, they define validity of configurations of features as valid when for each family of features, exactly one variant is chosen in a final configuration [70]. Yet no detailed analysis of the different views of validity nor a holistic overall picture covering all elements of a portfolio (features and items, configuration rules and item usage rules) are given there.

The product development process has been described from a validation view by Tidstam & Malmqvist [69] as shown in Figure 15 below:

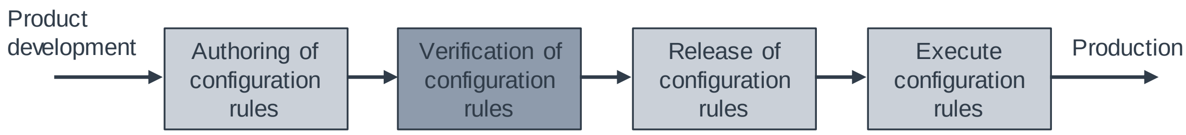


Figure 15: Validation process for configuration rules as shown by Tidstam & Malmqvist [69]

Tidstam & Malmqvist have given a high-level overview on how the validation of configuration rules is embedded in the product development process. Yet they only cover the validation of configuration rules and give no clear indication as to how the actual validation step (highlighted in Figure 15 above) should be carried out.

Voronov [70] outlines two main challenges when discussing the validity of configuration constraints:

- *Verification of new rules versus reference configurations*: When new configuration rules for features are developed by engineers, a check should be performed to see whether certain reference configurations are still valid, i.e. not violating the newly formulated configuration rules. This could also be addressed as a test case functionality
- *Verifying item usage rules for mutually-exclusive items*: item usage rules should be written in a way that always at least one item is selected within a configuration. This groups the Bill-of-Material validation criteria as outlined earlier on

Based on these requirements, Voronov [70] outlines different algorithmic approaches and methodologies to examine and ensure the validity of product configurations The most important algorithms are explained briefly in Table 11 below.

Table 11: Selected validation algorithms as described by Voronov [70]

Algorithm / methodology	Explanation
Constraint satisfaction	Constraint satisfaction problems (CSPs) are constraint problems, in which the typical analysis is to determine one or all of the possible configurations fulfilling the constraints. For this task, constraint satisfaction solvers or Boolean satisfiability solvers are used
Synthesis based on Supervisory Control Theory	Supervisory Control Theory is an approach based on automatically generated supervisors that try to control and forbid any undesired behaviour of a plant. It can be adapted to the needs of validation as well
Knowledge compilation methods	To allow for faster results compared to constraint satisfaction, knowledge can be precomputed offline using different methodologies, e.g. Binary Decision Diagrams, Decomposable Negation Normal Form, etc…

Although covering different approaches to and methodologies for verification and validation, no detailed procedure for the actual validation process is suggested, both with Tidstam & Malmqvist [69] and Voronov [70].

The list of different algorithms and information modelling techniques, that was started in Table 11 above can be easily expanded as a lot of research exists here, especially originating from the Information Science research community. As explained before in chapter 2.5.1, the different types of actual validation algorithms and information science technologies are not in the focus of this research, so that there will be no further investigation of algorithms here.

2.4 Directions from the state of the art

In this section, the key insights of the review of the current state of literature are derived. The current gaps and shortcoming are briefly highlighted, and the solution space for this research is explained.

In chapter 2.1, different approaches to model large, *multi-variant product portfolios* are explained, including the SAP iPPE model and a similar, generalized framework, as depicted in Figure 16 below. Furthermore, the broad usage of these types of portfolio models in the automotive passenger car industry, e.g. with BMW, Volvo or Mercedes, as well as within the commercial vehicle industry, e.g. with Scania or John Deere add relevance to this research.

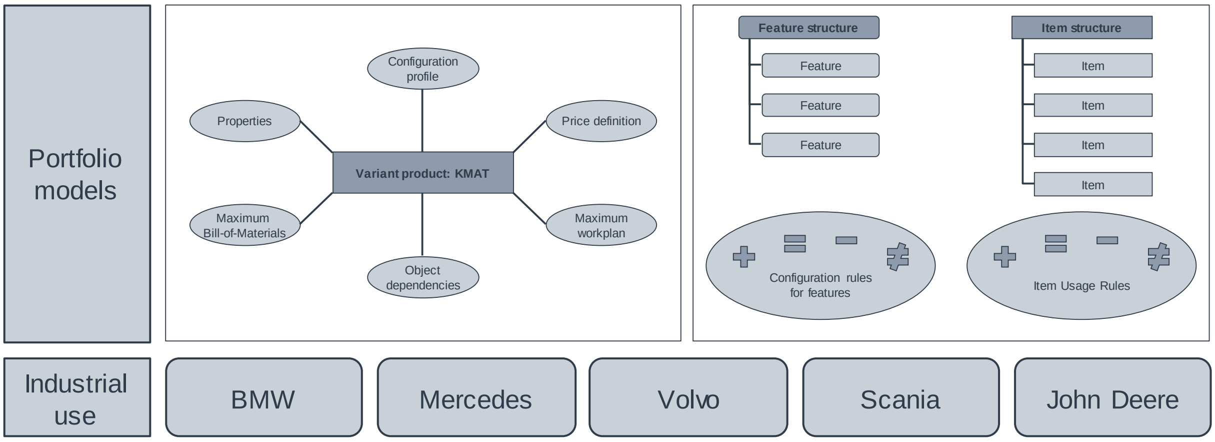


Figure 16: Overview of portfolio models and their usage within the industrial application

Therefore, this research will rely on a product portfolio definition that can be directly related to the portfolio models found with most of the automotive OEMs, as shown in Figure 16 above. This ensures that the results of this research can also be transferred and applied to other product developing companies with comparable complex, multi-variant product portfolios.

In chapter 2.2, an overview of verification and validation aspects is given, as well as a clear definition of validity is derived. Based on a broad analysis of definitions regarding validation and verification, the process and desired outcome described in this research are classified as a *validation process*. Next, different data quality classifications are explained in detail. Based on the literature research, the four criteria *Completeness*, *Unambiguity*, *Meaningfulness* and *Correctness*, are chosen. Finally, these four criteria are adapted to clearly define the relevant aspects regarding the validity of multi-variant product portfolios.

In chapter 2.3, existing approaches to the validation of multi-variant product portfolios are examined. Although a considerable amount of research on the validation of constraint logics has been performed so far, the existing approaches and solutions still lack some important aspects for the application in the industrial practice, as shown in Figure 17 below:

Figure 17: The four key weaknesses of existing validation approaches

Concise definition of validity for multi-variant product portfolios

Many authors have dealt with different aspects of validity, e.g. regarding the fulfilment of configuration rules, correct Bill-of-Materials or product changes. Within these approaches, no clear definition of the validity of an entire product portfolio was found, as only isolated aspects are covered. To close this gap, this research provides transparent requirements regarding the validity of entire product portfolios, based on well-known data quality criteria.

Holistic focus on all elements of a multi-variant product portfolio

As stated above, different aspects regarding portfolio validity have been assessed by the authors examined. Yet their focus is mostly on certain items of a portfolio, e.g. on constraints in the form of configuration rules for features, on a Bill-of-Material validation perspective or on re-configuration only. Therefore, this research proposes a clear validation framework covering all elements relevant within a multi-variant product portfolio.

Integrating the product portfolio management perspective

Although the aspect of changes over time has been covered by some authors, no recommendation for the integration of the validation process into the portfolio management activities within a company is given. Therefore, this research gives an outlook for the integration of the validation process into the activities around the portfolio management, especially around the product development process

Detailed and applicable validation process for multi-variant product portfolios

Numerous authors have given recommendations for certain validation process steps and activities. Also, a wide range of algorithms and automated checks have been developed by information scientists over time to solve the relevant tasks being part of a validation process. Yet no detailed step-by-step validation process that integrates the requirements regarding entire portfolio validity, the existing tools and algorithms and regarding the link to the portfolio management process has been described. This research closes the gap between the different approaches and methodologies, provided by engineering and information scientists. As this research is closely linked to a comprehensive PLM-project with a large commercial vehicle manufacturer, it will also bridge the gap between the scientific formulation of procedures and the actual application of these procedures in the industrial application.

Figure 18 below integrates the main implications of the current related state of the art and outlines the scientific contribution this research aims for.

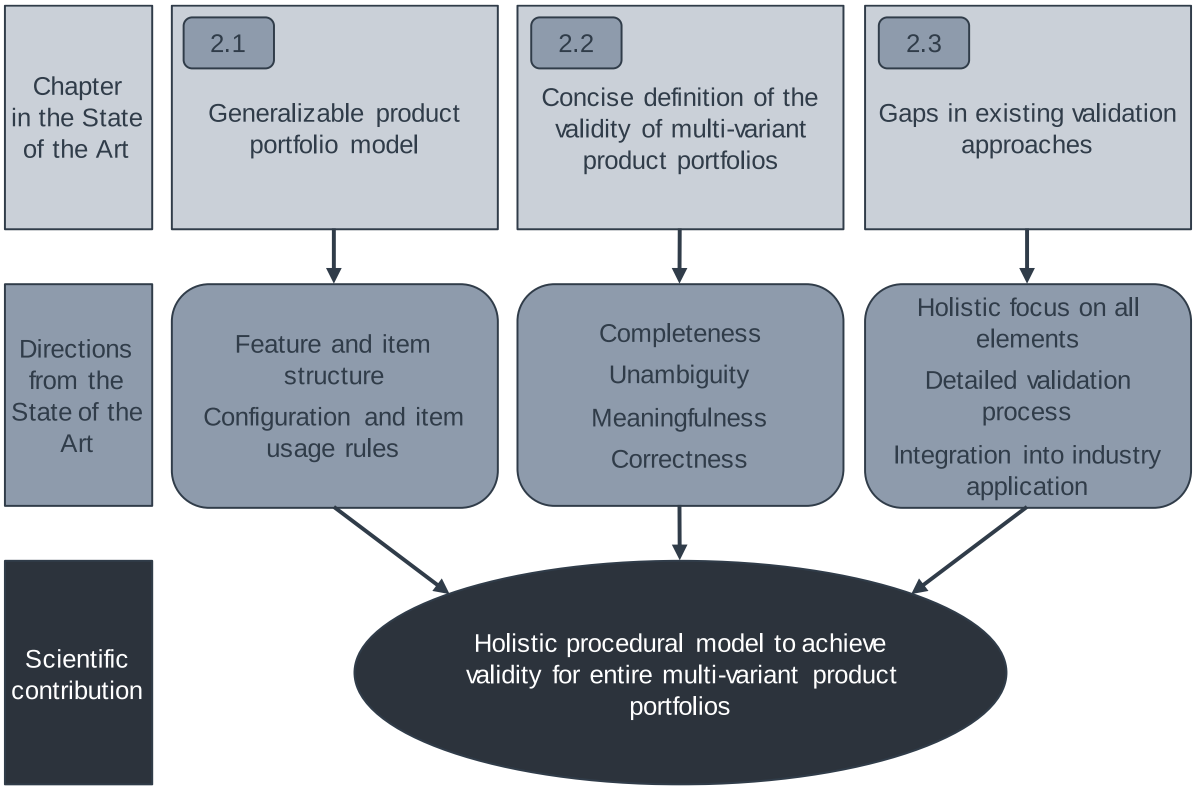


Figure 18: Scientific contribution of this research, based on the related state of the art

As outlined in chapter 1.4 the aim of this research is to develop a procedural model that helps to address all requirements regarding the validity of multi-variant product portfolios including all portfolio elements by giving a clear recommendation for the necessary procedures to obtain validity including the procedural model's context in the portfolio management. This aim is supported by the findings based on the related state of the art, as shown in Figure 18 above.

2.5 Research questions and underlying hypotheses

Based on the findings of the literature review in combination with the problem description in chapter 1.3, four main hypotheses can be identified that will be covered in this research:

(1) Challenges regarding the validity of multi-variant product portfolios exist (e.g. non-selectable features or contradicting rules) due to numerous departments working on portfolio rules

(2) As a result, portfolio errors occur that cannot be identified manually in multi-variant product portfolios due to the large number of variants, portfolio rules and resulting configurations

(3) Algorithmic validation tools already exist and can be used to identify portfolio errors

(4) A generic process and a sequence of applying algorithms in validation steps allow for establishing and maintaining an overall consistent product portfolio description

The first hypothesis states that challenges result from multi-variant product portfolios in large organizations and that different aspects need to be considered to ensure the validity of a multi-variant product portfolio. As shown before for data sets in general, Wand & Wang [61] or Askham et al. [62] outline requirements regarding validity, e.g. Correctness, Meaningfulness or Timeliness. These general data requirements need to be adapted to the application with multi-variant product portfolios.

The second hypothesis assumes that portfolio errors can occur due to the violation of data validity requirements. In large and complex, multi-variant product portfolios, it is impossible to manually detect any possible error within a variant space of over 10^{300} possibilities [71].

The third hypothesis states that algorithmic validation tools can be used in general and that certain approaches already exist to automatically detect errors in product portfolios. Here, different approaches have been described and tested by information scientists and mathematicians, e.g. with Sinz [65] or others [72], [73], as shown in chapter 2.3.

The fourth hypothesis assumes that existing validation approaches can be combined and adapted to form a procedure covering all necessary steps to validate entire product portfolios [74].

To answer these four hypotheses, a set of six comprehensive research questions is dealt with in the context of this research. The questions are outlined in the following:

- What challenges exist regarding the validity and consistency of multi-variant product portfolio definitions?
- What types of validation errors can exist in complex portfolio definitions?

- In what way has the underlying documentation logic to be defined (data model and its implementation in IT-systems) to allow for the application of validation tools?
- Which models and tools are necessary to structure and implement the validation process?
- What steps are necessary to achieve the requirements set for the validity of product portfolios?
- What is the optimal sequence of validation steps to achieve validity of an entire portfolio?

The four main hypotheses will be examined and discussed with the help of the six research questions above as shown in Figure 19 below:

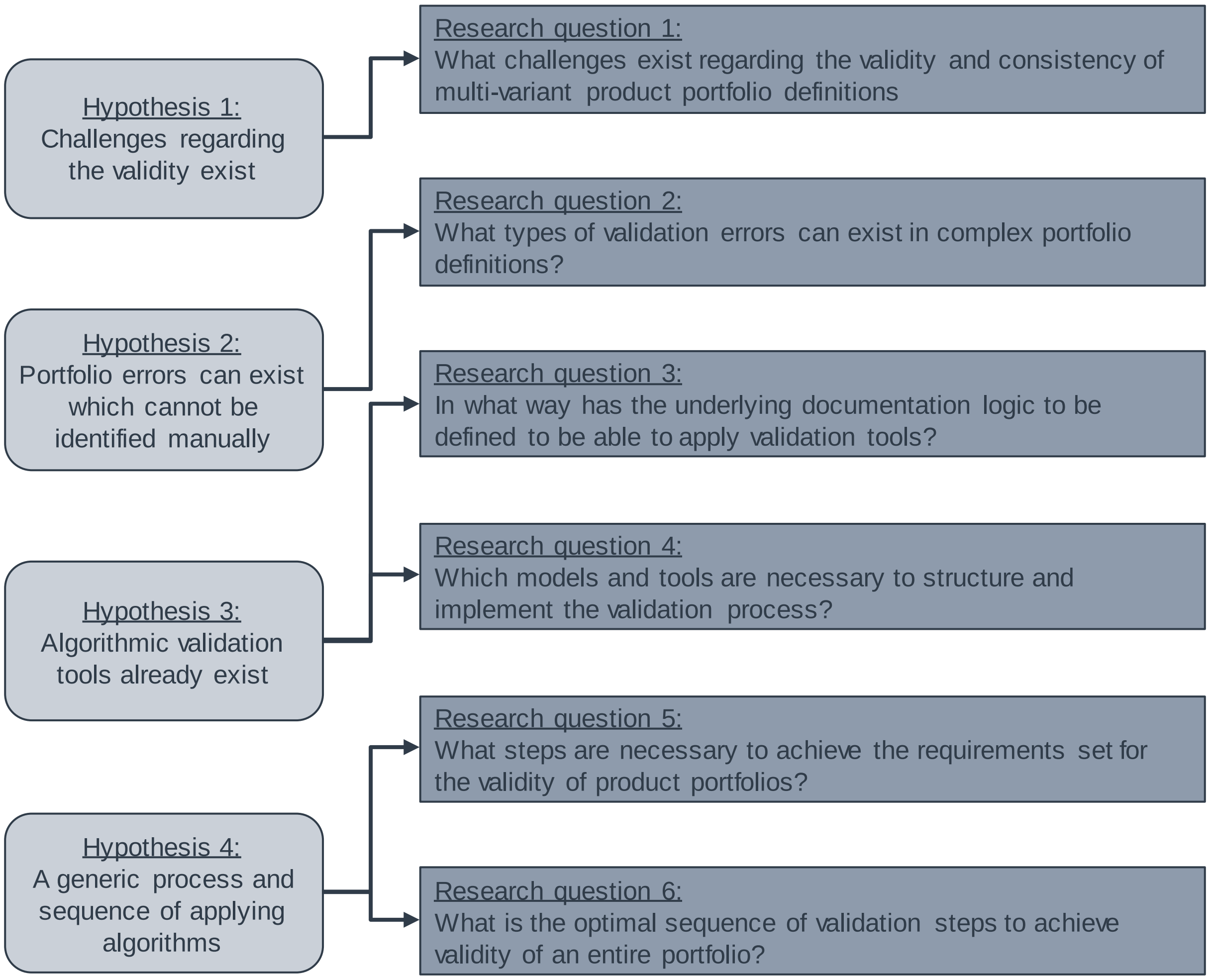


Figure 19: The four main hypotheses and relevance for the six research questions

The aim of this research is to define requirements regarding portfolio validity and to examine the necessary documentation logic for multi-variant product portfolios. Furthermore, a generic model involving the necessary steps, processes and tools is developed to give a recommendation on how to build and maintain a valid multi-variant product portfolio. Additionally, different portfolio errors are classified to give an overview on possible error types.

A short example based on alienated real data is useful to outline this challenge. Within an exemplary truck portfolio, two different fuel tank sizes, a small fuel tank *T_small* and a large fuel tank *T_large,* can be chosen. In addition, two different truck layouts are possible, a compact truck layout *Layout_CD* and a spacious truck layout *Layout_SD*, as outlined in Table 12 below:

Table 12: Two exemplary categories within a truck portfolio

Feature category	Feature	Description
Fuel Tank	T_small	Small fuel tank
	T_large	Large fuel tank
TruckLayout	Layout_CD	Compact truck design
	Layout_SD	Spacious truck design

For the compact layout Layout_CD, a Boolean rule exists describing its use in a configuration: For the large fuel tank, a compact layout is only possible together with certain wheel bases, as shown in Table 13 below.

Table 13: An exemplary Boolean combinatorics rule

Condition	Consequence	Start	End
$(R3600 \wedge T_{large}) \vee$ $(R5300 \wedge T_{large} \wedge SW_{with})$	$\Rightarrow Layout_{CD}$	$PP201801$	

The third component in this example is the technical solutions, i.e. the different variants of the component fuel tank and their selection rules, as outlined in Table 14 below:

Table 14: An exemplary component: 81#0990 – Fuel tank

Item ID	Item name	Item selection rule
81#0990	Fuel tank	
81#0990-001	Fuel tank small	$(T_{small} \neg\ Layout_{CD})$
81#0990-001-SE01	Fuel tank small	
81#0990-001-SE01-Trafo01	Fuel tank small	
81#0990-002	Fuel tank small with integrated step tread	$(T_{small}\ \wedge\ Layout_{CD})$
81#0990-002-SE01	Fuel tank small with integrated step tread	
81#0990-002-SE01-Trafo01	Fuel tank small with integrated step tread	

The second product variant, *Fuel tank small with integrated step tread*, is chosen when a small tank *T_small* has been configured together with a compact truck layout *Layout_CD.*

Yet, the Boolean rule outlined in Table 13 only allows large tanks for the *Layout_CD*, so a small tank can never be selected together with the compact layout. Therefore, the component *Fuel tank small with integrated step tread* cannot be used in any configuration.

This simple example already shows that manual error detection is difficult, especially for large multi-variant product portfolios. Therefore, automated validation tools and the right validation process are crucial to establish valid and consistent product portfolio definitions.

2.5.1 Aspects this research does not deal with

In general, many aspects exist regarding product portfolios, modularization strategies and variant management, as well as different views and perspectives on validation and verification in the engineering process from different points-of-view. Based on the areas of literature covered before, a short clarification of possible misunderstandings of which aspects this research is covering not has to be made to ensure that the scope of this research is understood correctly.

This research does not give any recommendation on the advantages or disadvantages of different portfolio models or modularization strategies. The developed approach will be generic, i.e. working with all types of object-relation-oriented portfolio definitions. Therefore, the modularization strategies leading to different product decompositions [45] are not of importance here.

Furthermore, this research is focussing on technically complex hardware products only, although certain techniques and models can be applied to software product portfolios as well. This is due to both the background of the research coming from a joint collaboration project with a Truck manufacturer and the engineering background of this research.

This research is not examining different validation algorithms in detail or providing information technology solutions to build new validation solving tools. Neither are existing tools improved nor optimized regarding performance as part of this research. As many different solving technologies, as shown before in chapter 2.3, are evaluated by information scientists globally, e.g. in the annual, global SAT competitions [75], the algorithmic improvement of these tools is not covered here.

Neither are strategies on how to deal with and fix detected errors or inconsistencies part of this research as the best process can differ largely for different users, e.g. regarding the organizational set-up, involved business units or the particular business process.

3 Procedural model for the validity of complex, multi-variant product portfolios

Based on the findings in literature shown in chapter 2.4 and the research questions outlined in chapter 2.5, the detailed requirements for the proposed solution are derived in section 3.1 first. The solution proposed in this research, the *holistic procedural model for the validity of complex, multi-variant product portfolios*, is then explained in section 3.2 with regard to the up-front defined requirements.

3.1 Requirements for the solution

The assessment of the current, related state of the art shows four main shortcomings that are not properly addressed in the present approaches towards the validation of multi-variant product portfolios. Based on these shortcomings, the requirements for the solution proposed in this research are developed.

Requirement R.1 - Concise definition of validity for multi-variant product portfolios

The proposed solution must be based on a clear and precise definition of validity in terms of multi-variant product portfolios. The definition can be based on the general data quality criteria stated by Wand & Wang [61] in section 2.2.2. These general validity criteria are adapted to the context of the problem description, as explained in section 2.2.3. The four sub-requirements for the definition of validity can be derived, as summarized in Table 15 below.

Table 15: Requirement R.1 – Concise definition of validity

Requirement	Specific data quality definition	Detailed requirement
Requirement R.1.1	*Completeness*: All existing features of the products have to be present in the data set, i.e. need to be selectable in a configuration	Involve a process step to identify all features that are not selectable in any case
Requirement R.1.2	*Unambiguity*: No configuration rule must contradict any other rule	Involve a process step to identify any configuration rules which lead to effects not represented within the feature structure
Requirement R.1.3	*Meaningfulness*: For every complete configuration of properties, a unique Bill-of-Materials exists	Involve a process step to ensure the error-freeness of any item usage rules
Requirement R.1.4	*Correctness*: Any possible configuration within the portfolio has to be buildable in the end	Involve a process step to ensure the correct positioning of any items

First, the proposed solution must be capable of ensuring the *completeness* of the entire product portfolio definition. The completeness of a product portfolio is reached – in that sense – when it represents the "*complete*" product variance theoretically available with the manufacturer. All the different product variants are documented as features within a feature structure, as described with Tidstam & Malmqvist [34]. In order to be able to offer the complete product portfolio to the customers from a configuration perspective, every feature documented within the features structure needs to be selectable in at least one configuration within the sales configurator. Thus, the holistic procedural model must involve process steps to identify all features that are not selectable in any configuration.

Second, the proposed solution must be capable of ensuring the *unambiguity* of the entire product portfolio definition. Unambiguity is related to the possible combinations of both features and items and therefore concerns the different rule types. Unambiguity concerning the configuration rules is reached when no configuration rule contradicts any other rule. A highly simplified example is used to illustrate such a conflict based on two configuration rules:

$$engine: 500\ PS\ \Rightarrow cab: large$$

$$cab: large \Rightarrow\ \neg\ engine: 500\ PS$$

In this case, a 500 PS engine can never be selected, because it results in a large cab, which again cannot be combined with a 500 PS engine. Thus, the requirement for unambiguity regarding configuration rules can be satisfied by executing the same validation process as for the completeness check above, which means proving whether all features are selectable in at least one configuration. Item usage rules are rules that relate any item to a selection (or combination) of features. Item usage rules are unambiguous when each item has exactly only one item usage rule that is valid for one dedicated time range. Thus, the holistic procedural model must consist of a process step to check the quality of the item usage rules.

Third, the proposed solution must be able to ensure the *meaningfulness* of the entire product portfolio definition. Meaningfulness is achieved when all the different product variants (in this case all possible combinations of features) within a portfolio have a meaning. From a configuration perspective, a meaningful configuration is reached when it can also exist like this in the physical world. This physical representation is the individual Bill-of-Materials for the product consisting of the actual parts that are later assembled in the manufacturing process. Therefore, the holistic procedural model must involve process steps to ensure that for any configuration of features, exactly one unique Bill-of-Materials can be derived. Furthermore, any configuration must not be possible for which no or only incomplete Bills-of-Materials can occur. Here again, the effects of all the item usage rules combined with the absence of errors need to be addressed.

Fourth, the proposed solution must be capable of ensuring the *correctness* of the entire product portfolio definition. The product portfolio is not only defined correctly when any configuration results in a unique Bill-of-Materials. This can be made clear with a short example: Although all the parts of a product might be identified correctly, they still don't fit in the actual manufacturing process, because there could be no building space or no clear positioning for certain parts. Therefore, the actual buildability for any configurations also needs to be assured. Thus, the holistic procedural model must involve process steps to test the correct positioning of all items for all possible configurations of features.

Requirement R.2 - Holistic focus on all elements of a multi-variant product portfolio

The existing approaches dealing with the validity of multi-variant product portfolios mostly cover only some aspects, as explained in chapter 2.4. Either the focus is on generating well-defined Bill-of-Materials taking only the item usage rules into consideration, or the focus is more on the configuration perspective covering features and the configuration rules for features. Yet, for the successful implementation in an industrial application, all elements of the product portfolio, both the customer-oriented feature structure as well as the engineering-oriented item structure need to be considered. To stay in the example with the engine from above, the entire feature category *engine* with all of its features (*engine: 270 PS, 350 PS, 450 PS, 500 PS*) must be considered. Furthermore, the respective item structure, e.g. the *cylinder head* with its items (*cylinder head: component variant for 4 cylinders*, *component variant for 6 cylinders*, *component variant for 8 cylinders*) must be in focus. Also, the interaction and the interdependencies between all different types of portfolio rules (configuration rules for features, item usage rules, positioning rules) have to be taken into account. Thus, the holistic procedural model must consist of all elements of the product portfolio and must integrate them into one consistent process that ensures validity in any of the previously mentioned dimensions.

Requirement R.3 - Integrating the product portfolio management perspective

The validation approaches found so far have been developed mostly by engineers or information scientists. They often go into great detail regarding the algorithmic concepts and methodologies, yet lack recommendations for the integration into the actual business process, e.g. into portfolio management activities or the product development process. For the industrial application, it is considered particularly important to integrate the validation process into the high-level business processes. Thus, the holistic procedural model must give a recommendation for the integration of the proposed procedural model into the generic business processes of a larger product-development company.

Requirement R.4 - Detailed and applicable validation process for multi-variant product portfolios

A large gap between theories and recommendations of scientific research and the application of these recommendations in practice is found in many disciplines, within the engineering community as well, as Connor [76] has outlined. This is also true for the gap between research on the validation of multi-variant product portfolios and the application for large product manufacturers. As shown in the previous chapter, a lot of singular methodologies and approaches have been found in literature. However, these singular approaches must be combined to account for all elements of a product portfolio and to ensure validity regarding all requirements. To be applicable in the industrial practice, a precise and stringent step-by-step approach is necessary to provide engineers, salesmen and portfolio managers with a "*cooking recipe*" for the organization of their validation process. Thus, the holistic procedural model must involve a precise and stringent step-by-step approach that can be directly applied within the industrial practice.

3.2 Proposed solution: a holistic procedural model to ensure validity of complex, multi-variant product portfolios

To address all the requirements for the solution outlined in section 3.1 above, a “*holistic procedural model to ensure validity of complex, multi-variant product portfolios” (short: “holistic procedural model”)* is proposed. The first version of the procedural model is described first by the author of this research in [74].

In chapter 3.1, the requirements to the solution, i.e. the “*what*” has been described in detail. In chapter 3.2, the potential solution, the “*how*” is in focus. The elements “*what*” and “*how*” are also the main elements of a classical management strategy approach. Therefore, an existing business management structure was searched for to serve as a basis framework to structure the procedural mode. This procedural model relies on the “*St. Gallen Managementmodell*”, as described for example with Schwaninger [77], Rüegg-Stürm [78] and Rüegg-Stürm & Grand [79]. This structure model is chosen as it is known for its “clarity, its optimal simplification of complex relationships and its immediate applicability” [78]. Also according to Doleski [80] it is a “practical concept” that “offers a good conceptual framework”. Therefore, the St. Gallen Managementmodell shall be used in the context of this research to structure the procedural model. The St. Gallen Managementmodell consists of three levels, as depicted in Figure 20 below:

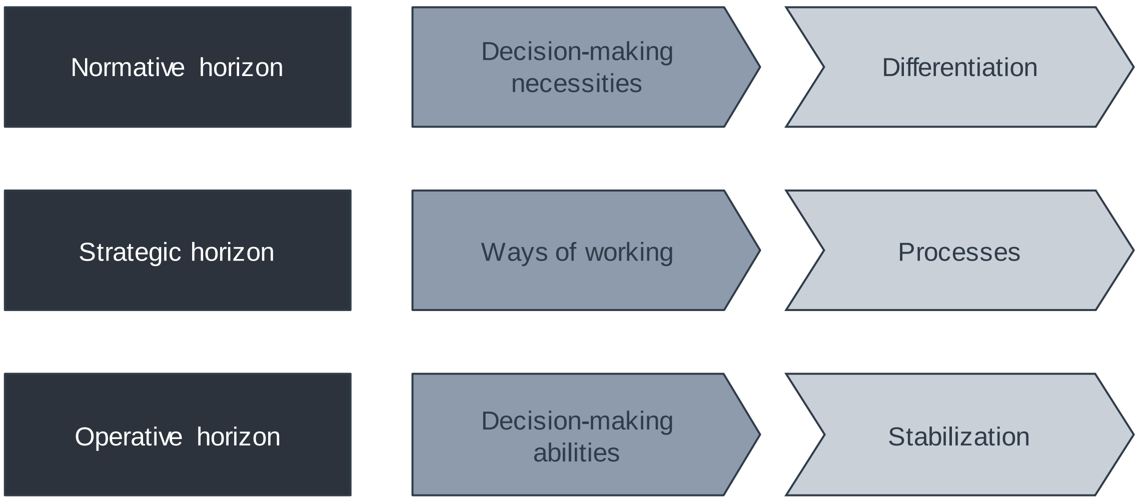


Figure 20: The three levels of the St. Gallen Managementmodell, adapted from Rüegg-Stürm & Grand [79]

The first level is called the “*normative horizon*”, as shown in the first row in Figure 20 above. From a management perspective, the normative level describes the aims and targets of an organization leading to decision-making necessities, e.g. concerning the foundations, directions, and future of an organization, according to Bleicher [81].

The second level is called the “*strategic horizon*”. It defines the strategies and procedures of an organization (i.e. the ways of working) resulting in processes necessary to achieve the aims and targets set on the normative horizon [81].

The third level is called the “*operative horizon*”. Here, the singular process-steps and tools (i.e. the objects necessary for the decision-making abilities) are examined stabilizing and supporting the processes [81].

The St. Gallen Managementmodell is modified to form the basis for the holistic procedural model. The basic structure of the procedural model consists of the three levels taken from the St. Gallen Managementmodell, as shown in Figure 21 below.

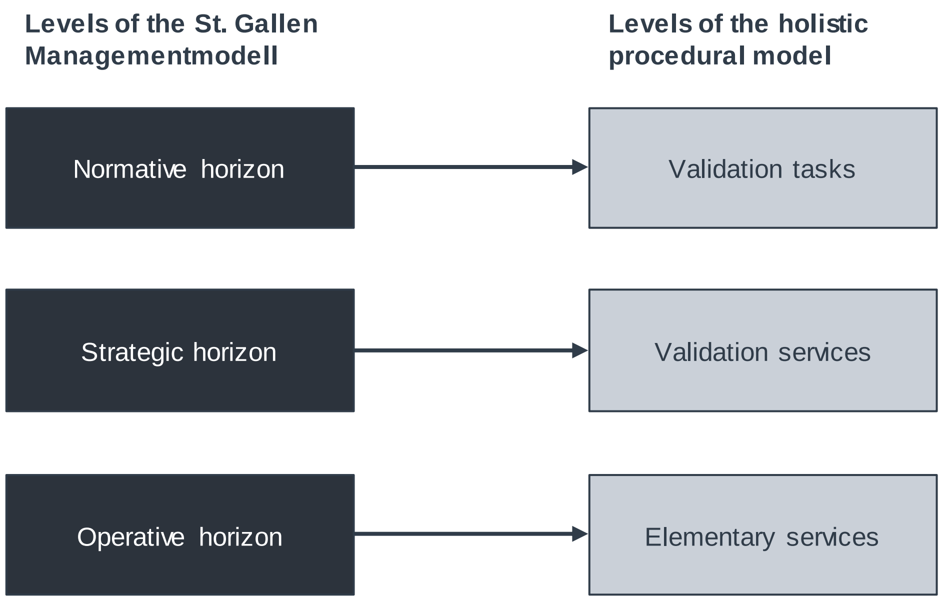


Figure 21: Three levels of the holistic procedural model, projected from the St. Gallen Managementmodell

Figure 21 shows the three levels *Validation tasks*, *Validation services* and *Elementary services* that structure the holistic procedural model. Each level originates from a projected level of the St. Gallen Managementmodell

3.2.1 Normative level: the four validation tasks

The normative level is represented by the validation tasks within the holistic procedural model. Here, the “aims and targets” perspective of the proposed validation process is covered. The validation tasks are four separate perspectives of the validation of multi-variant product portfolios and all four need to be addressed to ensure validity of the whole portfolio, as claimed by Requirement R.2 in chapter 3.1 above. The four validation tasks are illustrated in Figure 22 below.

Figure 22: The four elements of the validation tasks level in the holistic procedural model

The validation task *consistency validation*, depicted first in Figure 22 above, primarily addresses the requirement R.1.1 – Completeness. The aim of the consistency validation task is to identify all features that are part of a product portfolio within a feature structure and cannot be combined with other features to form a valid configuration. Thereby, all "*unselectable*" features (i.e. all features that can never be selected in a sales configuration) are detected. Furthermore, the consistency validation can also deliver input for the requirement R.1.2 – Unambiguity regarding the configuration rules for features, as explained in chapter 3.1 above.

The validation task *bijectivity validation*, depicted second in Figure 22 above, addresses the bijectivity of relations between categories of features including the related configuration rules for features. This is especially relevant for so-called "*feature-clusters*" and ensures together with the consistency validation that the requirement R.1.2 – Unambiguity concerning configuration rules is met.

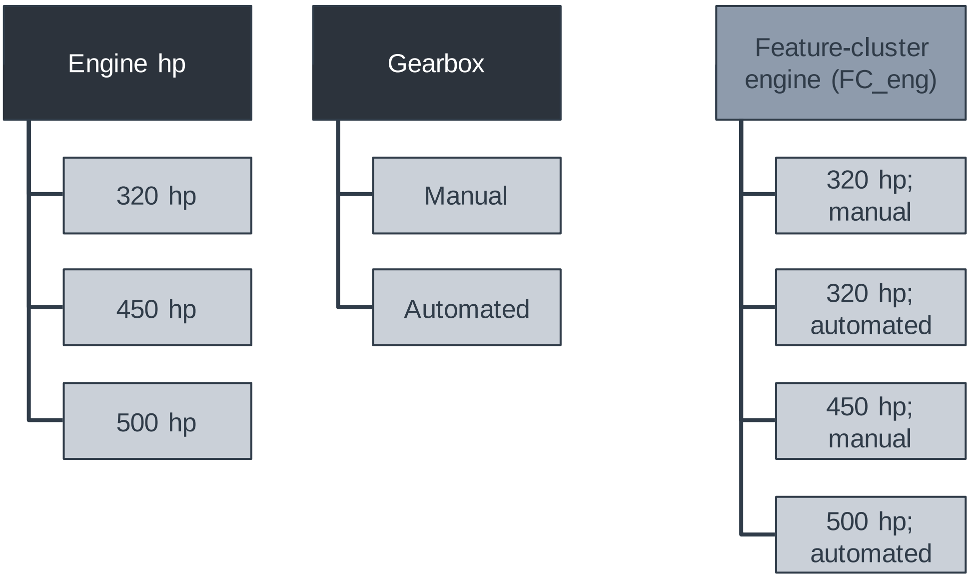


Figure 23: An exemplary feature-cluster for the features engine hp and gearbox

In Figure 23 above, on the left-hand side the two feature categories "*engine hp*" for the horsepower of an engine with the features "*320 hp*, *450 hp* and *500 hp*", as well as the feature category "*gearbox*" with the features "*manual* and *automated*" are displayed as an example of a part of a feature structure. On the right-hand side the feature-cluster engine "FC_eng" is shown with the four features "*320hp; manual*, *320 hp; automated*, *450 hp; manual* and *500 hp; automated*". This feature-cluster is built as a short-cut for the engine type, so that in a configuration process not all singular feature categories of an engine need to be determined, but instead the engine can directly be selected. Feature-clusters are often used in the industrial application for more complex parts of a portfolio where more than one configuration path is offered. Inexperienced users can use the individual feature categories, whereas skilled and experienced configuration users can determine the right sub configuration faster, in this example the correct engine type. The bijectivity of individual feature categories and a feature-cluster are now given, if both structures match one-on-one. In the example above illustrated in Figure 23, there could be six different combinations of features within the feature categories "*engine hp*" and "*gearbox*". As no other configuration rules restricting the combinability of this part of the product portfolio are present, the feature-cluster engine must have six features as well accounting for all possible combinations within "*engine hp*" and "*gearbox*". Here, either the features "*450 hp; automated*" and "*500 hp; manual*", or two configuration rules forbidding the combination of "*450 hp*" and "*automated*", as well as "*500 hp*" and "*manual*", would be missing. The bijectivity validation task aims to identify this unambiguity concerning the configuration rules for features, according to the requirement R.1.2 – Unambiguity with regard to the configuration rules.

The validation task *Bill-of-Materials (BoM) validation*, illustrated third in Figure 22 above, primarily addresses the requirement R.1.3 – Meaningfulness. The aim of the Bill-of-Materials validation is to find any errors within the item structure in combination with the item usage rules. Based on the findings in literature, as shown in chapter 2.3, three main error types within the Bill-of-Materials (i.e. the item structure) can be determined.

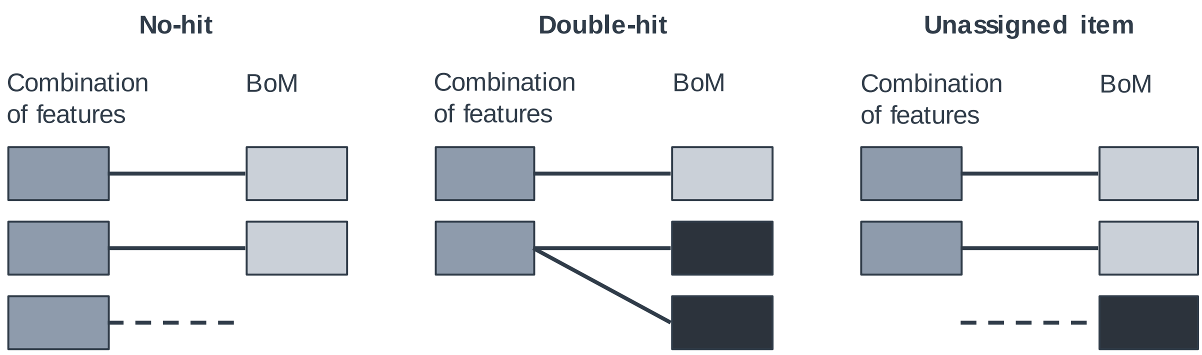


Figure 24: Three main error types within the Bill-of-Materials (errors in dark blue and with dotted lines)

The first error type is the so-called "*no-hit*" error shown on the left-hand side in Figure 24 above. Here, for a certain combination of features, no item within an item category in the Bill-of-Materials can be selected. This represents a configuration in which no parts are found within the respective Bill-of-Materials. For this error, three root causes are possible: either one item in the item structure dedicated for this usage is missing, or the item usage rule is false as it should point towards some other existing item, or the combination of features must not exist, this means that a configuration rule is missing.

The second error type is the so-called “*double-hit*” error shown in the middle of Figure 24. For one combination of features, two or more items under the same item category are selected through the item usage rules. This results in an unclear Bill-of-Materials, as now two parts of the same type would end up in the product. Here, the root cause is the false item usage rules, as the rules for two different items under the same item category do not differ enough to allow for a unique representation.

The third error type is the so-called “*unassigned item*” error depicted on the right-hand side in Figure 24 above. Within this error type, an item exists within one item category that is never assigned to any combination of features. Here again different root causes can be responsible for this error: either the item usage rule has been defined falsely or is missing, or the selection criteria of the item usage rule, which is the condition-part of the rule, could be forbidden by configuration rules.

The validation task *geometry validation*, depicted fourth in Figure 22 above, addresses the requirement R.1.4 – Correctness. This requirement is met when the entire product portfolio is buildable, as explained in chapter 3.1. For a product portfolio to be buildable, it is not only important to have a valid feature structure and an error-free Bill-of-Materials, but it is also necessary to be able to actually fit the parts together in the manufacturing process. Therefore, it is not only relevant to identify the correct parts, but also to find the right position regarding where they need to fit into the final product. Thus, the aim of the geometry validation is to ensure that for any configuration of features, a correct positioning is available for all the items selected for each specific Bill-of-Materials. The geometry validation can be considered as an extension of the Bill-of-Materials validation, as it builds upon a valid Bill-of-Materials. If for any correct configuration, exactly one unique item is found, then this item also needs a correct positioning. In the context of commercial vehicles, the fuel tank is a good example. It is not only important to identify the right fuel tank (e.g. 500 l steel tank vs. 700 l aluminium tank), but also to find the right positioning relative to the vehicle frame, as the same tank might be in different locations for different vehicles.

For the geometry validation, the same error types can occur as for the Bill-of-Materials validation. There can be a “*no-hit*” in terms of the correct positioning (no information on the position is found), a “*double-hit*” (more than one position is found for one item) or an “*unassigned position*” error.

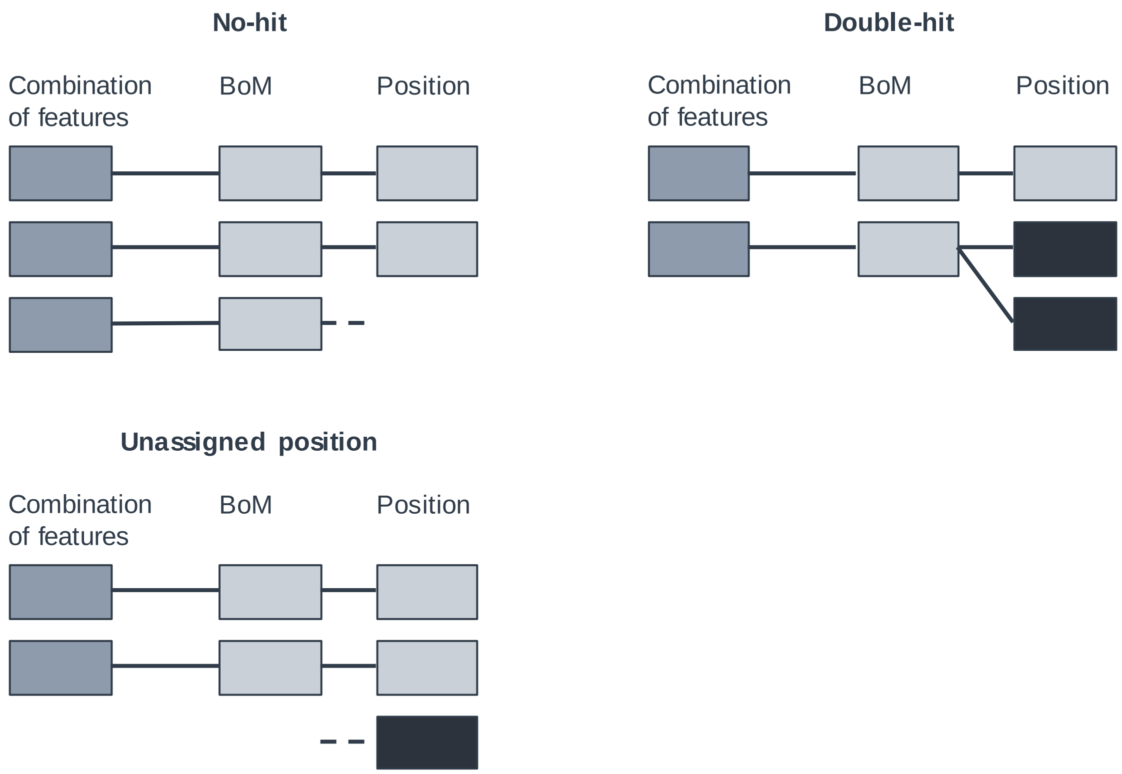


Figure 25: Three main error types within the geometry validation (errors in dark blue and with dotted lines)

Figure 25 above shows the three error types for the geometry validation. The similarity to the Bill-of-Materials validation can be seen in comparison with Figure 24 above. This also explains why the geometry validation is considered as an extension to the Bill-of-Materials validation.

The second requirement R.2 – the holistic focus, is achieved when all the four validation tasks have been performed repeatedly until no error is found anymore within any product portfolio structure: the feature structure, the item structure as well as for all the positions. Therefore, the normative level of the holistic procedural model provides support to not forget any category and helps to not deal with only some aspects of validity but take all relevant perspectives into account.

3.2.2 Strategic level: the three validation services

The strategic level consists of the validation services of the holistic procedural model. In the second level, the "strategies and procedures" of the proposed validation process are defined. The validation services are built by the actual algorithms and calculation services that are necessary to fulfil the validation tasks outlined for the normative level in section 3.2.1.

For the strategic level, the holistic validation framework does not give a clear recommendation for what the actual validation services should look like. There are numerous different approaches and algorithms used to identify the different error types. A few of them have been briefly introduced in chapter 2.3. The actual type and usage of algorithms and their integration into software solutions and tools to fulfil the tasks is an individual decision that each organization has to take. The selection of specific tools and algorithms depends on the three main aspects outlined in Table 16 below.

Table 16: Decision criteria for the use of different validation services

Decision criteria	Definition
Existing knowledge base	Knowledge regarding the different information science techniques as well as mathematical knowledge on the methodologies used can be different for each organization
Available computing power	Different IT approaches have different requirements regarding the available computation power. For fast algorithms with large product portfolio definitions, large computing power can also be necessary. Here, the possibilities can differ when comparing different organizations
Access to validation algorithms and tools	A few software solutions for validation services are offered on the commercial market already (e.g. offered by Configit). Others have been developed by companies individually and are not offered to other organizations. Therefore, access to validation tools can be different for each organization

In the following, the three validation services that have been developed in the context of this research, are described briefly to give an example of what the validation services can look like.

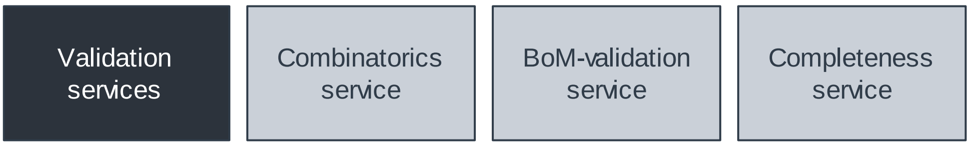


Figure 26: The three elements of the validation service level in the holistic procedural model

The first service that was built as an IT service is the *combinatorics service* as illustrated on the left-hand side in Figure 26. The functionality of the combinatorics service is shown in an input-output relation in Figure 27 below.

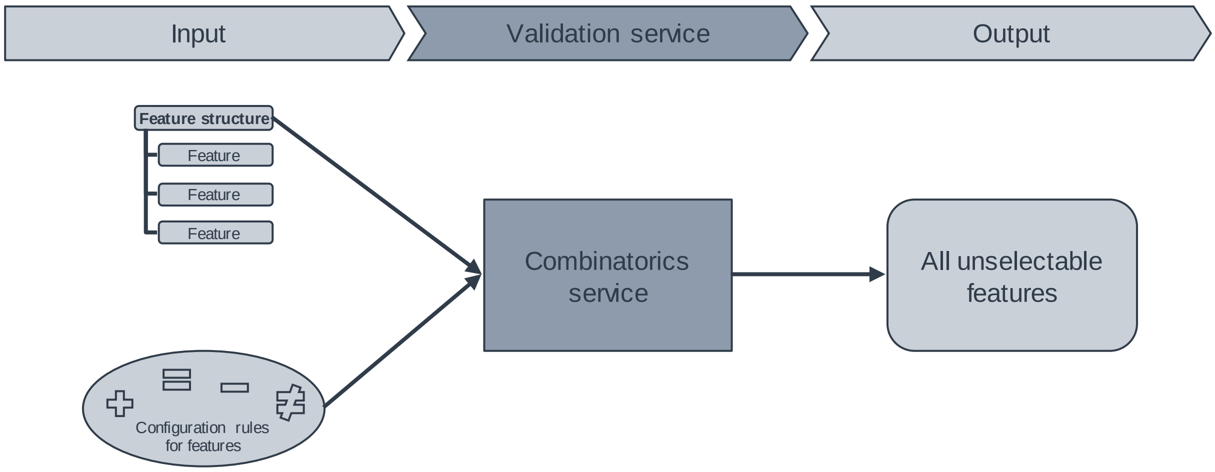


Figure 27: Input-output relation for the combinatorics service

The combinatorics service uses all the features of the feature structure and all the configuration rules for features that are part of the product portfolio as an input. The output of this service is a list of all the features within the feature structure that are not selectable in any configuration taking all the configuration rules into account.

Next, the *BoM-validation service* that was built for this research is explained, based on the input-output-relation in Figure 28 as well.

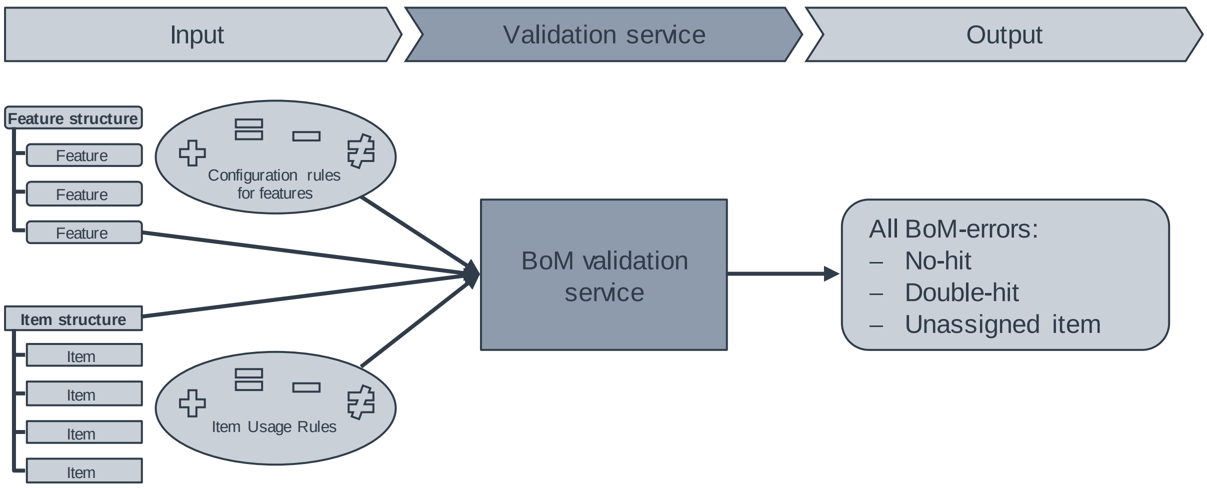


Figure 28: Input-output relation for the BoM-validation service

For the Bill-of-Materials validation service, the item structure together with the items selected for this validation task must be taken into consideration. Next, the item usage rules for the selected items are analysed to identify all features of the feature structure that are involved in these rules. Then, all possible combinations of features taking all configuration rules into account, are formed. For these part configurations, the selected items with their item usage rules are applied to identify the three error types, as described before. The output of this service is a list of all the items and their item usage rules for which one of the three error types has been discovered.

The Bill-of-Materials validation service is built for a dual-use, as it is also capable of handling the geometry validation. The position rules follow the same logic and structure as the item usage rules, therefore the same validation service can be applied.

The third service built for this research is the *completeness service*. The completeness service loads any desired structure (the feature structure or the item structure) including the relation between feature / item categories and their underlying objects: the features and items. On that basis, the completeness service can perform two checks:

- A check of a (part) configuration if exactly one feature or item has been selected for every feature or item category (e.g. required to analyse the completeness of an entire product configuration)
- A check of a feature or item category if all features / items under this category are considered (e.g. required to analyse the completeness for a Bill-of-Materials validation)

As outlined above, from an information technology perspective these services can be built in various ways and combinations, depending on the capabilities one organization has, as outlined in Table 16. Therefore, this chapter can only give an indication of a possible set-up for the validation services based on the implementation in this research project.

Nevertheless, the strategic level with the validation services is required for the holistic procedural model, especially taking the requirement R.4 – detailed and applicable validation process into account. Without the integration of the actual computing services in the procedural model, the whole validation process based on this model would fail in the application in the industrial practice.

3.2.3 Operative level: the three elementary services

As described before, the strategic level can differ from organization to organization depending on their prevalent conditions and capabilities. To build a generalized and universal procedural model, these validation services are broken down into so-called "*elementary services*" that form the operative level. These elementary services are atomic validation activities that can be composed in various ways to form different validation services. In total three different elementary services could be identified, as shown in Figure 29 below.

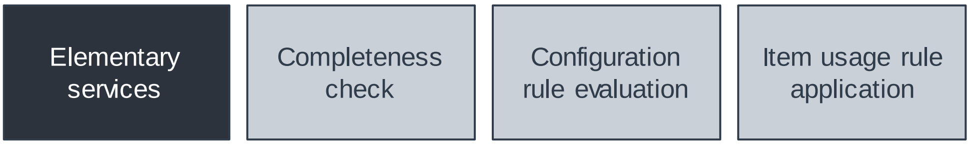


Figure 29: The three elements of the elementary service level in the holistic procedural model

The first elementary service is the so-called *completeness check*. A completeness check simply compares a list of selected elements with a second list of desired elements and highlights any differences. For instance, it can be used to determine whether the feature categories of the features used for a configuration are complete when comparing them with the list of all possible feature categories. For the item structure, the same check can be performed: compare the list of selected items and their item categories with the list of all possible item categories. The input for the completeness check is any structure with the link between feature or item categories and their assigned features / items.

The second elementary service, illustrated in the middle in Figure 29 above, is the *configuration rule evaluation*. As an input, this elementary service loads all features and all configuration rules for features. Based on the configuration rules, it calculates the allowed and forbidden combinations of features for any given feature category. Therefore, it can be used to detect unselectable features, as well as calculate combinations of features or validate any given (part) configuration against the configuration rules.

The third elementary service is the item usage rule application. The input for this elementary service is only the item usage rules that are selected for the task. This service compares the selection criteria, i.e. the condition-part of the item usage rule with a given (part) configuration of selected features and delivers a TRUE / FALSE answer depending on whether the set of selection criteria is satisfied or not. It can be used to perform any checks on the usage of items for the Bill-of-Materials or position validation, as well as simply "*translate*" a (part) configuration of features into the correct Bill-of-Materials in the item structure.

3.2.4 Adding the portfolio management perspective

So far, the three levels of the holistic procedural model have been setup to fulfil the requirements regarding validity (R.1.1 until R.1.4) as well as the requirements regarding the holistic focus (R.2) and applicability (R.4). Yet, the procedural integration into the core processes of a product manufacturing organization, as characterized in requirement R.3 – integration into the portfolio management perspective, needs to be addressed as well. Therefore, a *process integration level* is added to form the basis for the three validation levels. Within the process integration level, guidance on when to go through the holistic procedural model is given with respect to the underlying core business processes of a manufacturing organization, e.g. the portfolio management process or the product development process.

In general, two approaches to modelling the process integration have been seen, a *modular approach* and an *integral approach*., as shown in Figure 30 below.

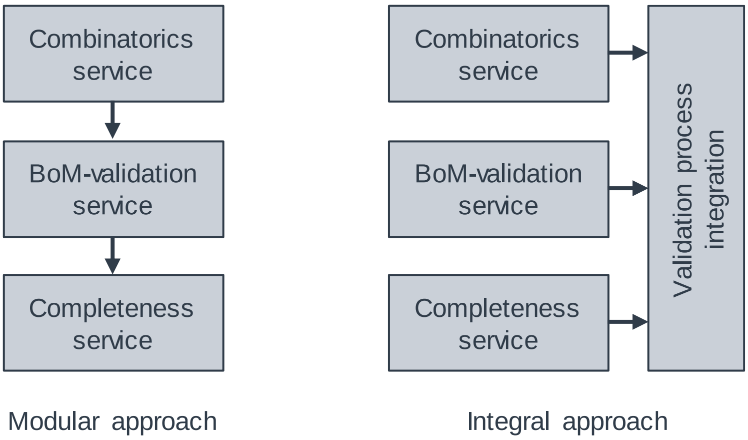


Figure 30: modular approach vs. integral approach to validation tools

Within a *modular approach*, the different validation services are implemented in separate tools with separate process steps. In an integral approach, the different validation services are integrated into one common software platform consisting of both all relevant tools and a process flow guiding users through the validation process.

This research project started with a modular approach for the validation services, as they have been implemented continuously during the project phases. But the set of different tools makes it hard for the users to easily understand the steps and the right order of steps in the validation process. Therefore, an integrated platform including both tools and processes is developed meanwhile to facilitate the entire validation process. For any companies newly adopting a validation approach, it is highly recommended to start with an integral approach already from the beginning to rely on the integrated advantages of having a clear process implemented already as part of the validation toolchain.

3.2.5 Integration of the four layers to form the holistic procedural model

The four layers that have been described before, the normative level with the validation tasks, the strategic level with the validation services, the operative level with the elementary services and the process integration level as a basis can now be combined to form the *holistic procedural model to ensure validity of complex, multi-variant product portfolios*. All the elements of the holistic procedural model are illustrated in Figure 31 below.

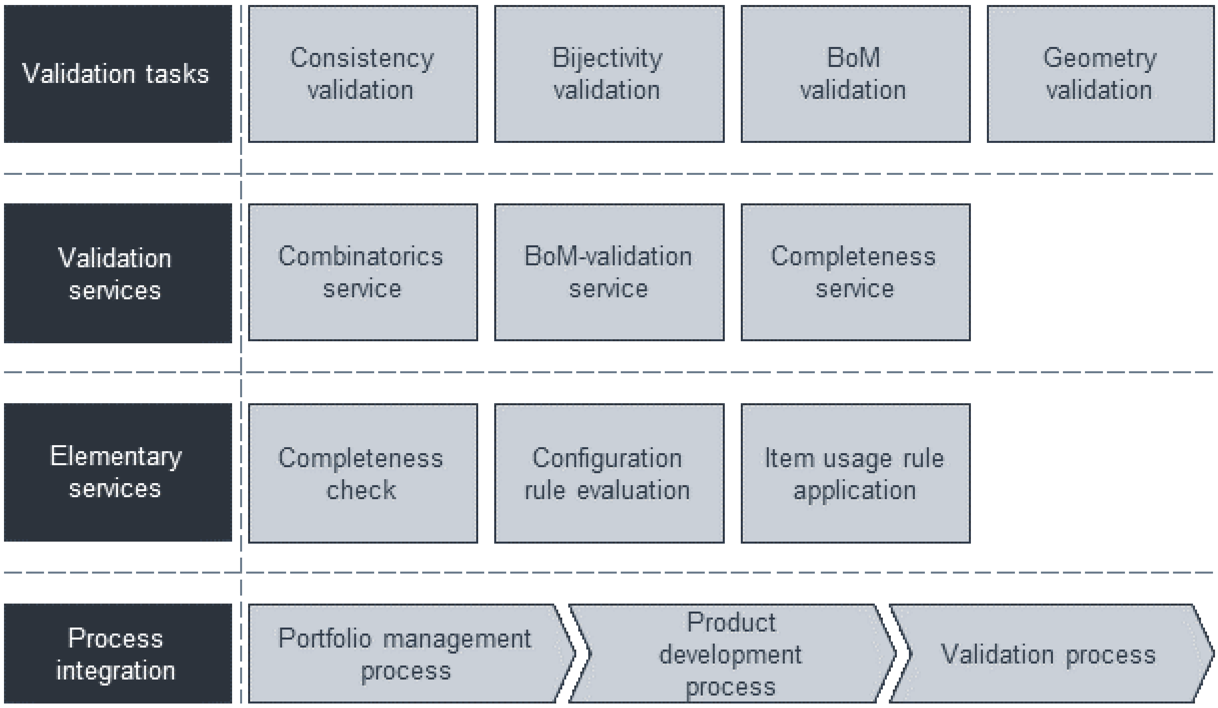


Figure 31: The holistic procedural model to ensure validity of complex, multi-variant product portfolios

The top three layers in Figure 31 above are arranged in the order of the St. Gallen Management-modell and follow the same logic: each validation task is fulfilled by applying one or more of the validation services. Each validation service again consists of a different recombination of the three elementary services. The process integration layer below provides the basis for the application of the holistic procedural model within the underling core business processes.

Based on the elements of the holistic procedural model, the relations, interdependencies and the optimal sequence of going through this model can now be evaluated in the following chapter 4.

4 Working with the elements of the procedural model

In this chapter, the way of working with the elements of the procedural model, including its relations and interdependencies, are described. First, the detailed relations between the different elements are outlined in section 4.1. Based on these relations, the optimal sequence of going through the procedural model is then examined in section 4.2, in which a standard process for the holistic procedural model is proposed. In the third section 4.3, the integration into the underlying business processes is described.

4.1 Relations between the three levels

Between the first three levels of the procedural model, a hierarchical top-down relation exists, as already shortly introduced in chapter 3.2.5. This type of relation can also be labelled as *vertical relation*. Each of the validation tasks is fulfilled by the execution of one or more validation services. Again, each validation service is formed through a recombination of the three elementary services. In the following, this top-down process is explained in detail for all the four validation tasks.

Consistency validation

The first validation task described here is the consistency validation. Here, the aim is to identify all unselectable features, as explained in chapter 3.2.1. To address this validation task, the combinatorics service is required. The user of the combinatorics service needs to select both all the feature categories of the product portfolio he wants to validate and all the configuration rules he wants to take into account. For the selection criteria for rules as well as feature categories, typical product life cycle management aspects need to be taken into consideration. Both their life cycle state (e.g. released for production, released for testing, in work, obsolete) and the point in time for which the validation is carried out, need to be specified. Now the combinatorics service has all the elements required to carry out this validation task. The service now runs through two of the three elementary services, first the configuration rule evaluation and second the completeness check. In the configuration rule evaluation, every feature is checked against the set of all the configuration rules to test whether there is any rule or set of rules that constrain the application of this context in any configuration. A simple example for such a constraint is found below for the feature category "*steering wheel*" with the only feature "*standard steering wheel*" and the feature category "*remote control steering wheel*" with the features "*without remote control steering wheel*" and "*premium remote control"*:

$$\begin{gathered} steering\ wheel{:}\, standard\ steering\ wheel \neg \\ remote\ control\ steering\ wheel{:}\, premium\ remote\ control \end{gathered}$$

In this case, the standard steering wheel disables the premium remote control. As the standard steering wheel is the only feature in the feature category steering wheel, every product has to have the standard steering wheel. Based on the constraint above, the premium remote control can never be configured, as it is always disabled through the standard steering wheel.

After the configuration rule evaluation has taken place, the completeness check is executed. Here, the completeness check compares the list of the analysed features with their classification as selectable / unselectable with the list of all the features of every feature category taken into account. With this check, it is ensured that every feature has been evaluated and that the final result is valid. The output of the combinatorics service as an answer for the consistency validation task is now the final list of all unselectable features.

Bijectivity validation

The second validation task is the bijectivity validation. The aim is to validate the bijectivity of relations, especially with regard to the feature-clusters as explained in section 3.2.1. For the bijectivity validation task, the combinatorics service is chosen as well. Yet, the service uses a different type of input this time. Here, not all feature categories and features with their feature rules are taken into consideration, as the focus is on the feature-clusters. Therefore, only the corresponding feature categories that were summarized within a certain feature-cluster are chosen as an input. Again, the selection needs to be done according to the correct product life cycle elements, e.g. life cycle state or point in time.

For this validation task, the combinatorics service does not check all the features whether they are selectable just as before, but calculates all possible combinations of the selected feature categories, again using the configuration rule evaluation. Next, the completeness check is performed by the combinatorics service to prove whether all feature categories have been calculated. The result is now a list of all the feature combinations that are allowed based on the configuration rules.

To complete the bijectivity validation task, the completeness service has to be applied next. The completeness service needs the list of feature combinations delivered by the combinatorics service and the considered feature-cluster as an input. With the help of the elementary service completeness check, this service now compares the calculated feature-combinations with the feature-cluster to identify any differences. The final result of the bijectivity validation task is now a list with all the elements of a feature-cluster that are either missing or too many, compared to the calculated number of feature-combinations.

Bill-of-Materials validation

The third validation task is the Bill-of-Materials validation. It is a more complex validation task compared to the first two tasks as it involves more process steps. The aim is to identify all errors in the item structure and the item usage rules, based on the three error definitions as shown in Figure 24. As an input, the item category that represents one special component of the product portfolio is chosen together with its items. Additionally, all the configuration rules for features have to be taken into account, as they define the selection criteria, i.e. the condition part of the item usage rules. For the Bill-of-Materials validation, a separate validation service has been developed as part of this research, which is called the Bill-of-Materials validation service.

The Bill-of-Materials validation service is best explained along a simplified example, adapted from the one shown by Braun et al [74], as illustrated in Figure 32 below.

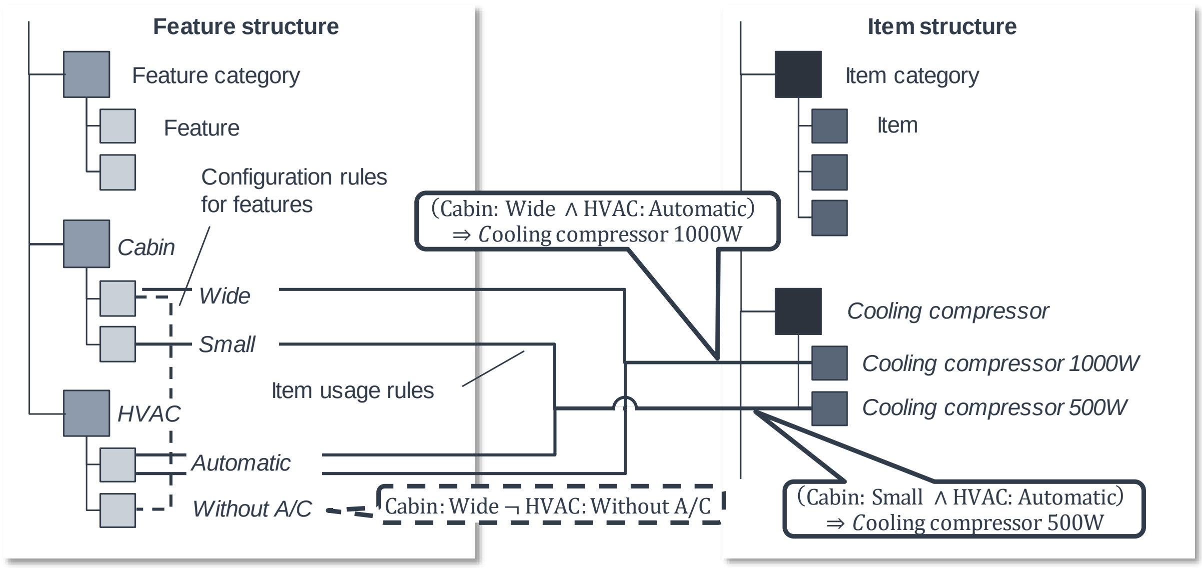


Figure 32: Extract of a product portfolio model, adapted from Braun et al. [74]

On the left-hand side of Figure 32 above, an extract of a feature structure is shown with the two feature categories "*cabin*" and "*HVAC*" (heating, ventilation and air-conditioning). Both feature categories have two features that can be selected. For the cabin this is the feature "*wide*" or "*small*", for the HVAC this is the feature "*automatic*" or "*without A/C*". Furthermore, one configuration rule is present in this context that forbids the combination of a wide cabin without air-conditioning:

$$Cabin: Wide \neg HVAC: Without\ A/C$$

On the right-hand side of Figure 32 above, an extract of an item structure is depicted with one item category "*cooling compressor*" and the two items "*cooling compressor 1000W*" and "*cooling compressor 500W*". Both of the items have their own item usage rule connecting them to a combination of features on the left-hand side in the feature structure:

$$(\textit{Cabin: Wide} \wedge HVAC\!: Automatic) \Rightarrow Cooling\ compressor\ 1000W$$

$$(\textit{Cabin: Small} \wedge HVAC\!: Automatic) \Rightarrow Cooling\ compressor\ 500W$$

With this input, the Bill-of-Materials validation service can be applied. First, the item usage rule application is executed on the elementary service level. The item usage rules are loaded and all the feature categories present in these rules are extracted. In this case, these are the two feature categories *cabin* and *HVAC*. With this information, the second elementary service is applied, which is the configuration rule evaluation. Here again, the combination of all features for the two feature categories cabin and HVAC is calculated taking all the configuration rules into account. In this example it results in a list of three possible combinations:

- case 1: cabin:wide ∧ HVAC:automatic
- case 2: cabin:small ∧ HVAC:automatic
- case 3: cabin:small ∧ HVAC:without A/C

The fourth combination cabin:wide ∧ HVAC:without A/C is not possible due to the constraint in the existing configuration rule in which a wide cabin cannot be combined without air-conditioning. With this list of feature combinations, again the elementary service item usage rule application is executed. Now, the two item usage rules of the items are evaluated against the possible feature combinations:

- for case 1 the item *cooling compressor 1000W* is selected as the item usage rule is TRUE
- for case 2 the item *cooling compressor 500W* is selected as the item usage rule is TRUE
- for case 3 no item is selected because both of the two item usage rules are FALSE

In the last step, the third elementary service completeness check is applied to compare all feature combinations with the assigned items of the item structure. In this example, the feature combination cabin:small ∧ HVAC:without A/C has no item assigned. This result corresponds to the "*no-hit*" error.

The output of the Bill-of-Materials validation service is now a list with both all the feature combinations for which no item was found (no-hit) or more than one item was found (double-hit) and the list of all the items that are never selected (unassigned item).

Geometry validation

The fourth validation task is the geometry validation. Due to the parallelism between the item structure and item usage rules and the positions and position rules, this validation task is similar to the Bill-of-Materials validation from a process point-of-view, as illustrated in Figure 33 below.

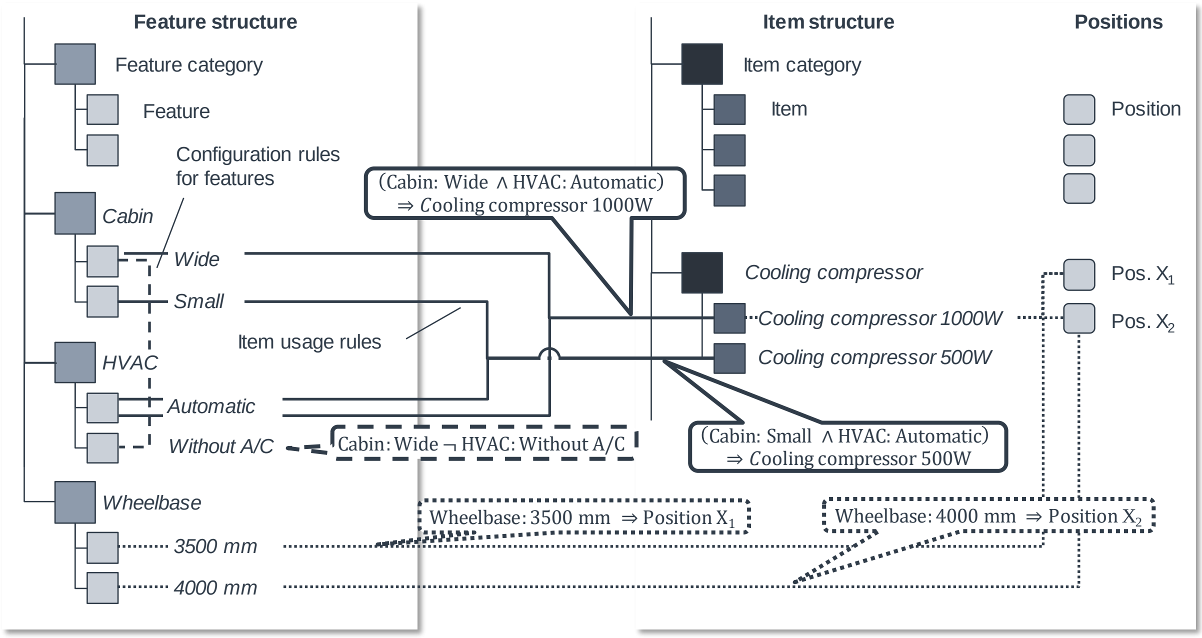


Figure 33: Extract of a product portfolio model, extended to the positions and position rules

In addition to the portfolio extract used to explain the Bill-of-Materials validation task, the feature category "*wheelbase*" with the two features "*3500 mm*" and "*4000 mm*" has been added. On the right-hand side of Figure 33 above, the positions have been added. Each item in the item structure has one or more positions that define the location of the components or parts in the final product, each depending on certain features of the feature structure. The correct position is defined through the position rules. For the item "*cooling compressor 1000W*", two positions exist, the position "X_1" and "X_2"with two individual position rules:

$$Wheelbase: 3500\ mm\ \Rightarrow Position\ X_1$$

$$Wheelbase: 4000\ mm\ \Rightarrow Position\ X_2$$

In this case, the position of the large cooling compressor with 1000W is depending on the layout of the product. If it has a smaller wheelbase, the compressor must be situated in a different position than compared to a larger wheelbase with more mounting space.

The input for the geometry validation task is now a selection of items from the item structure with their item usage rules, the correlating positions as well as their position rules and the configuration rules for features. With this input, now the Bill-of-Materials validation service is executed.

First, as already shown for the Bill-of-Materials validation above, the item usage rule application elementary service is performed for each item to extract all the features of both the item usage rules and the position rules. For the example of the cooling compressor here, these are the features "*cabin:wide*", "*HVAC:automatic*", "*wheelbase:3500 mm*" and "*wheelbase:4000mm*". Next, the configuration rule evaluation elementary service is executed to calculate all the possible combinations of these features. As no configuration rules are restricting the combinability here, two possible combinations exist:

- case 1: cabin:wide ∧ HVAC:automatic ∧ wheelbase:3500 mm
- case 2: cabin:wide ∧ HVAC:automatic ∧ wheelbase:4000 mm

Next, again the item usage rule application elementary service is used to evaluate the position rules:

- for case 1 the position X_1 is selected as the position rule is TRUE
- for case 2 the position X_2 is selected as the position rule is TRUE

As the last step, the completeness check is applied to compare the list of feature combinations, in this example the two combinations, with the list of identified, assigned positions. In this case, no errors could be detected, so the position of the items matches the possible combinations of features.

The output of the geometry validation is similar to the Bill-of-Materials validation: a list of all items with missing positions (no-hit error), with more than one position that cannot be differentiated (double-hit error) or with positions that are never assigned (unassigned item error).

For each of the validation tasks, the vertical relations within the three main levels have been outlined. These vertical relations are integrated into the holistic procedural model to document the first direction of relations within the model, as shown in Figure 34 below.

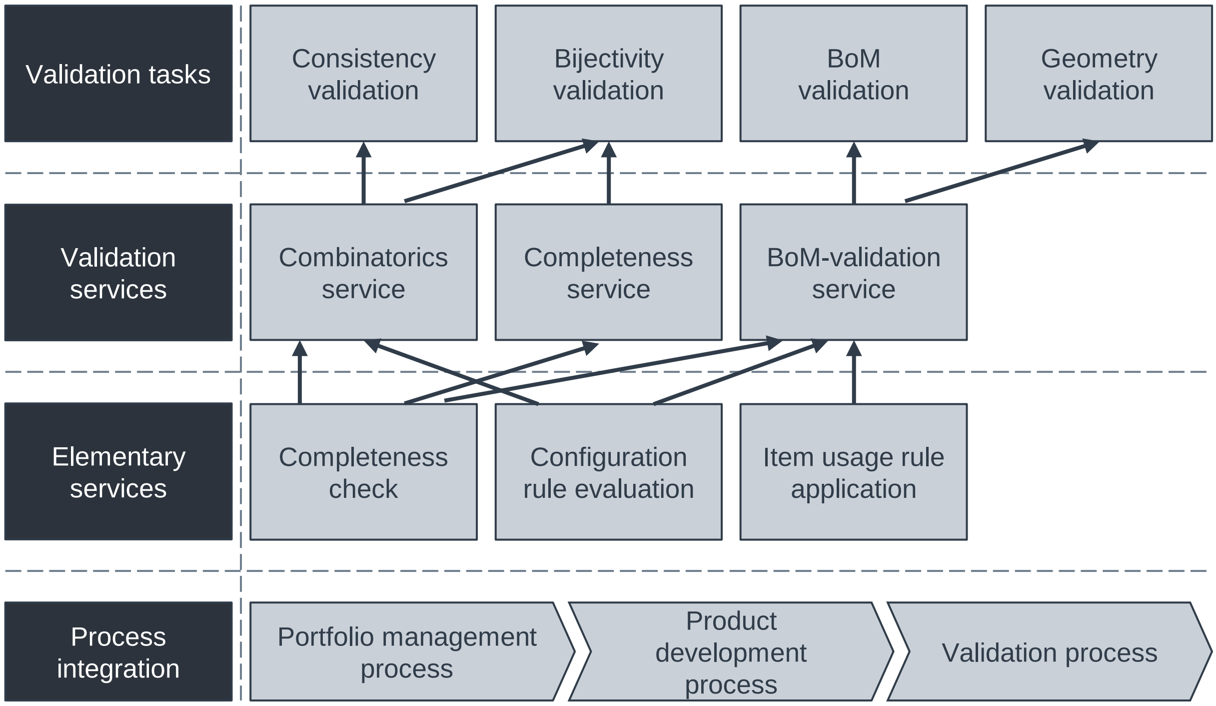


Figure 34: The holistic procedural model including vertical relations between the elements

For each of the four validation tasks, the process flow is documented in the holistic procedural model, starting from the validation task, the proposed validation services and the relevant elementary services with their combination and sequence.

4.2 Proposed sequence of the validation tasks

In chapter 4.1 the vertical relations (top-down) are described between the three levels of the validation tasks, the validation services and the elementary services. On this basis, the correct sequence of the validation tasks is examined in this chapter.

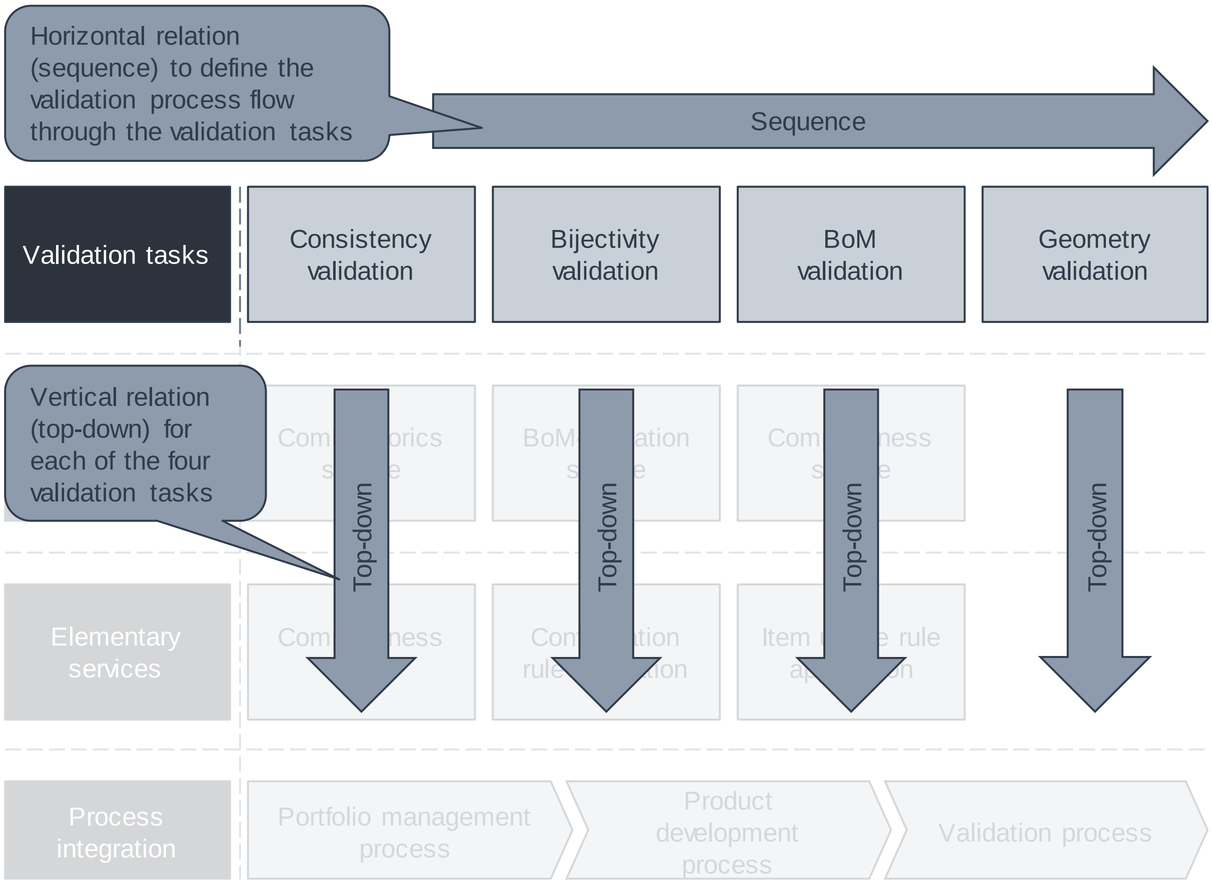


Figure 35: Vertical and horizontal relation in the holistic procedural model

As shown in Figure 35 above, the focus is on the horizontal relation which is the sequence of the validation tasks, i.e. how to combine the validation tasks one after the other to achieve validity for the entire product portfolio. For this, all requirements regarding every category of portfolio elements have to be taken into account.

In general, the four validation tasks can be executed independently from each other, as each of them has its own process regarding the vertical, top-down correlation with validation and elementary services, as explained in chapter 4.1. Therefore, any sequence is possible when going through the holistic procedural model from a theoretical logic-based point-of-view.

Nevertheless, content-based dependencies exist in terms of the product portfolio objects that are considered in the validation tasks. For example, both the consistency and the bijectivity validation directly deal with the feature structure and configuration rules for features. Indirectly the Bill-of-Materials validation task and the geometry validation task also rely on the feature structure and configuration rules for features. To achieve an optimised validation process with as few setbacks and iterations as possible, a correct sequence needs to be identified. Therefore, the content-based dependencies need to be considered in detail.

4.2.1 Content-based dependencies of the validation services

Within the product development processes in the automotive industry, different types of front-loading approaches are mainly used nowadays, as described by Thomke & Fujimoto [82] or Liker & Morgan [83]. In general, this means defining the requirements from a sales and product management perspective first and only then starting to develop the actual technical solutions. In terms of a multi-variant product structure, this means first defining the features structure with the configuration rules and then adding the necessary elements in the item structures to meet the sales requirements, as depicted in Figure 36 below.

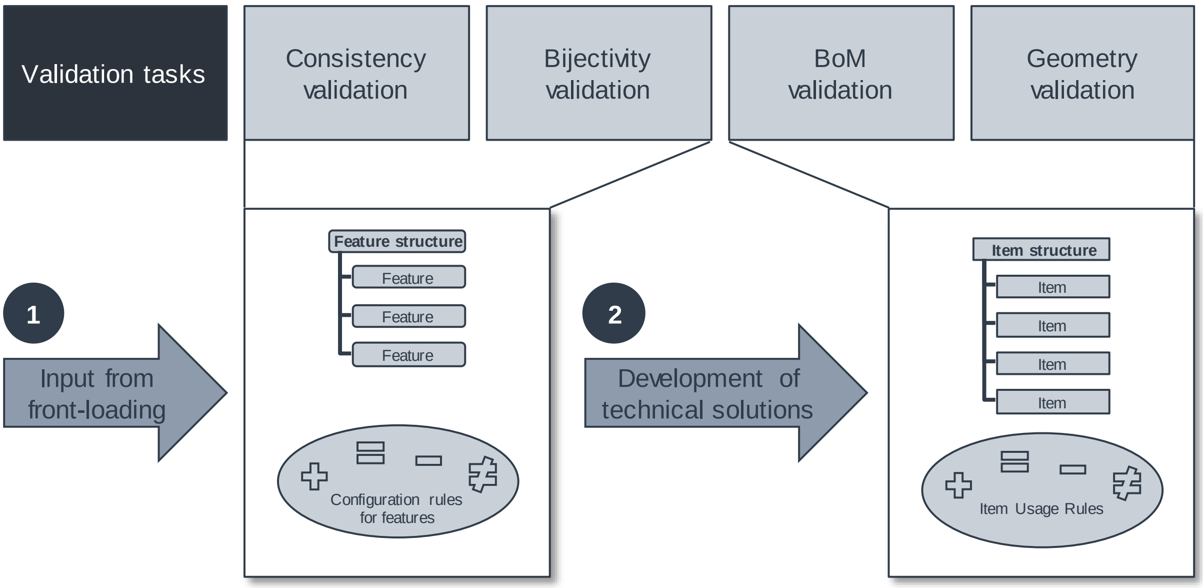


Figure 36: Influence of front-loading process on the validation sequence

Therefore, an integrated validation process should start with the consistency validation. In this validation task, the validity of the feature structure with its configuration rules is in focus. When all unselectable features have been identified and either corrected or technically accepted, the features themselves are in a valid state and it is clearly documented whether any feature is selectable or not for a certain time range.

Before starting a bijectivity validation, it needs to be clear whether a feature-cluster should be selectable or not at all for the given time range. As this has been validated in the consistency validation before, the bijective validation to test the mapping of feature-clusters and their respective features can be started next. Consequently, the bijectivity validation should take place after the consistency validation, as shown in Figure 37 below.

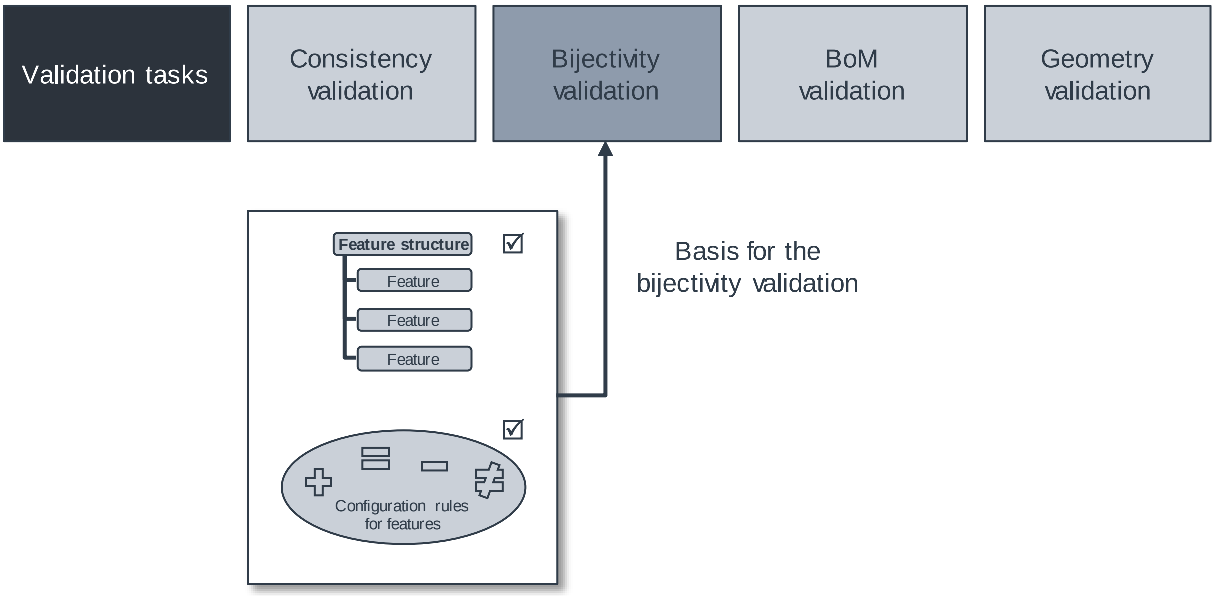


Figure 37: Dependency between consistency validation and bijectivity validation

As now both validation tasks addressing the feature structure and the configuration rules have been carried out, the input for the product development process resulting from the front-loading process has been validated. Next, the validation of the results of the second phase in the product development process which are the newly developed technical solutions, can take place starting with the Bill-of-Materials validation, as illustrated in Figure 38.

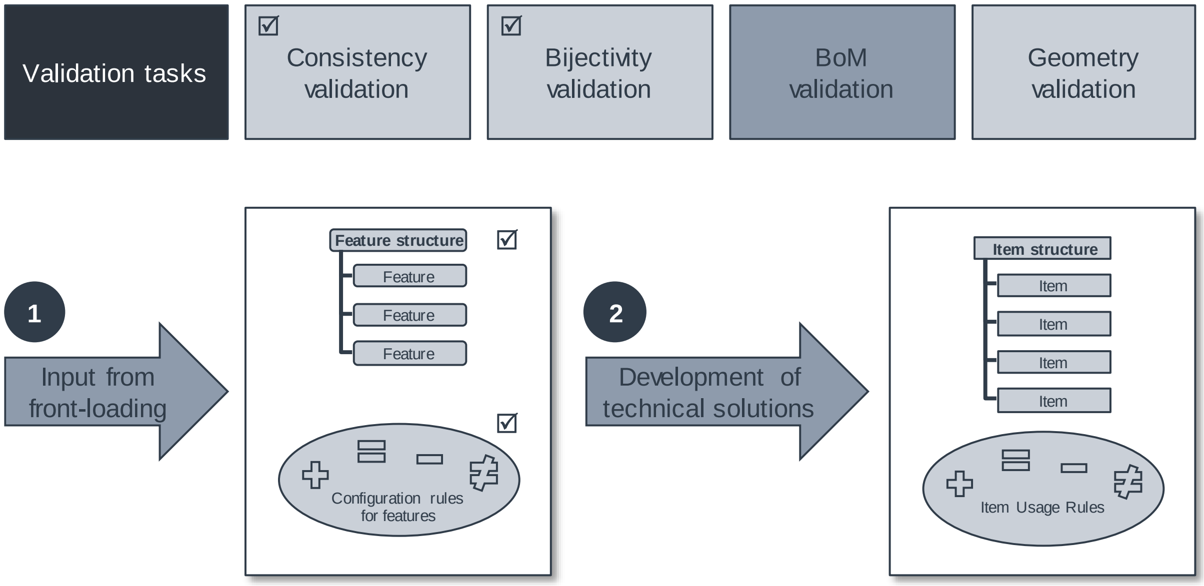


Figure 38: Starting-point for the BoM validation based on a valid feature structure and valid configuration rules for features

Here again a direct dependency between the BoM validation and the Geometry validation can be found. As explained earlier in section 3.2.1, the Geometry validation builds upon the Bill-of-materials validation, as both the positioning items in the item structure and the item usage rules for positions are an amendment to the correct item in the item structure.

Consequently, a simplified validation process is structured based on the dependencies between the input from the front-loading and the following development of technical solutions on the one hand and on the dependencies between the first two and the second two validation tasks on the other hand, as explained above. The resulting sequence is displayed in Figure 39 below. The four validation tasks are combined in a straight order starting with the consistency validation, with the bijectivity validation next and concluding with the Bill-of-Materials validation and the Geometry validation.

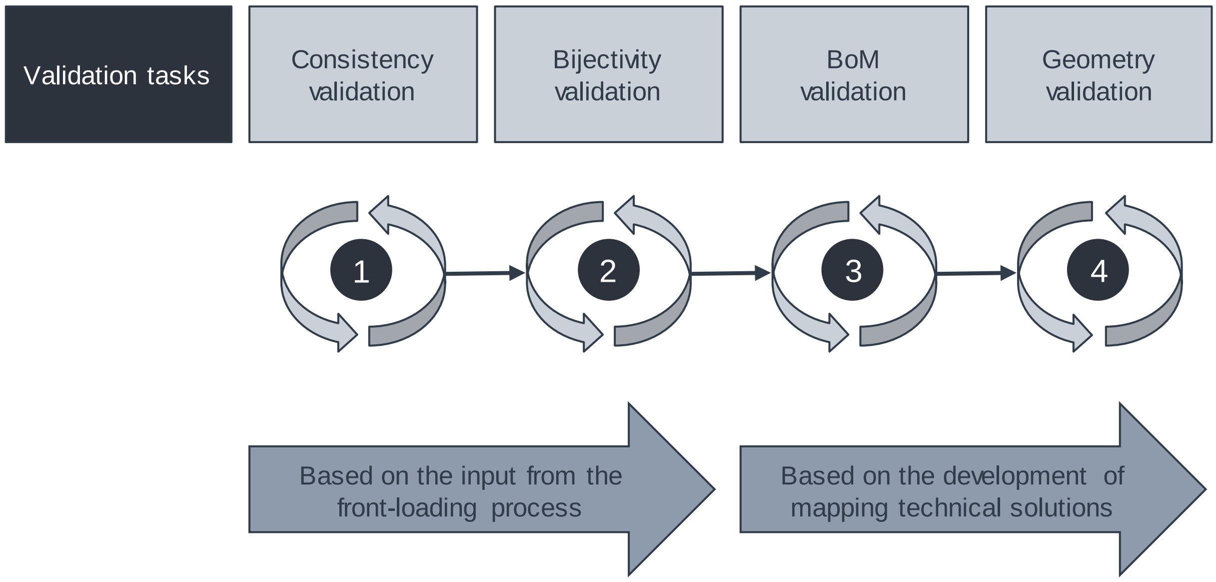


Figure 39: The simplified validation process based on the procedural model

Yet, the simplified validation process can lead to a larger number of iterations and setbacks. This is due to changes being made within the correction of errors after each validation step that could unintentionally result in creating new errors in parts of the product portfolio that have already been validated. Therefore, an optimised validation sequence is proposed in the following section 4.2.2.

4.2.2 Proposed optimised sequence to minimize iterations

If errors within the bijectivity validation are discovered, they will most often result in a correction of the configuration rules for features, as the mapping of feature-clusters was not correct based on the configuration rules beforehand. Nevertheless, changes in the configuration rules for features can unintentionally lead to new features not being selectable at all for the considered time range. As a result, it is worth executing another consistency validation after having corrected the errors resulting from the bijectivity validation to double-check if any new portfolio errors have been created.

When looking at the Bill-of-Materials validation and the Geometry validation, the same argument applies again. The correction of errors from the Bill-of-Materials validation can be done both in in the configuration rules and within the Item Usage Rules. If the item usage rule is just written incorrectly or not precisely enough, it is changed right there. But if certain selection criteria (i.e. a specific combination of features) need to be eliminated from the product portfolio, the configuration rules for features have to be changed. This can again result in unintentionally changing the configuration rules in a way that new features are not selectable any more. Therefore, the consistency validation should also be carried out after each Bill-of-Materials validation and Geometry validation.

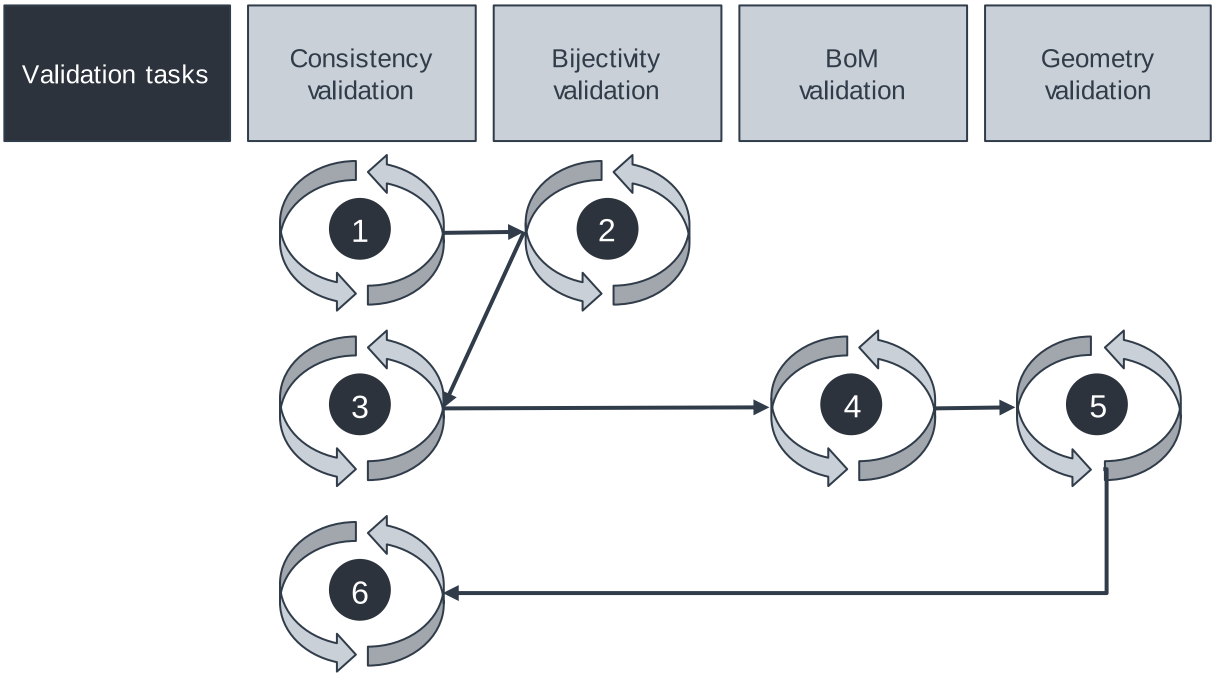


Figure 40: The optimized validation process based on the procedural model

As explained in Figure 40 above, two additional iterations of the consistency validation (validation step 3 and 6) are useful to minimize the number of iterations and setbacks within the entire validation process.

4.3 Integration into the underlying core business processes

It is not only the process for each individual validation task, as explained in chapter 4.1, and the optimal sequence of the validation tasks as examined in chapter 4.2 that have to be considered. For a successful application of the holistic validation framework in the context of product manufacturing organizations, the integration of the entire validation process into the general underlying business processes also has to be taken into consideration.

For the scope of this research, namely two main business processes are of interest: the *portfolio management process* as well as the *product development process*. As previously outlined in chapter 2.1.1, the portfolio management process focusses on the evaluation and prioritization of possible new product development projects. For these decisions, different mathematical and strategical approaches exist. The result of the portfolio management activities can be the kick-off of a new product development project. In large organizations, clearly documented product development processes exist consisting of different phases and stages from the product definition to the final solution. Widely used definitions of the product development process can be found for example with Pahl & Beitz [84] or Ehrlenspiel & Meerkam [85].

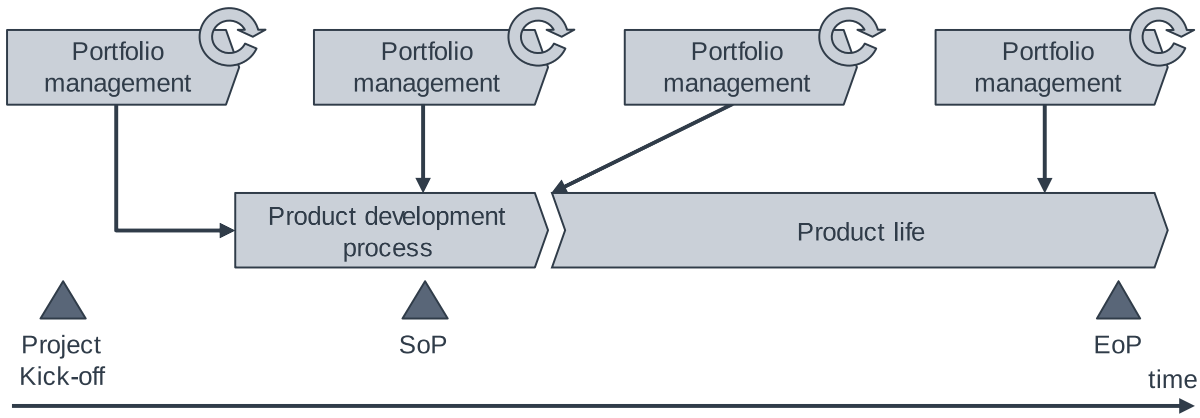


Figure 41: Relation between portfolio management process and product development process

The portfolio management process and the product development process are closely linked during the lifespan of a product, as shown in Figure 41. First, the current product portfolio is analysed within the portfolio management process. When either a gap in the existing portfolio or a future demand of new products have been identified, the development of a new product will be started next a product development project. This will happen when a new product development process starts with the project kick-off. When the start-of-production (SoP) is reached, the new product will be released into series production. During the whole phase of a product life, the portfolio management process is gone through repeatedly for the entire product portfolio. This can result in either a continuation, a change of the product or even a discontinuation ending the product life with the end-of-production (EoP). The case study conducted to support this research, as explained in detail in chapter 5, has shown the need for the validation process – as proposed within the holistic procedural model – to take place both during the portfolio management and the product development process.

Especially within the product development process, the close integration of the procedural model into the different stages is beneficial to the engineers and their activities.

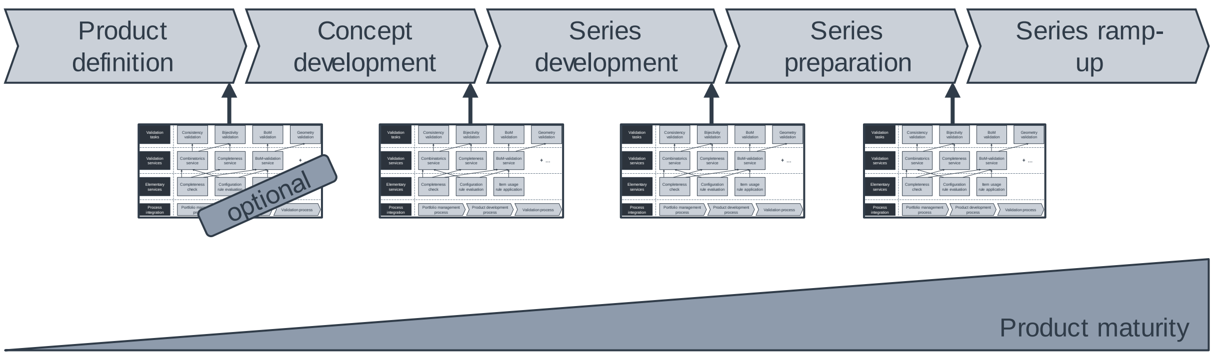


Figure 42: Integration of the holistic procedural model into a typical product development process for automotive companies, adapted from Rudert & Trumpfheller [86].

A typical example illustrating the main stages of the product development process for automotive companies is found with Rudert & Trumpfheller [86], as displayed in Figure 42 above. They include five different phases in their process view:

- *Product definition*: The basic requirements of all stakeholders for the new product are collected, prioritized and defined. This phase sets both the technical and economic basis for the following steps
- *Concept development*: First concept studies and virtual prototypes are developed. The final outcome of this phase is the agreed specification sheet for the product
- *Series development*: All the necessary components are developed by the engineers and integrated into physical prototypes. In parallel, the first steps of the launch management and supplier selection take place
- *Series preparation*: Different pre-series are produced to undergo all the necessary testing procedures. The supplier ramp-up and production preparation take place as well
- *Series ramp-up*: In the last phase, production volume is raised steadily to meet the necessary production units for the start-of-production. Here, the focus is finally more on the production and logistics aspects

Figure 42 shows the proposed integration of the portfolio validation process based on the holistic procedural model into the product development process for automotive products. Especially at the stage gates between the main development phases, the concept development, the series development and the series preparation, the portfolio validation process has to take place. When the holistic procedural model is applied, the entire future product portfolio including the new product, can be validated. Therefore, the model helps to achieve the right maturity for each process phase to go into the next product development phase, especially in terms of the documentation. The procedural model cannot only be used to support the quality gates at the end of each phase. In the industrial application, as described within the case study in the following chapter 5, the continuous application of the holistic procedural model has helped especially in the core development phases concept development and series development, to keep the focus of the product architects and engineers not only on their isolated component, but also on the effects of the whole portfolio, as well as the correct documentation of their development activities.

Furthermore, the holistic procedural model can also be applied at the beginning of the product development process within the product definition phase. Here it acts more as a support for the actual planning activities. With the help of the model, effects on the planned activities, e.g. changed relations and rules in the portfolio through new product variants, can be made visible very early on. Thus, the consequences for the entire product portfolio can be taken into consideration when deciding on different design alternatives.

Whereas the benefits of integrating the holistic procedural model into the portfolio validation process are more obvious, the holistic procedural model can also be applied within the portfolio management process, even before decisions on future portfolio changes are taken. The effects on the portfolio can be simulated, e.g. through the simple creation or deletion of portfolio objects (features or items) or the modification of both configuration and item usage rules. By going through the model, all effects that the considered portfolio decisions might have on the other products within the portfolio become visible. Therefore, an educated discussion based on facts rather than assumptions concerning the strengths and weaknesses of portfolio changes can be started very early on.

5 A case study from commercial vehicle engineering

The procedural model to validate complex, multi-variant product portfolios, as explained in detail in the previous chapters 3 and 4, is tested and validated in a joint case study with MAN Truck & Bus SE based on a real-world product data example.

In this chapter, the real-world example will be explained in detail in section 5.1 first. In the following section 5.2, the proposed procedural model will be executed based on the real-world industry example including the corrections of all detected portfolio errors. At the end of chapter 5, the results of the application of the procedural model are evaluated based on the requirements regarding validity, as defined previously in chapter 3.1., and thereby validated in section 5.3.

5.1 Description of the real-world industry example

The case study is based on a product portfolio test case that has been developed within MAN Truck & Bus SE. This test product portfolio follows the same structure and logic as the current standard product portfolio, but has a reduced level of content and complexity. In the practical industrial application, this test data set can be used to validate the correct functionality of all the validation services with their algorithms, and to test the entire validation process as well.

It is also used in the context of this research, as it is representative of any larger product portfolio following a multi-variant structure as outlined in chapter 2.1.3, but has a context that is smaller and therefore easier to understand so that it allows for non-experts to also better understand the content of the product portfolio.

The product portfolio test case consists of all elements mentioned in chapter 2.1.3, namely a feature structure, a set of configuration rules for features, an item structure with both items and positions, as well as both a set of item usage rules and item usage rules for positions. Additionally, the portfolio example has feature-clusters as explained in chapter 3.2.1.

The feature structure consists of five feature groups with twelve feature categories with 30 different features in total, as shown in Figure 43, Figure 44, and Figure 45 below. Each feature is shown here with a short name, e.g. "*HG_with*" and a textual description, e.g. "*Hazardous goods transporter*".

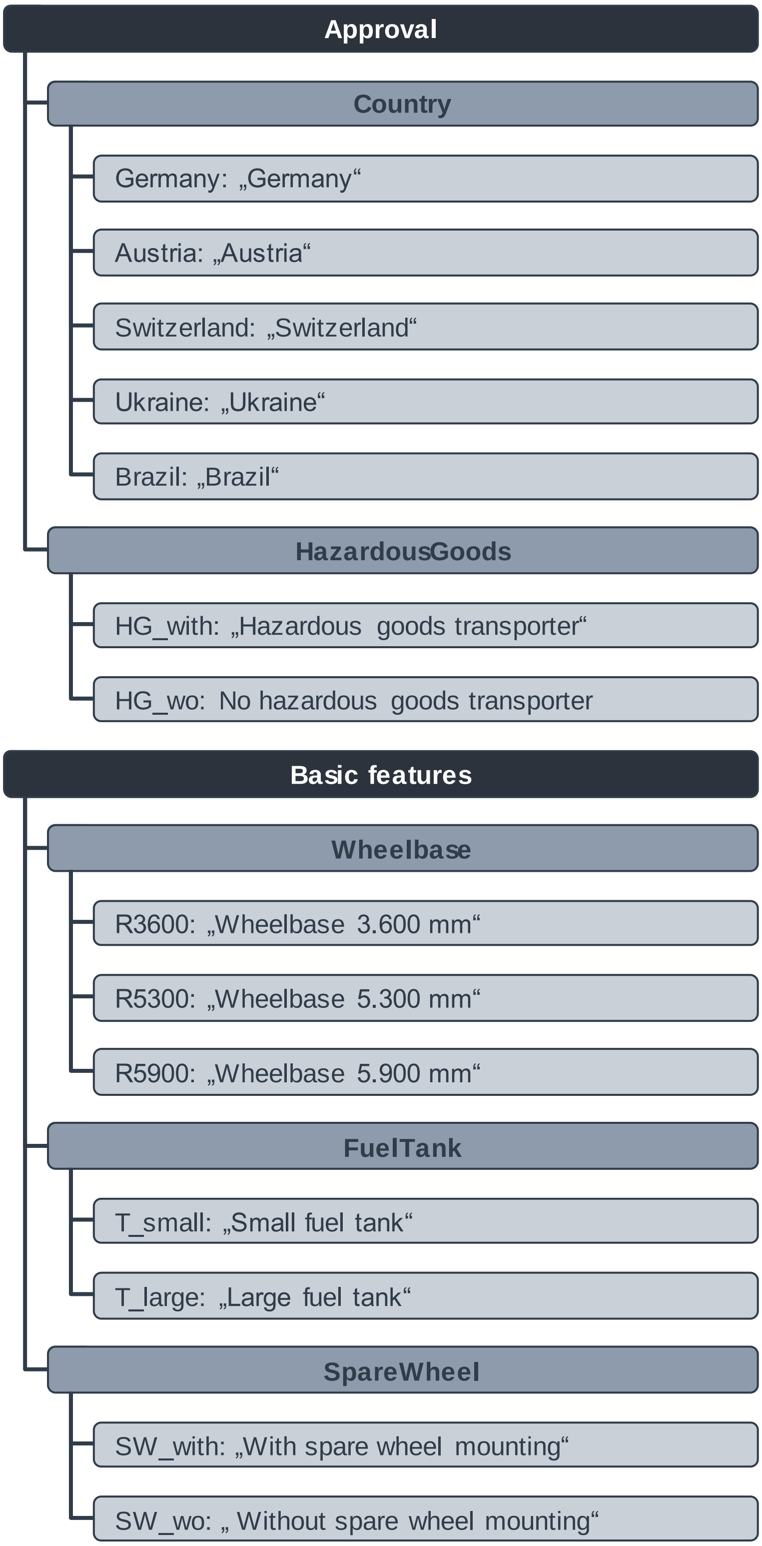


Figure 43: Feature structure of the real-world industry example (1/3)

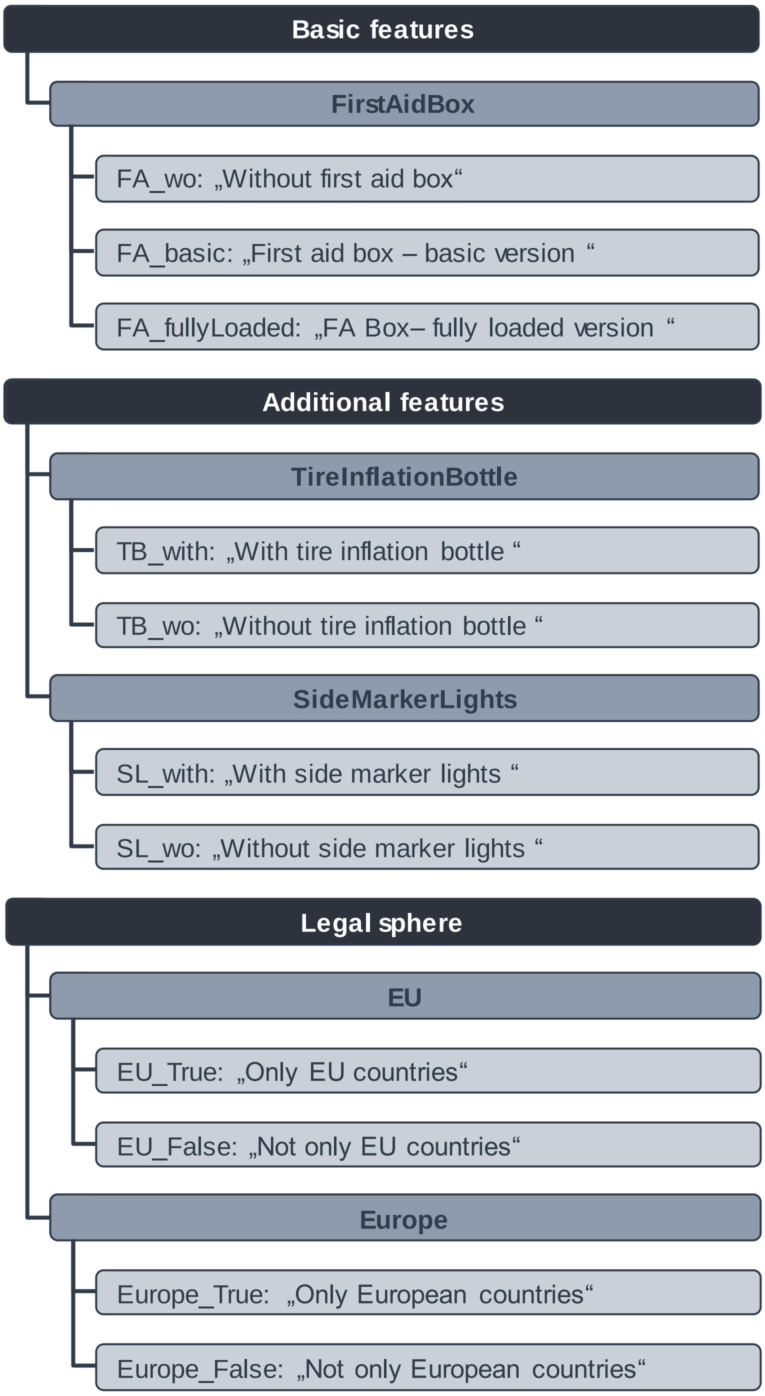


Figure 44: Feature structure of the real-world industry example (2/3)

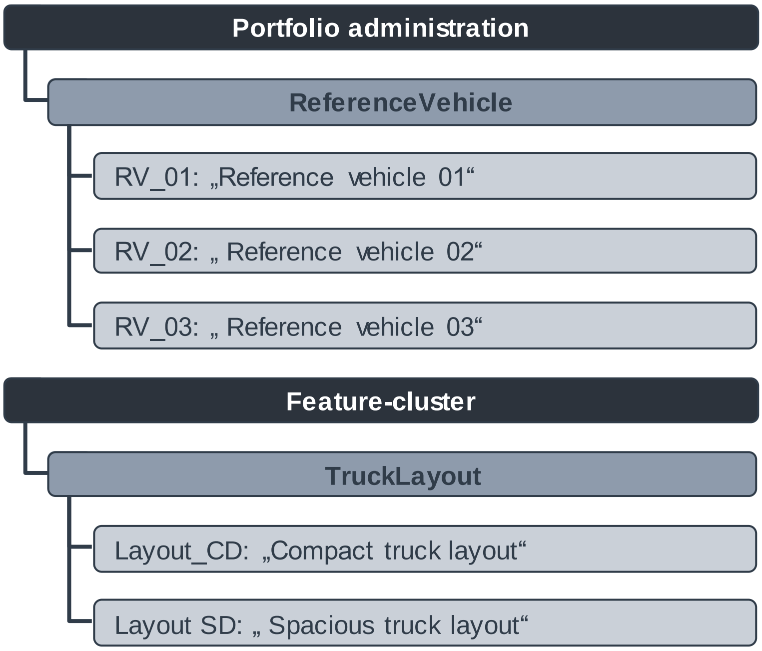


Figure 45: Feature structure of the real-world industry example (3/3)

Within the product portfolio data model, additional meta information is stored for each feature, the detailed data set is found in the Appendix 8 of this research.

Additionally, the real-world industry example consists of thirteen configuration rules for features, as outlined in the following Table 17.

Table 17: Configuration rules for features of the real-world example

Configuration rules for features
$R3600 \Rightarrow \neg SW_{with}\ from\ PP201801$
$HG_{with} \Rightarrow \neg R5300\ from\ PP201801$
$(EU_{True} \wedge HG_{with}) \Rightarrow (SW_{with} \vee TB_{with})\ from\ PP201801$
$EU_{True} \Rightarrow \neg FA_{wo}\ from\ PP201801$
$SL_{wo} \Rightarrow (R3600 \vee R5300)\ from\ PP201801$
$RV_{01} \Rightarrow (Germany \vee Austria)\ from\ PP201801$
$RV_{02} \Rightarrow Germany\ from\ PP201801$
$RV_{03} \Rightarrow Austria\ from\ PP201801\ until\ PP201907$
$RV_{03} \Rightarrow (Austria \vee Switzerland \vee Ukraine \vee Brazil) from\ PP201907$
$(R3600 \wedge T_{large}) \vee (R5300 \wedge T_{large} \wedge SW_{with}) \Rightarrow Layout_{CD}\ from\ PP201801$

$\neg\left((R3600 \wedge T_{large}) \vee (R5300 \wedge T_{large} \wedge SW_{with})\right) \Rightarrow Layout_{SD}\ from\ PP201801$
$(Germany \vee Austria) \Rightarrow EU_{True}\ from\ PP201801$
$\neg(Germany \vee Austria) \Rightarrow EU_{False}\ from\ PP201801$
$(EU_{True} \vee Switzerland \vee Ukraine) \Rightarrow Europe_{True}\ from\ PP201801$
$\neg(EU_{True} \vee Switzerland \vee Ukraine) \Rightarrow Europe_{False}\ from\ PP201801$

In this example, the effectivity in time of a rule (i.e. its start and end date) is documented in the form of a planning period. Each year is thereby divided into 36 planning periods and saved in the following format:

$$PPYYYYNN: Planning\ Period\ \mathrm{PP}, Year\ \mathrm{YYYY}, Number\ of\ Planning\ Period\ "NN"$$

This is a convention that is used in the case study and the real-world application, the effectivity of a rule could also be in a calendric format without any problem like the following:

$$DDMMYYYY: Day\ \mathrm{DD}, Month\ MM, Year\ YYYY$$

In the item structure, the industry example consists of four item categories with thirteen items in total and 26 geometry variants. The components, i.e. the items in the item structure, are illustrated in Figure 46 below.

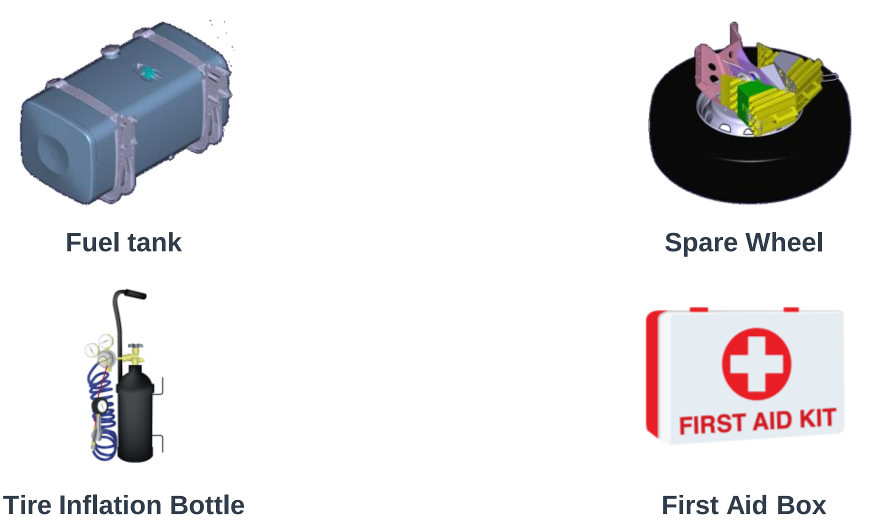


Figure 46: Technical components represented within the item structure

In this industrial application, a two-step geometry information is used, which consists of an internal geometry object called *solution element SE* (the position of the actual parts of each item relative to each other) and an external geometry object called *transformation Trafo* (the position of the entire item relative to all other items). To develop the generic procedural model, the geometry has been simplified into one aggregated geometry structure, but will be shown in detail here within this case study, as shown in Figure 47, Figure 48 and Figure 49 below.

Figure 47: Item and position structure of the real-world industry example (1/3)

Figure 48: Item and position structure of the real-world industry example (2/3)

Figure 49: Item and position structure of the real-world industry example (3/3)

According to the generic data model as described before in chapter 2.1.3, every item within the item structure has to have its own Item Usage Rule. If for one item in the item structure no usage rule is present, it symbolizes that the item is always effective, i.e. is chosen for any configuration of features in the feature structure.

Table 18 gives an overview of all Item Usage Rules of this industry example below.

Table 18: Item Usage rules of the real-world example

Item Usage Rules
$(T_{small} \neg\, Layout_{CD}) \Rightarrow\ 81\#0990-001\ from\ PP201801$
$(T_{small} \wedge\ Layout_{CD}) \Rightarrow\ 81\#0990-002\ from\ PP201801$
$(T_{large} \neg\, Layout_{CD}) \Rightarrow\ 81\#0990-003\ from\ PP201801$
$(T_{large} \wedge\ Layout_{CD}) \Rightarrow\ 81\#0990-004\ from\ PP201801$
$SW_{wo} \Rightarrow\ 81\#0991-000\ from\ PP201801$
$SW_{with} \Rightarrow\ 81\#0991-001\ from\ PP201801$
$\neg\,(R3600\ \vee\ T_{large}) \Rightarrow\ 81\#0991-001-SE01$
$T_{small} \Rightarrow\ 81\#0991-001-SE01-Trafo01$

$(T_{large} \wedge R3600) \Rightarrow 81\#0991 - 001 - SE01 - Trafo04$
$(T_{large} \wedge R5300) \Rightarrow 81\#0991 - 001 - SE01 - Trafo05$
$(T_{large} \wedge R5900) \Rightarrow 81\#0991 - 001 - SE01 - Trafo06$
$(R3600 \wedge T_{large}) \Rightarrow 81\#0991 - 001 - SE02$
$TB_{wo} \Rightarrow 81\#0992 - 000\ from\ PP201801$
$TB_{with} \Rightarrow 81\#0992 - 001\ from\ PP201801$
$FA_{wo} \Rightarrow 81\#0992 - 001 - SE01 - Trafo01$
$\neg (FA_{wo} \wedge (Germany \vee Austria)) \Rightarrow 81\#0992 - 001 - SE01 - Trafo02$
$FA_{wo} \Rightarrow 81\#0993 - 000\ from\ PP201801$
$FA_{basic} \wedge (Germany \vee Austria) \Rightarrow 81\#0993 - 001\ from\ PP201801$
$FA_{fullyLoaded} \wedge (Germany \vee Austria) \Rightarrow 81\#0993 - 002\ from\ PP201801$
$Brazil \Rightarrow 81\#0993 - 003\ from\ PP201801$
$FA_{fullyLoaded} \wedge Brazil \Rightarrow 81\#0993 - 004\ from\ PP201801$

In the industrial application as well as for the case study, this product portfolio information is stored in an overarching product model in the data format "*.json*" (JavaScript Object Notation). The entire product model is loaded into the validation services to perform the validation tasks with the help of tailored algorithms. The entire product model for this example can be found in the Appendix in chapter 8. Therefore, the following Figure 50 only gives a short insight into what a product model looks like in the .json-format.

Figure 50: Extract from the overarching product model in the .json-format

Within this product portfolio example, typical error cases have been integrated to test and validate the procedural model that is described in chapters 3 and 4. The application of the procedural model in this test data set is explained in the next chapter.

5.2 Application of the procedural model based on the industry example

The application of the procedural model is structured according to the optimized sequence of going through the procedural model as proposed in chapter 4.2.2 and displayed in Figure 51 below.

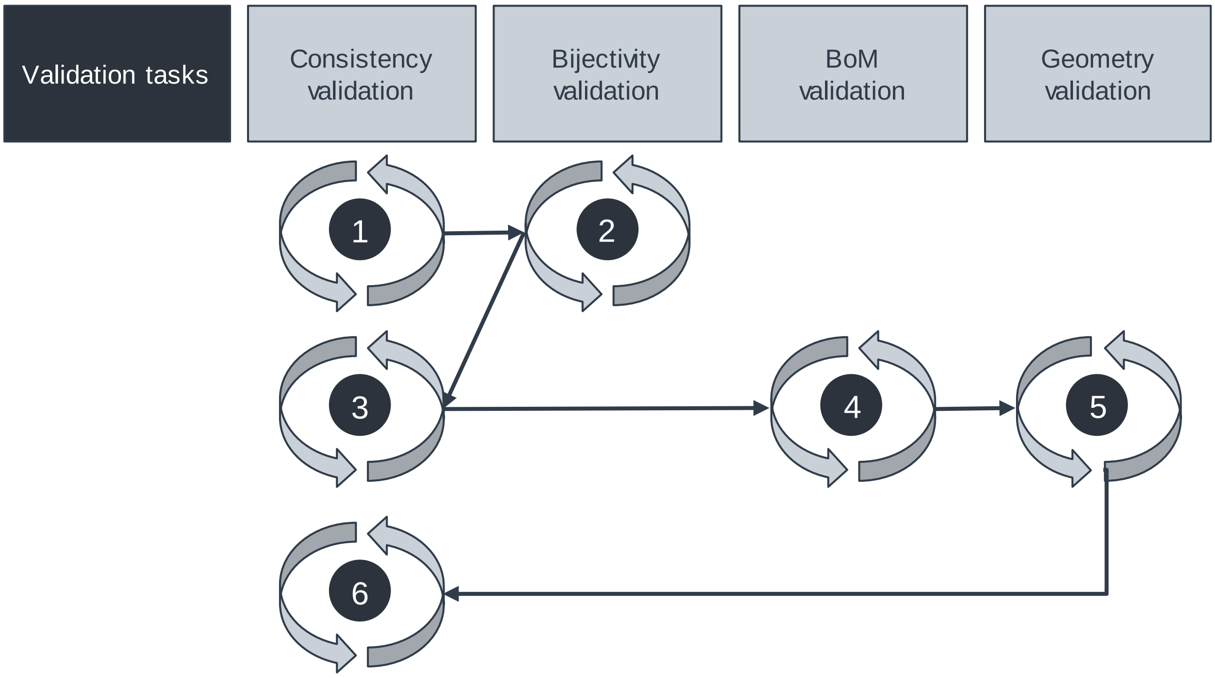


Figure 51: Sequence of the validation tasks in the procedural model

To begin with, the consistency validation task (1) is carried out based on the entire product model and the identified errors are corrected. Next, the bijectivity validation task (2) is performed and again errors are corrected. Then, the second consistency validation task (3) is executed to check for any newly created errors. After this, the Bill-of-Materials validation task (4) takes place to check for any inconsistencies in the Bill-of-Materials. When they have been corrected, the Geometry validation task (5) is carried out next. Finally, the third consistency validation task (6) ensures that the feature structure with the configuration rules is still valid.

5.2.1 The Consistency validation task

As explained before, the consistency validation checks for any errors within the feature structure, i.e. identifies all features that are part of the feature structure but can never be selected within any configuration. This task fulfils the requirements *R.1.1 – Completeness and R.1.2 – Unambiguity*. The result of this task based on the industry example is shown in Figure 52 below.

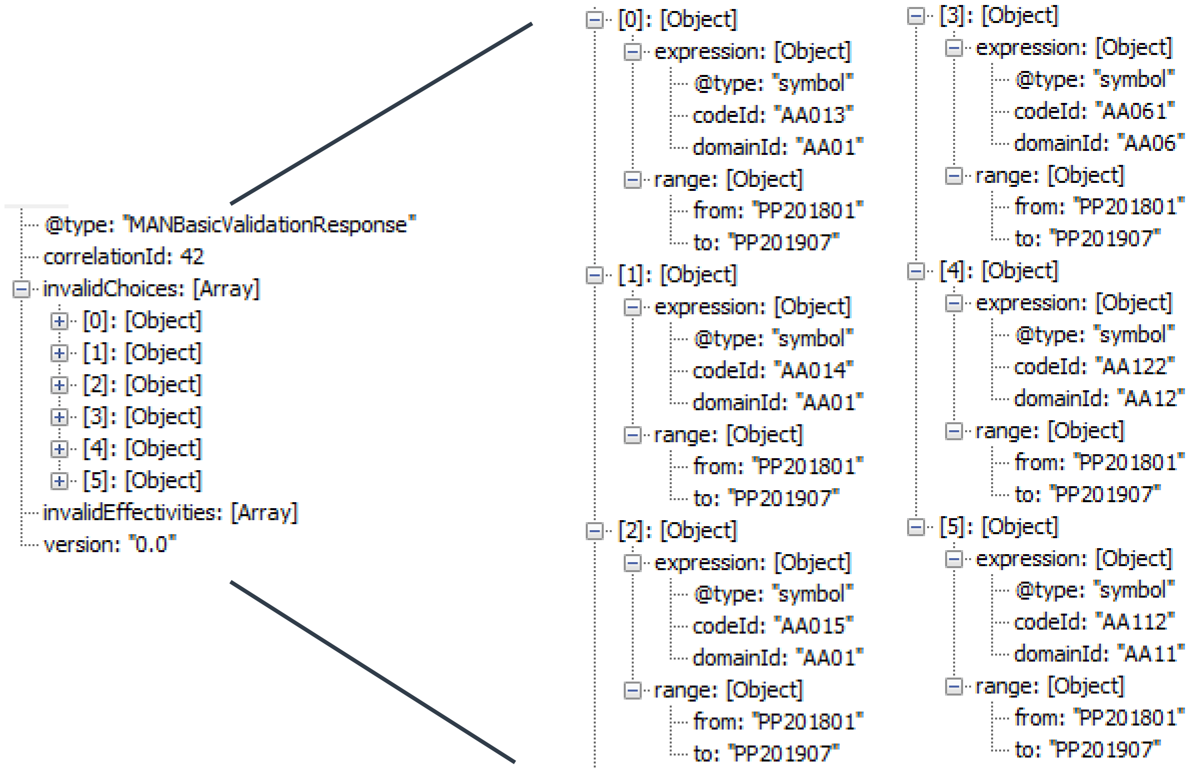


Figure 52: Results of the first Consistency Validation task

In total, six non-selectable features have been identified. After translating the *codeIds* into the features, the following features are not selectable from PP201801 until PP201907: *Switzerland*, *Ukraine*, *Brazil*, *FA_wo*, *Europe_False*, *EU_False*.

This inconsistency is due to the following three configuration rules according to which the countries can only be *Germany* or *Austria* for any of the three reference vehicles between PP201801 and PP201907:

$$RV_{01} \Rightarrow (Germany \vee Austria)\ from\ PP201801$$

$$RV_{02} \Rightarrow Germany\ from\ PP201801$$

$$RV_{03} \Rightarrow Austria\ from\ PP201801\ until\ PP201907$$

To change this effect of the rules in the feature structure, the third rule needs to be deactivated and deleted, so that all countries can be selected at any time. In consequence, the other three features *FA_wo*, *Europe_False* and *EU_False* will also be selectable, as they depend on the countries as documented in the last four rules in Table 17.

5.2.2 The Bijectivity validation task

With the bijectivity validation task, the fulfilment of the requirement R.1.2 is ensured, as the feature-clusters are tested whether they have documented the identical variance in the portfolio when compared to the list of the possible feature combinations.

In the case study here, the bijectivity validation is carried out for the feature-cluster *TruckLayout* with the features *Layout_CD* and *Layout_SD*, as shown in Figure 45 before. The Bijectivity validation task now tests the combinability of all features that are part of the feature-cluster's configuration rules. According to the two configuration rules outlined below, these are the feature categories *WheelBase*, *FuelTank* and *SpareWheel*.

$$(R3600 \wedge T_{large}) \vee (R5300 \wedge T_{large} \wedge SW_{with}) \Rightarrow Layout_{CD}\ from\ PP201801$$

$$\neg\left((R3600 \wedge T_{large}) \vee (R5300 \wedge T_{large} \wedge SW_{with})\right) \Rightarrow Layout_{SD}\ from\ PP201801$$

These feature categories have seven different features in total, as shown in Figure 53 below.

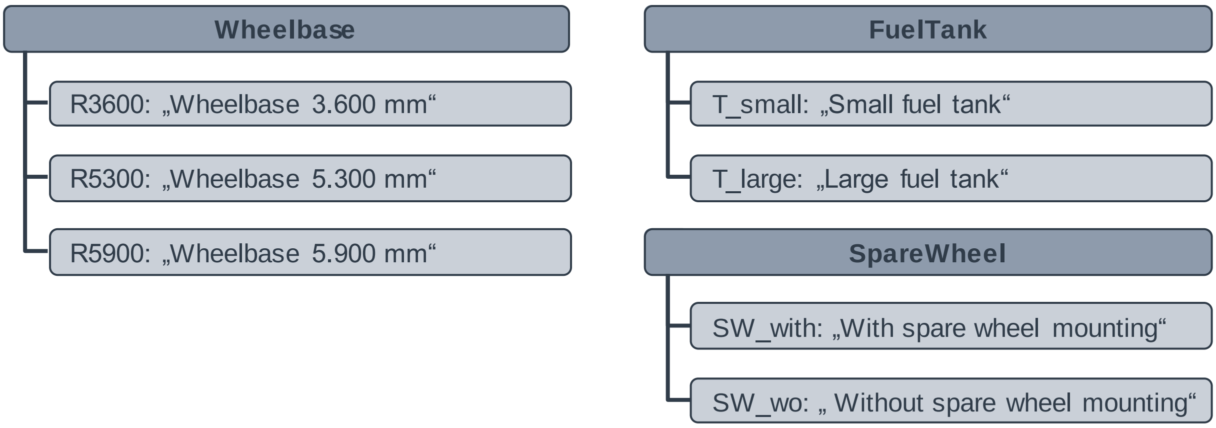


Figure 53: The three feature categories relevant for the bijectivity validation

The possible combinations are dependent on the effect of the configuration rules for features within the portfolio. In this case study, the result of the combination of all these features are eight possible combinations in total. The result generated by the validation algorithms is a response file in the .json-format like before and shown in the following Figure 54.

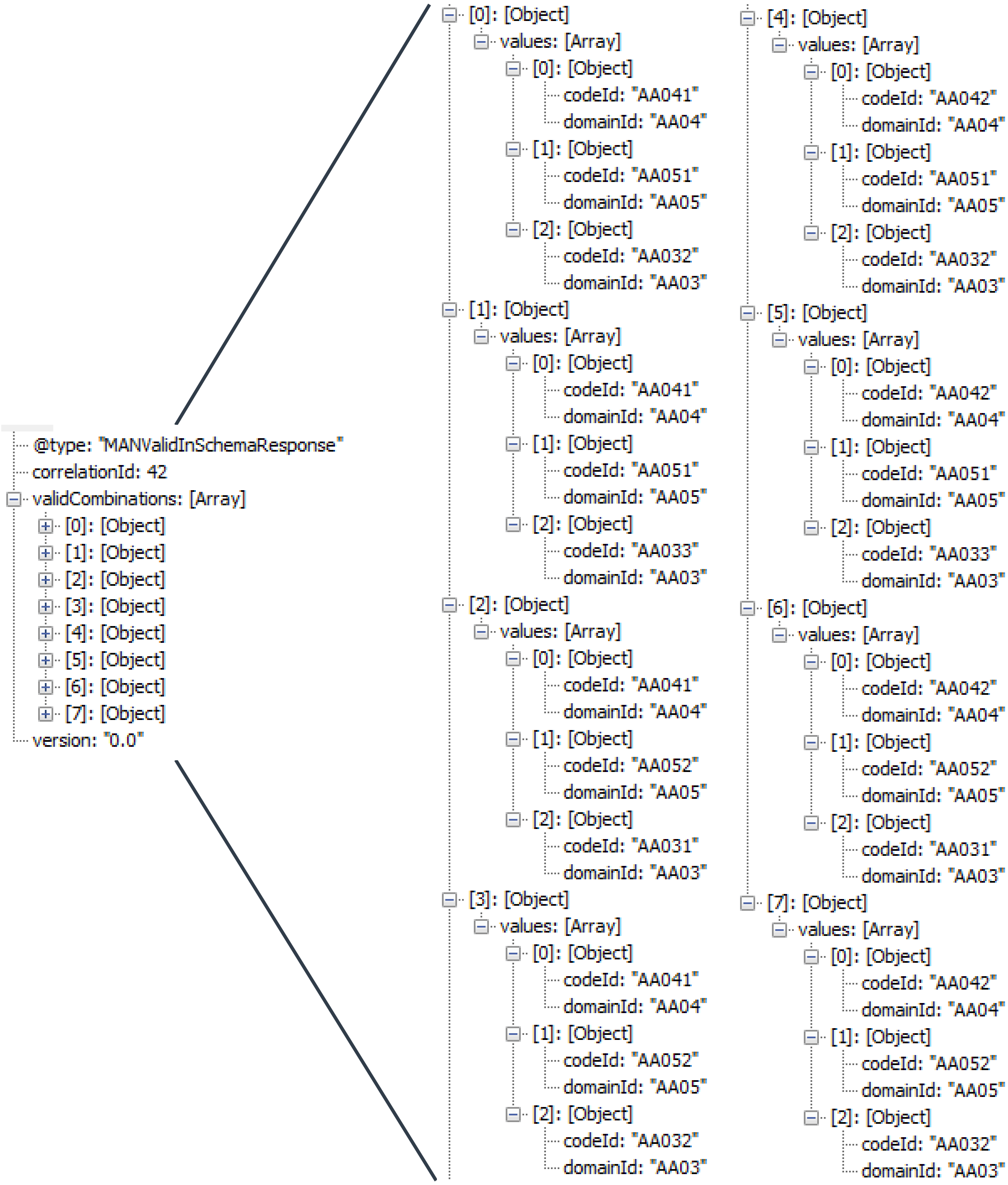


Figure 54: Results of the Bijectivity Validation task

As part of the bijectivity validation, all the possible combinations are now tested against the features of the feature-cluster to check whether they match or not. For a better understanding of the results, the possible combinations are shown with the correct feature names in Table 19 below.

Table 19: Processed result of the Bijectivity Validation task

Possible combinations of features	Corresponding feature cluster
$(T_{small} \wedge SW_{with} \wedge R5300)$	*Layout_SD*
$(T_{small} \wedge SW_{with} \wedge R5900)$	*Layout_SD*
$(T_{small} \wedge SW_{wo} \wedge R3600)$	*Layout_SD*
$(T_{small} \wedge SW_{wo} \wedge R5300)$	*Layout_SD*
$(T_{large} \wedge SW_{with} \wedge R5300)$	*Layout_CD*
$(T_{large} \wedge SW_{with} \wedge R5900)$	*Layout_SD*
$(T_{large} \wedge SW_{wo} \wedge R3600)$	*Layout_CD*
$(T_{large} \wedge SW_{wo} \wedge R5300)$	*Layout_SD*

All the eight possible combinations of features fulfil either the first or second configuration rule of the feature cluster TruckLayout, i.e. can be related uniquely to either the feature *Layout_SD* or *Layout_CD*. Therefore, no error is present within this feature-cluster in the portfolio example.

After this validation task, the second Consistency Validation task can take place. The result of the application of the validation services is again depicted in Figure 55.

@type: "MANBasicValidationResponse"
correlationId: 42
invalidChoices: [Array]
invalidEffectivities: [Array]
version: "0.0"

Figure 55: Results of the second Consistency Validation task

The second Consistency Validation task delivers an empty result, which means that no errors are present within the feature structure anymore. The corrections of the configuration rules, as explained for the first consistency validation in section 5.2.1, was successful and no new errors have been created.

Therefore, this part of the product portfolio is now in a fully valid state in line with the requirements *R.1.1 – Completeness* and *R.1.2 – Unambiguity*.

5.2.3 The Bill-of-Materials validation task

Based on the results from the first three validation tasks above, the Bill-of-Materials validation task can be carried out next. In this validation task, the absence of errors within the Item Usage Rules is validated to fulfil the requirement *R.1.3 – Meaningfulness*. The Bill-of-Materials validation task is applied on all the five items shown before in Figure 47, Figure 48 and Figure 49. The result of the application of the validation services is illustrated in the following Figure 56.

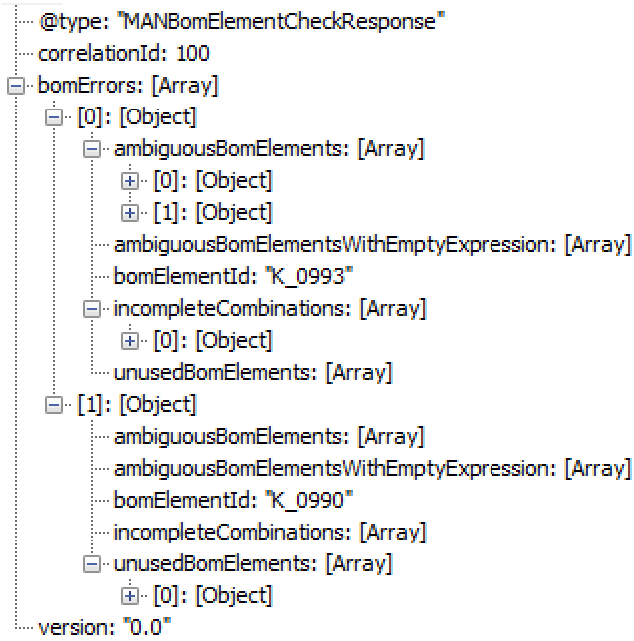


Figure 56: Results of the Bill-of-Materials validation task

Validation errors are found within two different items of the item structure. Based on their ID, these are the following two items: *81#0990: Fuel tank* and *81#0993: First Aid Box*.

The portfolio errors shown in Figure 56 can be classified according to the three error types of Figure 24, the *no-hit error*, the *double-hit error* and the *unassigned item error*. The relation of the responses from this validation task to the three error categories is found in Table 20 below.

Table 20: Categorization of the portfolio errors detected within the BoM-validation task

Error category	Result of the Bill-of-Materials validation
No-hit error	For the following combination of features $(FA_{basic} \vee FA_{fullyLoaded}) \wedge (Switzerland \vee Ukraine)$ $from\ PP201907$ no item of the item category *81#0993: First Aid Box* is selectable
Double-hit error	For the following combination of features $FA_{fullyLoaded} \wedge Brazil\ from\ PP201907$ both the items *81#0993-003: First Aid Box Basic, label Portuguese* and *81#0993-004: First Aid Box Fully loaded, label Portuguese* can be selected For the following combination of features $FA_{wo} \wedge Brazil\ from\ PP201907$ both the items *81#0993-003: First Aid Box Basic, label Portuguese* and *81#0993-000: Without Firs Aid Box* can be selected
Unassigned item error	The item *81#0990-002: Fuel tank small with integr. step tread* is not selectable $from\ PP201801$

For each one of the four portfolio errors above a valid solution has to be found now. This discussion takes place between all relevant stakeholders dealing with the portfolio and its rules who have interests in the part of the portfolio currently being examined, i.e. the items in which errors have been detected. For the scope of this case study, the product architects as well as the construction engineers responsible for the First Aid Box and the Fuel tank have to align with both the representatives responsible for the feature structure, the configuration rules for features and the sales representatives dealing with the precise market requirements. In their discussions they have to sort out whether the feature combination resulting in the No-hit error above in Table 20 should be selectable at all, so that a First Aid Box is required for that design space. Furthermore, they have to agree on which First Aid Box to choose correctly in the double-hit error case and then they have to change the Item Usage Rules accordingly. For the two unassigned item errors, the product architects have to discuss together with sales representatives and the portfolio managers whether the technical solutions should be offered to customers at all.

Then, they have to agree on how to change the configuration rules and item usage rules so that these items can be selected in at least one valid configuration.

Within the case study, this error handling and error resolution process has turned out to be a highly manual process, as it involves a lot of detailed expert discussions and alignments with both the technical and sales-related product portfolio details. Often, the detailed technical plans and drawings need to be studied, sales expectations need to be verified or legal aspects have to be evaluated. Also, this process is hard to standardize as within different corporations, the responsibilities and competencies can be spread differently across the organization.

For the correction of the errors in the case study, the following decisions have been taken:

- To fix the no-hit error, a new configuration rule is written that forbids the selection criteria for this case
- To fix the first double-hit error, the item usage rule of the item *81#0993-003: First Aid Box Basic, label Portuguese* is adjusted so that this item is only chosen when the feature FA_basic is selected. The second double-hit error is solved by this change as well.
- To fix the unassigned item error, either the selection condition can be permitted, or the item has to be removed from the product portfolio. In this case, the alternative solution is to ignore the error and keep the item in the portfolio, as it might be offered at a later point-in-time on the market

After the manual correction of the configuration rules and item usage rules containing errors, the Bill-of-Materials validation job can be carried out successfully when no new errors occur after repeating the Bill-of-Materials validation task. Hereby, the requirement *R.1.3 – Meaningfulness* is fulfilled and the second-last validation task, the Geometry validation can take place.

5.2.4 The Geometry validation task

In the Geometry validation task, the correct geometry and positioning of all items of the item structure is tested, based on the already validated feature structure, the configuration rules for features and the item usage rules. In this case study here the 26 different positions, which are the solution elements with their respective transformations, need to be validated to fulfil the requirement *R.1.4 – Correctness*.

To perform the Geometry validation task, the relevant validation service – the completeness service – is carried out. The result of this algorithmic service, which is similar to the Bill-of-Materials validation task as it is the list of all position items that have either a no-hit error, a double-hit error or an unassigned item error, is shown in Figure 57 below. In total, 21 error messages are provided, which can be classified again according to the error categories as explained in Figure 25.

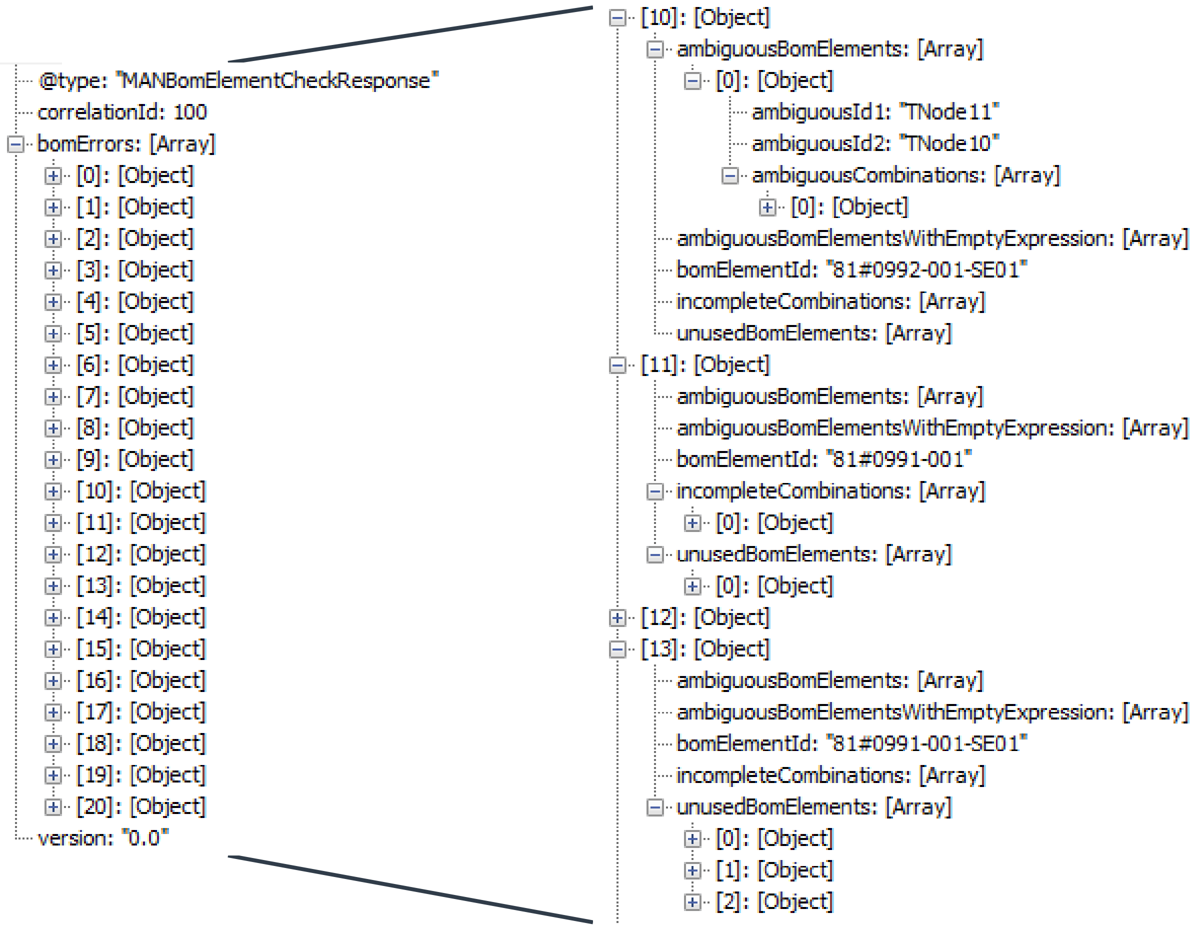


Figure 57: Extract from the response of the Geometry validation task

Due to the way the validation algorithm is configured in this case study, not all of the error messages of the Geometry validation task represent real portfolio errors. The first message relates to the unassigned item that has been accepted as *ok* in the Bill-of-Materials validation and seventeen messages only state that no additional item usage rule for the solution element or transformation is found. If there is only one solution element or transformation present, this is correct as then, the one position is always the right one. In total, three different error messages are relevant concerning the transformations 8*1#0992-001-SE01-Trafo01: Tire Inflation Bottle if no First Aid Box is present* and *81#0992-001-SE01-Trafo02: Tire Inflation Bottle with First Aid Box*, the solution elements *81#0991-001-SE01: SW Mounting – Mounting positioning left* and *81#0991-001-SE02: SW Mounting – Mounting positioning right*.

The classification of the errors along the defined error types leads to the following result shown in Table 21 below.

Table 21: Categorization of the portfolio errors detected within the Geometry-validation task

Error category	Result of the Bill-of-Materials validation
No-hit error	For the following combination of features $(R5300 \vee R5900) \wedge (T_{large}) \wedge (SW_{with})\ from\ PP201801$ no solution element of the item *81#0991-001: Spare Wheel Mounting* is found
Double-hit error	For the following combination of features $(FA_{wo}) \wedge (Switzerland\ \vee Ukraine \vee Brazil)\ from\ PP201801$ both the transformations *81#0992-001-SE01-Trafo01: Tire Inflation Bottle if no First Aid Box is present* and *81#0992-001-SE01-Trafo02: Tire Inflation Bottle with First Aid Box* can be selected
Unassigned item error	The solution element *81#0991-001-SE02: SW Mounting – Mounting positioning right* is not selectable $from\ PP201801$ The transformations *81#0991-001-SE01-Trafo04: SW Mounting – attachment left w/ large fuel tank & WB3.600, 81#0991-001-SE01-Trafo05: SW Mounting – attachment left with large fuel tank and WB 5.300* and *81#0991-001-SE01-Trafo06: SW Mounting – attachment left with large fuel tank and WB 5.900* are not selectable $from\ PP201801$

Based on the results of the Geometry validation task, the identified errors can now be resolved. Again, an expert discussion needs to take place to figure out the correct solutions for these portfolio errors. In terms of the correct positioning and geometry of the items, the focus of the solution teams was directed towards the actual core engineering departments, especially the product architects, the construction engineers and the truck layout and package experts. This is due to the fact that the position is of less relevance for the sales and portfolio management departments but of more relevance for the engineering departments and their requirements.

To fix the identified portfolio errors, the item usage rules for the geometry items need to be adapted so that a valid state is reached:

- To fix the no-hit-error, the item usage rule for the solution element *81#0991-001-SE01: SW Mounting – Mounting positioning left* is adjusted to work for all large fuel tanks.

- To fix the double-hit error, the item usage rule of the transformation *81#0992-001-SE01-Trafo02: Tire Inflation Bottle with First Aid Box* is adjusted so that it is selected for all vehicles with a Tire Inflation Bottle and a First Aid Box, not only if they go to Germany or Austria.
- To fix the first unassigned item error the solution element *81#0991-001-SE02: SW Mounting – Mounting positioning right* can be deleted. The spare wheel is always mounted on the left, as the selection criterion cannot be fulfilled (large fuel tanks are not offered for the wheelbase 3.600 mm)
- The second unassigned item error is corrected by having already changed the item usage rule for correcting the no-hit error

When the error corrections have been carried out correctly and the Geometry validation identifies no errors any more, the fourth requirement *R.1.4. – Correctness* is fulfilled.

According to the procedural model, the Consistency validation task has now to be carried out once more. For the corrected industry example here, no more portfolio errors are identified in the consistency validation. Therefore, all four requirements regarding the validity of a multi-variant product portfolio, *R.1.1 – Completeness, R.1.2 – Unambiguity, R.1.3 – Meaningfulness and R.1.4 – Correctness* have been fulfilled. Thus, the entire product portfolio definition is now in a fully valid state and can be released for series without any restrictions.

5.3 Observations and findings from the case study

The purpose of the case study that was conducted together with the industry partner of this research is to evaluate and validate the applicability of the proposed procedural model outlined in chapter 3. In total, four key observations which are explained further in this section have been made, as illustrated in Figure 58.

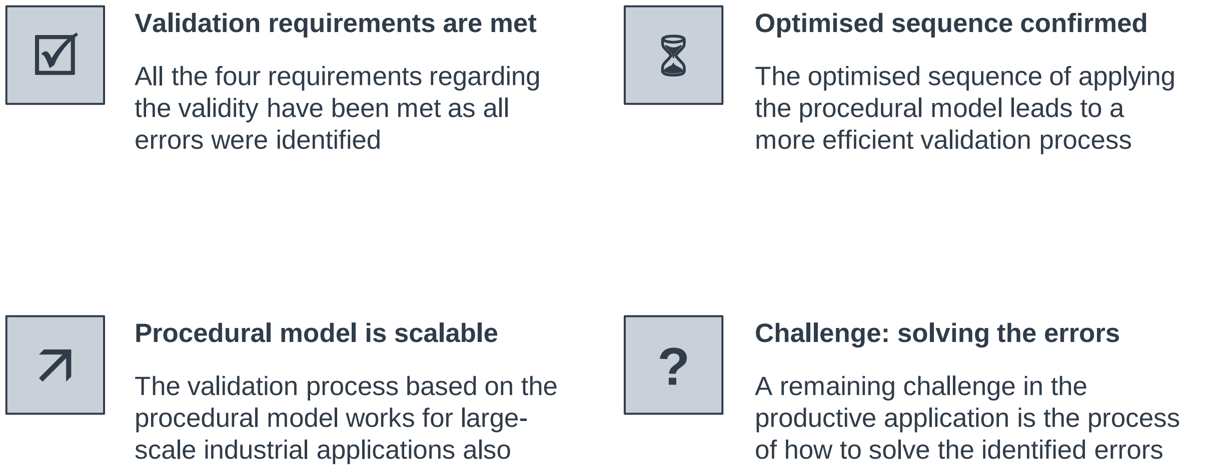


Figure 58: Four key observations based on the case study and real-world application

Validation requirements are met

As the aim of the procedural model is to develop a validation process that ensures overall validity for the entire product portfolio definition, the success of the application needs to be evaluated with regard to the successful fulfilment of the requirements defined upfront.

In terms of the validity of multi-variant product portfolios, the four requirements: *R.1.1 – Completeness, R.1.2 – Unambiguity, R.1.3 – Meaningfulness and R.1.4 – Correctness* have been defined as basis for this research. When applying the procedural model to the product portfolio of the case study, all portfolio errors have been detected in the course of the validation process, as illustrated in Figure 59 below.

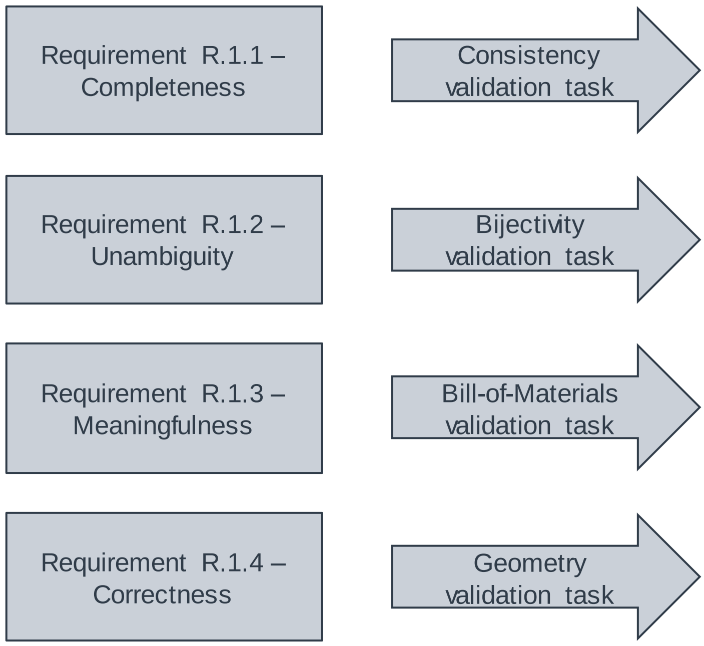


Figure 59: Requirements met when applying the procedural model

With the help of the consistency validation task, six portfolio errors within the feature structure have been identified and corrected. As a result, no unselectable features are present any more in the feature structure. So the requirement *R.1.1 – Completeness,* which is defined as “*All existing features of the products have to be present in the data set, i.e. need to be selectable in a configuration*”, is met and the product portfolio is completely defined and available.

In addition, with the application of the second validation task, the bijectivity validation task, no more errors have been identified in the feature structure and the configuration rules for features. So the second requirement *R.1.2 – Unambiguity,* which is defined as “*No configuration rule must contradict any other rule*”, is also achieved as the product portfolio definition consists of an unambiguous set of portfolio rules.

With the application of the Bill-of-Materials validation task, the objects of the item structure and the item usage rules are taken into consideration. In this step, the four errors in the item usage rules were identified. When correcting these portfolio errors, the third requirement *R.1.3 – Meaningfulness,* which is defined as “*For every complete configuration of properties, a unique Bill-of-Materials exists*”, is met as now exactly one item is found for any configuration of features possible according to the configuration rules.

With the help of the fourth validation task, the Geometry validation, the geometry items are analysed. In this step, ten errors have been found and corrected within the geometry item usage rules. So, the requirement R.1.4 – Correctness is met as well. To fulfil this requirement, any possible configuration within the portfolio has to be buildable in the end. By testing whether every part (i.e. item) for any configuration has an exact positioning and geometry, it is ensured that it can be positioned in the later building process as well.

To sum up, all requirements regarding the validity of the multi-variant product portfolio have been met. Therefore, the proposed procedural model is a valid approach to help structure and support the validation process for these types of product portfolios.

Optimised sequence confirmed

With the optimised sequence of going through the procedural model, seventeen errors in total have been identified and corrected. The whole validation process can also be carried out in the unstructured form of applying the validation tasks without any pre-defined order. To compare the results and show the improved efficiency, an unstructured validation process is also applied to the same portfolio example, in which all validation tasks are carried out parallel to each other. In that case, twenty-seven errors in total have to be dealt with, which leads to a 25 % increased efficiency with the optimized sequence as shown in Figure 60 below.

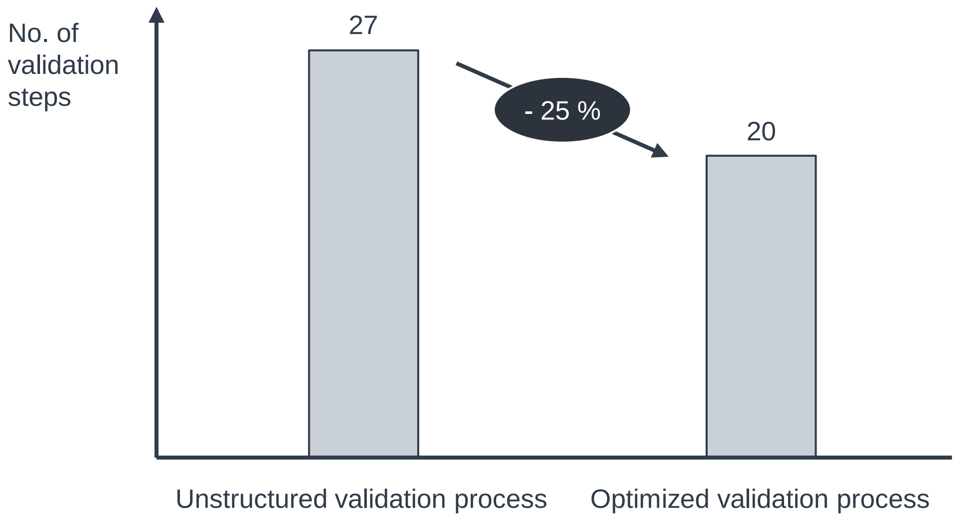


Figure 60: Increased efficiency in the validation process based on the optimised sequence

The smaller number of detected errors is not a sign of a less accurate validation process with the optimised sequence. As explained in chapter 4.2.2 before, errors in the feature structure and the configuration rules for features can trigger subsequent errors the item structure and item usage rules. When the validation process is carried out according to the optimised sequence, these cross-effects can be minimised, which leads to a more focussed error detection and error resolution. Assuming that each error requires the same amount of time to be resolved, the optimised validation process with the application of the procedural model can lead to a 25% higher efficiency in the overall validation process.

Procedural model is scalable

With the help of the case study, the requirements set as the basis of this research could be fulfilled and validated. In the productive, real-world application within the project partner MAN Truck & Bus SE, first approaches of the proposed procedural model could already be implemented and tested: The consistency validation task and the Bill-of-Materials validation task together with a close feedback loop there. The effective product portfolio currently consists of a huge amount of possible variants (~ 10^{300}, as explained earlier on). Also, for such large product portfolios, a validation process can be established and successfully carried out. With the industry project partner, a 99% valid state regarding the item structure and item usage rules can be reached, for example.

Therefore, first insights show that the validation process proposed within the procedural model is also beneficial in an actual application in large-scale and complex, multi-variant product portfolios as they occur for example in the commercial vehicle engineering.

Challenge: solving the errors

One remaining challenge has already become obvious in the course of the execution of the case study: the resolution of the detected errors. In the real-world application with the project partner, this is currently a highly manual process in line with the process described for the case study. Within the manual process, two minor setbacks have been detected. First, it can be difficult to detect the actual root cause of an error when many rules are involved within a large portfolio. Figure 61 shows an example that occurred in a real-world Bill-of-Materials validation task with 30 involved configuration rules resulting in just one error.

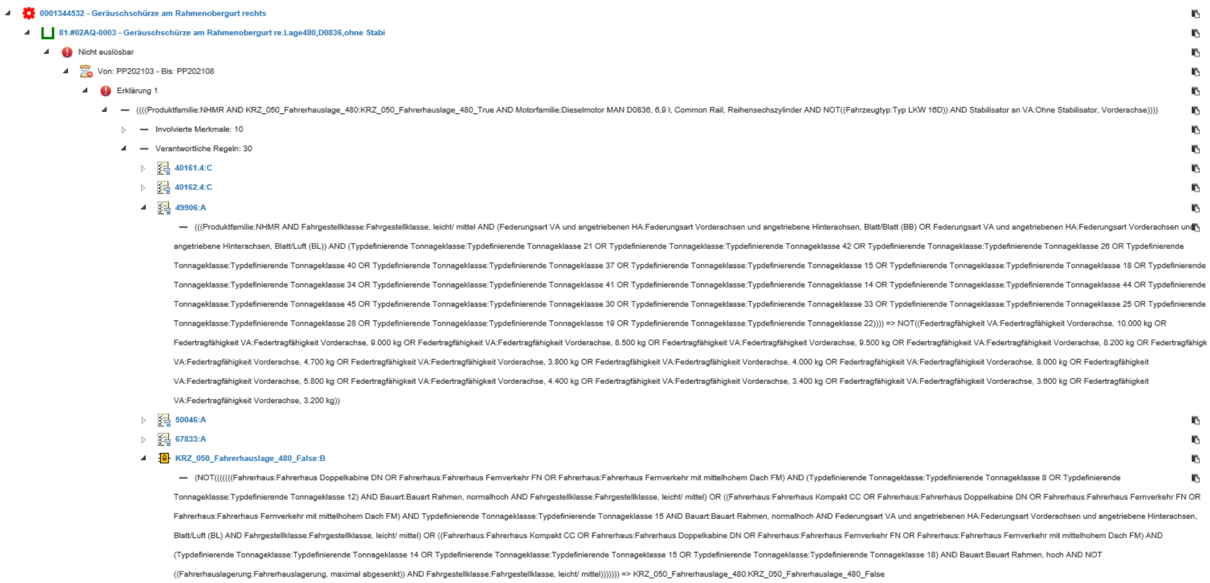


Figure 61: Screenshot of a real-world Bill-of-Materials validation task example

Especially in a textual representation as shown above, it is hard to manually find the actual root cause. Therefore, additional tools need to be developed in the future to both visualise and help analyse the effects and relations of rules within complex, multi-variant product portfolios.

The second drawback is that even if the stakeholders working on the product portfolio definition have identified the error root cause, it can still be hard to identify the right correction within all the ten thousands of rules. The right correction must of course solve the identified portfolio error entirely but without creating any new errors in other parts of the portfolio. Therefore, algorithms and systems automatically proposing possible error resolutions need to be combined with an automated validation process so that correct solutions are directly presented to the relevant decision-makers in the organisation. This is another field of research that should be covered in more detail in the future.

6 Conclusions and outlook

At the beginning of the last chapter of this research, a comprehensive summary of the key results is presented in section 6.1. Based on the results, both the strengths and weaknesses and the implications of the findings for the industrial practice and the scientific research are discussed in the reflection in section 6.2. At the end, in section 6.3, a concise outlook is given to outline the possibilities and needs for further research based on the insights of this research.

6.1 Summary of results

This research is following the four key hypotheses first formulated in chapter 1.3. In this section, the findings and results regarding these four hypotheses are briefly outlined:

- Generic documentation logic and data models for complex, multi-variant product portfolios exist and are frequently used in the industrial practice
- Accepted criteria exist regarding the assessment of data quality that can be adapted for the validation of complex, multi-variant product portfolios
- Approaches for the automated assessment of different part-aspects regarding the validity of a product portfolio exist. Yet, a holistic approach covering all aspects of the validity of product portfolios is missing
- A holistic procedural model can be developed that covers all relevant process steps to achieve entire validity of product portfolios with the help of it-based validation algorithms

In chapter 2.1, different approaches to documenting complex, multi-variant product portfolios have been outlined and examined, for example the SAP iPPE-model or a generalised framework introduced by Tidstam & Malmqvist [34]. All these frameworks and approaches can be generalised with regard to four elements: a feature structure, configuration rules for features, an item structure and item usage rules, as shown in Figure 62 below.

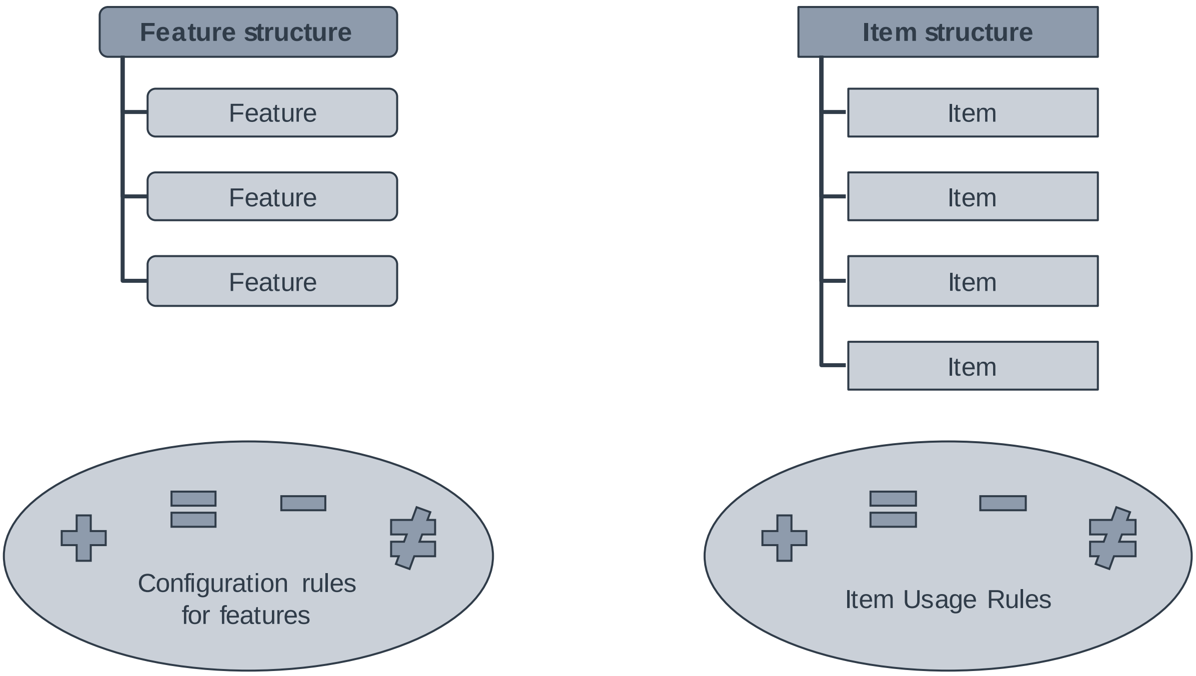


Figure 62: The generalised product portfolio structure found in the industrial application

This archetype of portfolio models has been found in numerous industrial applications, e.g. with Mercedes, Volvo, MAN Truck & Bus and others. As the procedural model proposed in this research relies on the same type of portfolio definitions, it can be generalised and transferred for the application within any organisation working with such a portfolio definition.

In chapter 2.2, different approaches of criteria to assess data quality have been outlined. Based on these general data quality dimensions, four key criteria have been identified that are relevant for the scope of this research. These four criteria have been formulated as the central validation requirements, as described in chapter 3.1:

- *Completeness*: All existing features of the products have to be present in the data set, i.e. need to be selectable in a configuration
- *Unambiguity*: No configuration rule must contradict any other rule
- *Meaningfulness*: For every complete configuration of properties, a unique Bill-of-Materials exists
- *Correctness*: Any possible configuration within the portfolio has to be buildable in the end

Any product portfolio definition following the generalised structure above can be tested against these four criteria. If they are all met, i.e. free of errors, the whole product portfolio definition is in a valid state.

In chapter 2.3, numerous approaches have been presented, starting from the well-known approaches of Sinz [65] to new and more refined validation approaches, e.g. as proposed by Tidstam & Malmqvist [69] or Voronov [70]. A common gap has been found for all these authors and their approaches as none of them either gives a concise definition of what validity means in the terms of product portfolios, or describes how this state can be reached in a detailed process covering all aspects. Therefore, the main scientific contribution of this research is to close this gap by proposing a procedural model that helps to cover all aspects regarding validity and that is usable in the industrial application.

Based on the findings and results with regard to the first three hypotheses, the holistic procedural model to structure the validation process of complex, multi-variant product portfolios is developed, as outlined in detail in chapters 3 and 4 and illustrated in Figure 63 below.

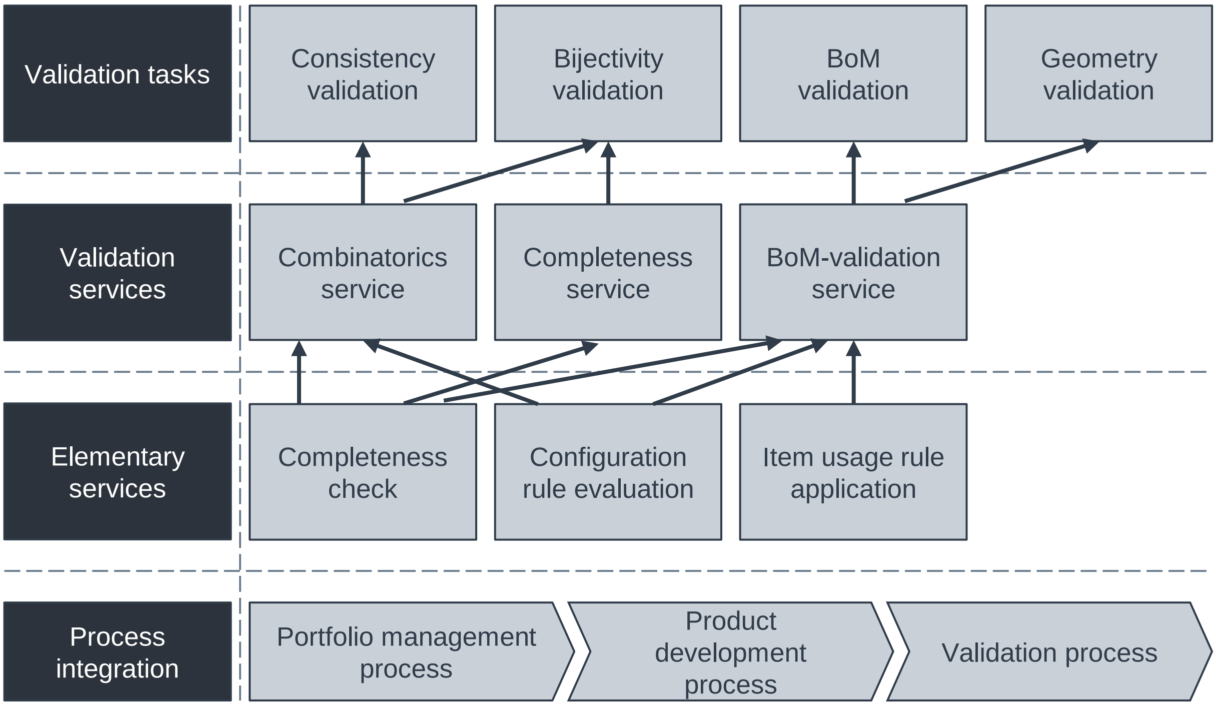


Figure 63: The holistic procedural model proposed in this research

The final, detailed procedural model is then applied to a real-world case study example in the industrial application with the project partner, MAN Truck & Bus SE. Based on the results of this case study, the applicability of the procedural model could be validated.

6.2 Reflection

In this chapter, the contribution this research makes is reflected on to briefly discuss its strengths and weaknesses in section 6.2.1. Furthermore, the implications of this research both on the industry and the scientific research are discussed in sections 6.2.2 and 6.2.3.

6.2.1 Strengths and Weaknesses of the solution

A brief summary of the key strengths and weaknesses of the proposed solution, the application of the procedural model, is depicted in Figure 64.

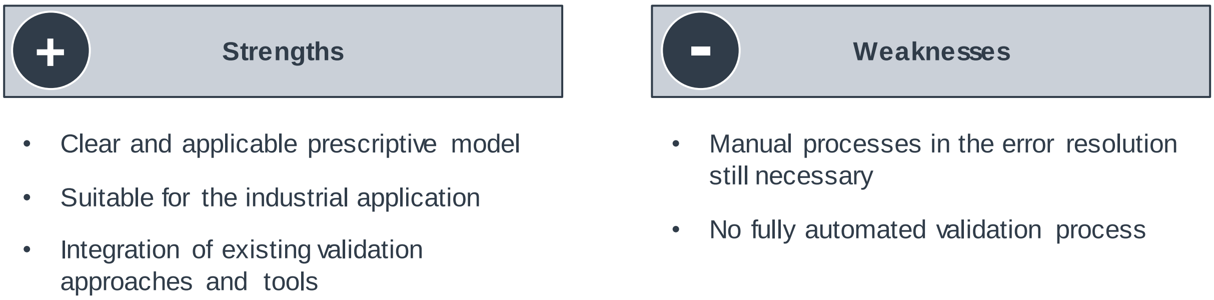


Figure 64: Strengths and weaknesses of the proposed procedural model

One of the key benefits the proposed procedural model offers is that it gives a clear and prescriptive approach to what validity of a multi-variant product portfolio is about and to what measures and processes are to establish to achieve validity regarding all the requirements set before.

Furthermore, the procedural model has proven to be applicable for use cases that actually exist in the industrial application, as briefly outlined in the case study in chapter 5. It is not only theoretically suitable for the industrial application, but has already found its entrance into the product development processes within the industry partner, MAN Truck & Bus SE with significant parts.

Another key strength of the procedural model is that it allows each group of users to integrate their own validation approaches and algorithmic tools. The procedural model only proposes the validation tasks and their sequence, but does not point out how these validation tasks are actually computed from an algorithmic information technology point-of-view. Therefore, all existing solutions that have already been described and developed can be integrated into the procedural model. Thereby, it offers a flexible and adaptable framework for structuring and guiding individual validation processes.

During the validation of the procedural model based on the case study and from the first implementation of parts of the model with the project partner, some weaknesses have already been discovered. One key aspect that leads to difficulties in the actual application is the question of how to actually resolve errors that have been identified. As this is rather easy for simple examples with limited complexity as in the case study, it becomes increasingly difficult for real-world applications in complex portfolios in which ten thousands of rules can be involved. Even though the procedural model helps to identify all errors, which is the necessary first step before resolving them, a challenge still remains on the way to the goal of a fully valid product portfolio.

Additionally, the application of the procedural model does not consist of a fully automated process yet. If the first challenge regarding better visual and algorithmic support on how to fix identified inconsistencies is solved in the future, these approaches can be combined with the procedural model to build an integrated, fully automated validation process. This would give great benefits to the users as it clearly speeds up their whole product development process.

6.2.2 Implications for industry

In the industrial application, two things have been missing so far: a clear vision of the requirements regarding a valid product portfolio and on top of that, an applicable process that guides users and ensures that entire validity is reached for a product portfolio.

This research provides solutions to both key challenges. On the one hand, clear definitions are given of what validity is about in the context of complex, multi-variant product portfolios with the four requirements. On the other hand, the proposed procedural model is actually capable of handling both very large product portfolios as they occur in the real-world application, especially within the commercial vehicle engineering and of giving a detailed prescription of what processes and methodologies need to be implemented in the industrial practice.

As this research relies on a generalised data logic and portfolio model that has been found in many large industry organisations, the proposed procedural model can be transformed to and adapted by a large number of potential users across different industries. Therefore, the procedural model offers valuable input not only for the project partner of this research, but also across borders to other potential users.

6.2.3 Implications for research

For the broader scientific research community, this research contributes to closing the gap between theoretical approaches that have been formulated already early on by different research groups from both the engineering and information scientists' research fields and the industrial application with tangible benefits. Additionally, a contribution to defining the validity of product portfolio definitions is given that might be of use for other researchers as well as dealing with validation challenges. Overall, this research could give new impulses to the scientific research community as only little research has been published covering the aspects of portfolio validity in the last, most recent years. Still a lot of unsolved challenges remain in the industrial application, especially with regard to the gap between theoretical approaches and their practical applicability for the industrial use.

6.3 Outlook

In the context of this research project, three directions for potential future research projects that can build upon this work have been identified and outlined in Figure 65.

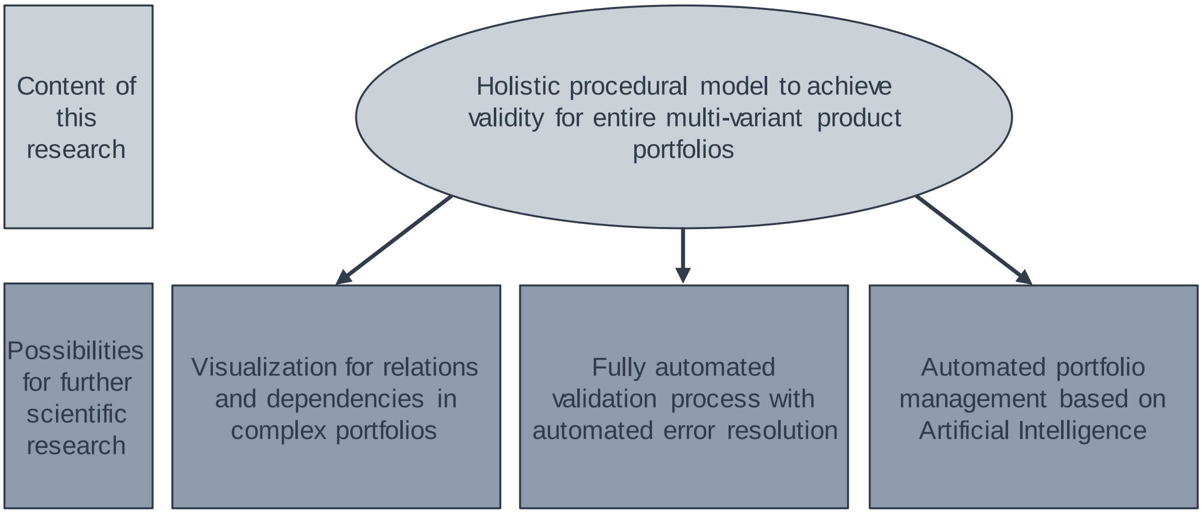


Figure 65: Possibilities for further research derived from this research project

The first potential field of research is the visualization of relations and dependencies of rules and their effects in large and complex portfolios. As seen in the industrial example illustrated in Figure 61 it is hard to analyse dependencies when it comes to very complex and interlinked portfolio errors. Therefore, new ideas, possibly with the help of graph-based visualization techniques, need to be developed to support the users working on these types of product portfolios. Although a lot of research exists on both different visualization techniques and the domain of variant management in general, still specialized approaches for the industrial application are missing.

The second potential field of research is about the development of a fully automated validation process, as explained in chapter 6.2.1 as one of the identified weaknesses. Here the key focus can be on strategies for an automated error resolution for which a close collaboration between engineers and information scientists is required. First approaches exist for example in the context of reconfiguration to reach a valid configuration state again, yet the automated proposal of error fixes within existing portfolio rules seems to be a new domain.

The third potential field of research is the development of an entirely automated portfolio management toolchain, potentially involving the application of artificial intelligence methodologies. In a final expansion stage, an advanced algorithm could be responsible not only for coping with all the validation aspects, but for actually anticipating future customer needs and market trends, deciding on which development projects to start and how to change the product portfolio definition to integrate these new products into the product portfolio.

7 References

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8 Appendix

In the appendix, the original elementary example in the .json format is provided in section 8.1. All the requests and responses to the algorithmic validation services as part of the real-world case study are displayed in the appendix in section 8.2. Finally, the corrected version of the product portfolio example case is displayed in section 8.3 in the appendix.

8.1 The case study example in the original version

In this section of the appendix, the original version of the case study example is shown. It consists of the entire real-world case example in the original, un-modified version. All the portfolio errors are part of this example.

Original example


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    "rootNode": {
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          "children": [
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              "id": "PMOption1",
              "name": "Country",
              "children": [
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```

```
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```

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```

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                  "name": "R3600"
                },
                {
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                  "id": "PMChoice09",
                  "name": "R5300"
                }
              ],
              "operatorType": "OR"
            }
          ],
          "operatorType": "AND"
        }
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                  "id": "PMChoice02",
                  "name": "Austria"
                }
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              "operatorType": "OR"
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          "operatorType": "AND"
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              "name": "RV_02"
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          "operatorType": "AND"
        }
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                    "name": "Switzerland"
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                    "id": "PMChoice04",
                    "name": "Ukraine"
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                    "id": "PMChoice08",
                    "name": "R3600"
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                    }
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                      "id": "PMChoice12",
                      "name": "T_large"
                    },
                    {
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                      "id": "PMChoice13",
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                    }
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                  "operatorType": "AND"
                }
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                  {
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                    "id": "PMChoice02",
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            }
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                    },
                    {
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                      "name": "Austria"
                    }
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                  "operatorType": "OR"
                }
              ],
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                "name": "EU_True"
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                "id": "PMChoice03",
                "name": "Switzerland"
              },
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice04",
                "name": "Ukraine"
              }
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            "operatorType": "OR"
          }
        ],
        "operatorType": "AND"
      }
    ]
  },
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      ]
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                      "name": "EU_True"
                    },
                    {
                      "@type": "AtomicTermNode",
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                      "name": "Switzerland"
                    },
                    {
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                      "id": "PMChoice04",
                      "name": "Ukraine"
                    }
                  ],
                  "operatorType": "OR"
                }
              ],
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          ],
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          }
        ]
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              }
            ],
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          "name": "Elementary example",
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              "id": "PMOption1",
              "name": "Country",
              "children": [
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                  "id": "PMChoice01",
                  "name": "Germany",
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                  "type": "STANDARD",
                  "numericValue": 0
                },
                {
                  "@type": "PMChoice",
                  "id": "PMChoice02",
                  "name": "Austria",
                  "id2": "AA012",
                  "type": "STANDARD",
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        "name": "Ukraine",
        "id2": "AA014",
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        "name": "Brazil",
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        "name": "HG_with",
        "id2": "AA021",
        "type": "STANDARD",
        "numericValue": 0
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        "id": "PMChoice07",
        "name": "HG_wo",
        "id2": "AA022",
        "type": "STANDARD",
        "numericValue": 0
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    "id2": "AA02",
    "type": "STANDARD"
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    "id": "PMOption3",
    "name": "WheelBase",
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        "name": "R3600",
        "id2": "AA031",
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        "id": "PMChoice09",
        "name": "R5300",
        "id2": "AA032",
        "type": "NUMERIC",
        "numericValue": 5300,
        "unitOfNumericValue": "mm"
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        "id": "PMChoice10",
        "name": "R5900",
        "id2": "AA033",
        "type": "NUMERIC",
        "numericValue": 5900,
        "unitOfNumericValue": "mm"
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    ],
    "id2": "AA03",
    "type": "NUMERIC"
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    "id": "PMOption4",
    "name": "FuelTank",
    "children": [
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        "@type": "PMChoice",
        "id": "PMChoice11",
        "name": "T_small",
        "id2": "AA041",
        "type": "STANDARD",
        "numericValue": 0
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        "@type": "PMChoice",
        "id": "PMChoice12",
        "name": "T_large",
        "id2": "AA042",
        "type": "STANDARD",
        "numericValue": 0
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    "type": "STANDARD"
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              "id": "PMChoice13",
              "name": "SW_with",
              "id2": "AA051",
              "type": "STANDARD",
              "numericValue": 0
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              "@type": "PMChoice",
              "id": "PMChoice14",
              "name": "SW_wo",
              "id2": "AA052",
              "type": "STANDARD",
              "numericValue": 0
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          "id": "PMOption6",
          "name": "FirstAidBox",
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              "id": "PMChoice15",
              "name": "FA_wo",
              "id2": "AA061",
              "type": "STANDARD",
              "numericValue": 0
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              "id": "PMChoice16",
              "name": "FA_basic",
              "id2": "AA062",
              "type": "STANDARD",
              "numericValue": 0
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              "id": "PMChoice17",
              "name": "FA_fullyLoaded",
              "id2": "AA063",
              "type": "STANDARD",
              "numericValue": 0
            }
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      "name": "TireInflationBottle",
      "children": [
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          "id": "PMChoice18",
          "name": "TB_with",
          "id2": "AA071",
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          "numericValue": 0
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          "id": "PMChoice19",
          "name": "TB_wo",
          "id2": "AA072",
          "type": "STANDARD",
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      "type": "STANDARD"
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      "id": "PMOption8",
      "name": "SideMarkerLights",
      "children": [
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          "id": "PMChoice20",
          "name": "SL_with",
          "id2": "AA081",
          "type": "STANDARD",
          "numericValue": 0
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          "id": "PMChoice21",
          "name": "SL_wo",
          "id2": "AA082",
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        "name": "RV_01",
        "id2": "AA091",
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        "id": "PMChoice23",
        "name": "RV_02",
        "id2": "AA092",
        "type": "STANDARD",
        "numericValue": 0
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        "id": "PMChoice24",
        "name": "RV_03",
        "id2": "AA093",
        "type": "STANDARD",
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    "type": "STANDARD"
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    "id": "PMOption10",
    "name": "TruckLayout",
    "children": [
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        "@type": "PMChoice",
        "id": "PMChoice25",
        "name": "Layout_CD",
        "id2": "AA101",
        "type": "STANDARD",
        "numericValue": 0
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        "@type": "PMChoice",
        "id": "PMChoice26",
        "name": "Layout_SD",
        "id2": "AA102",
        "type": "STANDARD",
        "numericValue": 0
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    "id2": "AA10",
    "type": "STANDARD"
  },
  {
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            "name": "EU",
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                "id": "PMChoice27",
                "name": "EU_True",
                "id2": "AA111",
                "type": "STANDARD",
                "numericValue": 0
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                "id": "PMChoice28",
                "name": "EU_TruEU_Falsee",
                "id2": "AA112",
                "type": "STANDARD",
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            "name": "Europe",
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                "@type": "PMChoice",
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                "name": "Europe_True",
                "id2": "AA121",
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              {
                "@type": "PMChoice",
                "id": "PMChoice30",
                "name": "Europe_False",
                "id2": "AA122",
                "type": "STANDARD",
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            ],
            "id2": "AA12",
            "type": "STANDARD"
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    ]
  },
  "name": "Elementary_Example"
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"productStructureTrees": [
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    "id": "Merged_Product_Structure",
    "name": "Merged Product Structure",
    "children": [
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        "@type": "KNode",
        "id": "KNode1",
        "name": "Fuel tank",
        "children": [
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            "@type": "KVNode",
            "id": "KVNode01",
            "name": "Fuel tank small",
            "children": [
              {
                "@type": "LENode",
                "id": "LENode01",
                "name": "Fuel tank small",
                "children": [
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                    "id": "TNode01",
                    "name": "Fuel tank small",
                    "oid": "TNode01",
                    "container": "Elementary Example",
                    "selectionRuleVersions": [
                    ]
                  }
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                "container": "Elementary Example",
                "manNumber": "81#0990-001-SE01",
                "selectionRuleVersions": [
                ]
              }
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            "container": "Elementary Example",
            "manNumber": "81#0990-001",
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                "id": "81#0990-001-TAR",
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                  "children": [
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                      "id": "PMChoice11",
                      "name": "T_small"
                    },
                    {
                      "@type": "OperatorNode",
                      "children": [
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```
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice25",
                "name": "Layout_CD"
              }
            ],
            "operatorType": "NOT"
          }
        ],
        "operatorType": "AND"
      },
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      "versionSortId": 1,
      "status": "Released",
      "startPP": "PP201801",
      "endPP": "PP203001"
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        "children": [
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            "id": "PMChoice11",
            "name": "T_small"
          },
          {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice25",
                "name": "Layout_CD"
              }
            ],
            "operatorType": "NOT"
          }
        ],
        "operatorType": "AND"
      },
      "version": "A",
      "versionSortId": 1,
      "status": "Released",
      "startPP": "PP201801",
      "endPP": "PP203001"
    }
  ]
},
{
  "@type": "KVNode",
  "id": "KVNode02",
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                    "name": "Fuel tank small with integrated step
tread",
                    "children": [
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                        "id": "LENode02",
                        "name": "Fuel tank small with integrated step
                         tread",
                        "children": [
                          {
                            "@type": "TNode",
                            "id": "TNode02",
                            "name": "Fuel tank small with integrated
                            step tread",
                            "oid": "TNode02",
                            "container": "Elementary Example",
                            "selectionRuleVersions": [

                            ]
                          }
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                              "@type": "AtomicTermNode",
                              "id": "PMChoice11",
                              "name": "T_small"
                            },
                            {
                              "@type": "AtomicTermNode",
                              "id": "PMChoice25",
                              "name": "Layout_CD"
                            }
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                        "version": "A",
                        "versionSortId": 1,
                        "status": "Released",
                        "startPP": "PP201801",
                        "endPP": "PP203001"
                      }
```

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                  "@type": "AtomicTermNode",
                  "id": "PMChoice11",
                  "name": "T_small"
                },
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice25",
                  "name": "Layout_CD"
                }
              ],
              "operatorType": "AND"
            },
            "version": "A",
            "versionSortId": 1,
            "status": "Released",
            "startPP": "PP201801",
            "endPP": "PP203001"
          }
        ]
      },
      {
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        "id": "KVNode03",
        "name": "Fuel tank large",
        "children": [
          {
            "@type": "LENode",
            "id": "LENode03",
            "name": "Fuel tank large",
            "children": [
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                "name": "Fuel tank large",
                "oid": "TNode03",
                "container": "Elementary Example",
                "selectionRuleVersions": [

                ]
              }
            ],
            "oid": "LENode03",
            "container": "Elementary Example",
            "manNumber": "81#0990-003-SE01",
            "selectionRuleVersions": [

            ]
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"container": "Elementary Example",
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      "children": [
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          "@type": "AtomicTermNode",
          "id": "PMChoice12",
          "name": "T_large"
        },
        {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "AtomicTermNode",
              "id": "PMChoice25",
              "name": "Layout_CD"
            }
          ],
          "operatorType": "NOT"
        }
      ],
      "operatorType": "AND"
    },
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    "versionSortId": 1,
    "status": "Released",
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    "endPP": "PP203001"
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      "children": [
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          "id": "PMChoice12",
          "name": "T_large"
        },
        {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "AtomicTermNode",
              "id": "PMChoice25",
              "name": "Layout_CD"
```

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                }
              ],
              "operatorType": "NOT"
            }
          ],
          "operatorType": "AND"
        },
        "version": "A",
        "versionSortId": 1,
        "status": "Released",
        "startPP": "PP201801",
        "endPP": "PP203001"
      }
    ]
  },
  {
    "@type": "KVNode",
    "id": "KVNode04",
    "name": "Fuel tank large with integrated step
    tread",
    "children": [
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        "id": "LENode04",
        "name": "Fuel tank large with integrated step
         tread",
        "children": [
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            "id": "TNode04",
            "name": "Fuel tank large with integr. Step
            tread",
            "oid": "TNode04",
            "container": "Elementary Example",
            "selectionRuleVersions": [

            ]
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        "selectionRuleVersions": [

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    "container": "Elementary Example",
    "manNumber": "81#0990-004",
    "tarVersions": [
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          "children": [
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                  "id": "PMChoice12",
                  "name": "T_large"
                },
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice25",
                  "name": "Layout_CD"
                }
              ],
              "operatorType": "AND"
            }
          ],
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        },
        "version": "A",
        "versionSortId": 1,
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        "endPP": "PP203001"
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              "children": [
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                  "id": "PMChoice12",
                  "name": "T_large"
                },
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice25",
                  "name": "Layout_CD"
                }
              ],
              "operatorType": "AND"
            }
          ],
          "operatorType": "AND"
        },
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        "versionSortId": 1,
        "status": "Released",
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            "endPP": "PP203001"
          }
        ]
      }
    ],
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    "oid": "81#0990",
    "id2": "0990"
  },
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    "id": "KNode2",
    "name": "Spare Wheel",
    "children": [
      {
        "@type": "KVNode",
        "id": "KVNode05",
        "name": "Without Spare Wheel Mounting",
        "oid": "KVNode05",
        "container": "Elementary Example",
        "manNumber": "81#0991-000",
        "tarVersions": [
          {
            "id": "81#0991-000",
            "ruleTree": {
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              "children": [
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice14",
                  "name": "SW_wo"
                }
              ],
              "operatorType": "AND"
            },
            "version": "A",
            "versionSortId": 1,
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            "endPP": "PP203001"
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              "children": [
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                  "@type": "AtomicTermNode",
                  "id": "PMChoice14",
                  "name": "SW_wo"
                }
              ],
              "operatorType": "AND"
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        "version": "A",
        "versionSortId": 1,
        "status": "Released",
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        "endPP": "PP203001"
      }
    ]
  },
  {
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    "id": "KVNode06",
    "name": "Spare Wheel Mounting",
    "children": [
      {
        "@type": "LENode",
        "id": "LENode05",
        "name": "SW Mounting - Mounting positioning
        left",
        "children": [
          {
            "@type": "TNode",
            "id": "TNode05",
            "name": "SW Mounting - attachment left with
            small fuel tank",
            "oid": "TNode05",
            "container": "Elementary Example",
            "selectionRuleVersions": [
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                "id": "TNode05-TRAFO",
                "ruleTree": {
                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice11",
                      "name": "T_small"
                    }
                  ],
                  "operatorType": "AND"
                },
                "version": "A",
                "versionSortId": 1,
                "status": "Released",
                "startPP": "PP201801",
                "endPP": "PP203001"
              }
            ]
          },
          {
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            "id": "TNode06",
            "name": "SW Mounting - attachmentleft with
            large fuel tank and WB 3.600",
            "oid": "TNode06",
            "container": "Elementary Example",
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                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice12",
                      "name": "T_large"
                    },
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice08",
                      "name": "R3600"
                    }
                  ],
                  "operatorType": "AND"
                }
              ],
              "operatorType": "AND"
            },
            "version": "A",
            "versionSortId": 1,
            "status": "Released",
            "startPP": "PP201801",
            "endPP": "PP203001"
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        ]
      },
      {
        "@type": "TNode",
        "id": "TNode07",
        "name": "SW Mounting - attachmentleft with
        large fuel tank and WB 5.300",
        "oid": "TNode07",
        "container": "Elementary Example",
        "selectionRuleVersions": [
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                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice12",
                      "name": "T_large"
                    },
                    {
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```
                "id": "PMChoice09",
                "name": "R5300"
              }
            ],
            "operatorType": "AND"
          }
        ],
        "operatorType": "AND"
      },
      "version": "A",
      "versionSortId": 1,
      "status": "Released",
      "startPP": "PP201801",
      "endPP": "PP203001"
    }
  ]
},
{
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  "id": "TNode08",
  "name": "SW Mounting - attachmentleft with
  large fuel tank and WB 5.900",
  "oid": "TNode08",
  "container": "Elementary Example",
  "selectionRuleVersions": [
    {
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      "ruleTree": {
        "@type": "OperatorNode",
        "children": [
          {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice12",
                "name": "T_large"
              },
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice10",
                "name": "R5900"
              }
            ],
            "operatorType": "AND"
          }
        ],
        "operatorType": "AND"
      },
      "version": "A",
      "versionSortId": 1,
      "status": "Released",
      "startPP": "PP201801",
      "endPP": "PP203001"
    }
  ]
```

```
        }
      ],
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      "container": "Elementary Example",
      "manNumber": "81#0991-001-SE01",
      "selectionRuleVersions": [
        {
          "id": "81#0991-001-SE01-AAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "OperatorNode",
                    "children": [
                      {
                        "@type": "AtomicTermNode",
                        "id": "PMChoice08",
                        "name": "R3600"
                      },
                      {
                        "@type": "AtomicTermNode",
                        "id": "PMChoice12",
                        "name": "T_large"
                      }
                    ],
                    "operatorType": "OR"
                  }
                ],
                "operatorType": "NOT"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    },
    {
      "@type": "LENode",
      "id": "LENode06",
      "name": "SW Mounting - Mounting positioning
       right",
      "children": [
        {
          "@type": "TNode",
          "id": "TNode09",
          "name": "SW Mounting attachment right",
          "oid": "TNode09",
          "container": "Elementary Example",
```

```
            "selectionRuleVersions": [

            ]
          }
        ],
        "oid": "81#0991-001-SE02",
        "container": "Elementary Example",
        "manNumber": "81#0991-001-SE02",
        "selectionRuleVersions": [
          {
            "id": "81#0991-001-SE02-AAR",
            "ruleTree": {
              "@type": "OperatorNode",
              "children": [
                {
                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice08",
                      "name": "R3600"
                    },
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice12",
                      "name": "T_large"
                    }
                  ],
                  "operatorType": "AND"
                }
              ],
              "operatorType": "AND"
            },
            "version": "A",
            "versionSortId": 1,
            "status": "Released",
            "startPP": "PP201801",
            "endPP": "PP203001"
          }
        ]
      }
    ],
    "oid": "81#0991-001",
    "container": "Elementary Example",
    "manNumber": "81#0991-001",
    "tarVersions": [
      {
        "id": "81#0991-001-TAR",
        "ruleTree": {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "AtomicTermNode",
              "id": "PMChoice13",
              "name": "SW_with"
            }
```

```
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ],
      "id2": "81#0991-001",
      "selectionRuleVersions": [
        {
          "id": "81#0991-001-TAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice13",
                "name": "SW_with"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    }
  ],
  "crossTreeUid": "81#0991",
  "oid": "81#0991",
  "id2": "0991"
},
{
  "@type": "KNode",
  "id": "KNode3",
  "name": "Tire Inflation Bottle",
  "children": [
    {
      "@type": "KVNode",
      "id": "KVNode07",
      "name": "Without Tire Inflation Bottle",
      "oid": "KVNode07",
      "container": "Elementary Example",
      "manNumber": "81#0992-000",
      "tarVersions": [
        {
          "id": "81#0992-000-TAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
```

```
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice19",
                "name": "TB_wo"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ],
      "id2": "81#0992-000",
      "selectionRuleVersions": [
        {
          "id": "81#0992-000-TAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice19",
                "name": "TB_wo"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    },
    {
      "@type": "KVNode",
      "id": "KVNode08",
      "name": "Tire Inflation Bottle",
      "children": [
        {
          "@type": "LENode",
          "id": "LENode07",
          "name": "Tire Inflation Bottle",
          "children": [
            {
              "@type": "TNode",
              "id": "TNode10",
              "name": "Tire Inflation Bottle if no First
              Aid Box is present",
              "oid": "TNode10",
              "container": "Elementary Example",
              "selectionRuleVersions": [
```

```
        {
          "id": "TNode10-TRAFO",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice15",
                "name": "FA_wo"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    },
    {
      "@type": "TNode",
      "id": "TNode11",
      "name": "Tire Inflation Bottle with First
      Aid Box ",
      "oid": "TNode11",
      "container": "Elementary Example",
      "selectionRuleVersions": [
        {
          "id": "TNode11-TRAFO",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "OperatorNode",
                    "children": [
                      {
                        "@type": "AtomicTerm
                        Node",
                        "id": "PMChoice15",
                        "name": "FA_wo"
                      },
                      {
                        "@type": "OperatorNode",
                        "children": [
                          {
                            "@type": "AtomicTerm
                             Node",
                            "id": "PMChoice01",
                            "name": "Germany"
                          },
                          {
```

```
                                          "@type": "AtomicTerm
                                           Node",
                                          "id": "PMChoice02",
                                          "name": "Austria"
                                        }
                                      ],
                                      "operatorType": "OR"
                                    }
                                  ],
                                  "operatorType": "AND"
                                }
                              ],
                              "operatorType": "NOT"
                            }
                          ],
                          "operatorType": "AND"
                        },
                        "version": "A",
                        "versionSortId": 1,
                        "status": "Released",
                        "startPP": "PP201801",
                        "endPP": "PP203001"
                      }
                    ]
                  }
                ],
                "oid": "81#0992-001-SE01",
                "container": "Elementary Example",
                "manNumber": "81#0992-001-SE01",
                "selectionRuleVersions": [

                ]
              }
            ],
            "oid": "81#0992-001",
            "container": "Elementary Example",
            "manNumber": "81#0992-001",
            "tarVersions": [
              {
                "id": "81#0992-001-TAR",
                "ruleTree": {
                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice18",
                      "name": "TB_with"
                    }
                  ],
                  "operatorType": "AND"
                },
                "version": "A",
                "versionSortId": 1,
                "status": "Released",
                "startPP": "PP201801",
                "endPP": "PP203001"
```

```
            }
          ],
          "id2": "81#0992-001",
          "selectionRuleVersions": [
            {
              "id": "81#0992-001-TAR",
              "ruleTree": {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice18",
                    "name": "TB_with"
                  }
                ],
                "operatorType": "AND"
              },
              "version": "A",
              "versionSortId": 1,
              "status": "Released",
              "startPP": "PP201801",
              "endPP": "PP203001"
            }
          ]
        }
      ],
      "crossTreeUid": "81#0992",
      "oid": "81#0992",
      "id2": "0992"
    },
    {
      "@type": "KNode",
      "id": "KNode4",
      "name": "First Aid Box",
      "children": [
        {
          "@type": "KVNode",
          "id": "KVNode09",
          "name": "Without First Aid Box",
          "oid": "KVNode09",
          "container": "Elementary Example",
          "manNumber": "81#0993-000",
          "tarVersions": [
            {
              "id": "81#0993-000-TAR",
              "ruleTree": {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice15",
                    "name": "FA_wo"
                  }
                ],
                "operatorType": "AND"
              },
```

```
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ],
      "id2": "81#0993-000",
      "selectionRuleVersions": [
        {
          "id": "81#0993-000-TAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice15",
                "name": "FA_wo"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    },
    {
      "@type": "KVNode",
      "id": "KVNode10",
      "name": "First Aid Box Basic, label German",
      "children": [
        {
          "@type": "LENode",
          "id": "LENode08",
          "name": "First Aid Box Basic, label German",
          "children": [
            {
              "@type": "TNode",
              "id": "TNode12",
              "name": "First Aid Box Basic, label Ge
              man",
              "oid": "TNode12",
              "container": "Elementary Example",
              "selectionRuleVersions": [

              ]
            }
          ],
          "oid": "LENode08",
          "container": "Elementary Example",
          "manNumber": "81#0993-001-SE01",
          "selectionRuleVersions": [
```

```
        ]
      }
    ],
    "oid": "KVNode10",
    "container": "Elementary Example",
    "manNumber": "81#0993-001",
    "tarVersions": [
      {
        "id": "81#0993-001-TAR",
        "ruleTree": {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "OperatorNode",
              "children": [
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice16",
                  "name": "FA_basic"
                },
                {
                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice01",
                      "name": "Germany"
                    },
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice02",
                      "name": "Austria"
                    }
                  ],
                  "operatorType": "OR"
                }
              ],
              "operatorType": "AND"
            }
          ],
          "operatorType": "AND"
        },
        "version": "A",
        "versionSortId": 1,
        "status": "Released",
        "startPP": "PP201801",
        "endPP": "PP203001"
      }
    ],
    "id2": "81#0993-001",
    "selectionRuleVersions": [
      {
        "id": "81#0993-001-TAR",
        "ruleTree": {
          "@type": "OperatorNode",
```

```
        "children": [
          {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice16",
                "name": "FA_basic"
              },
              {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice01",
                    "name": "Germany"
                  },
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice02",
                    "name": "Austria"
                  }
                ],
                "operatorType": "OR"
              }
            ],
            "operatorType": "AND"
          }
        ],
        "operatorType": "AND"
      },
      "version": "A",
      "versionSortId": 1,
      "status": "Released",
      "startPP": "PP201801",
      "endPP": "PP203001"
    }
  ]
},
{
  "@type": "KVNode",
  "id": "KVNode11",
  "name": "First Aid Box Fully loaded, label German",
  "children": [
    {
      "@type": "LENode",
      "id": "LENode09",
      "name": "First Aid Box Fully loaded, label Ger
       man",
      "children": [
        {
          "@type": "TNode",
          "id": "TNode13",
          "name": "First Aid Box Fully loaded, label
          German",
          "oid": "TNode13",
```

```
          "container": "Elementary Example",
          "selectionRuleVersions": [

          ]
        }
      ],
      "oid": "LENode09",
      "container": "Elementary Example",
      "manNumber": "81#0993-002-SE01",
      "selectionRuleVersions": [

      ]
    }
  ],
  "oid": "KVNode11",
  "container": "Elementary Example",
  "manNumber": "81#0993-002",
  "tarVersions": [
    {
      "id": "81#0993-002-TAR",
      "ruleTree": {
        "@type": "OperatorNode",
        "children": [
          {
            "@type": "OperatorNode",
            "children": [
              {
                "@type": "AtomicTermNode",
                "id": "PMChoice17",
                "name": "FA_fullyLoaded"
              },
              {
                "@type": "OperatorNode",
                "children": [
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice01",
                    "name": "Germany"
                  },
                  {
                    "@type": "AtomicTermNode",
                    "id": "PMChoice02",
                    "name": "Austria"
                  }
                ],
                "operatorType": "OR"
              }
            ],
            "operatorType": "AND"
          }
        ],
        "operatorType": "AND"
      },
      "version": "A",
      "versionSortId": 1,
      "status": "Released",
```

```
        "startPP": "PP201801",
        "endPP": "PP203001"
      }
    ],
    "id2": "81#0993-002",
    "selectionRuleVersions": [
      {
        "id": "81#0993-002-TAR",
        "ruleTree": {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "OperatorNode",
              "children": [
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice17",
                  "name": "FA_fullyLoaded"
                },
                {
                  "@type": "OperatorNode",
                  "children": [
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice01",
                      "name": "Germany"
                    },
                    {
                      "@type": "AtomicTermNode",
                      "id": "PMChoice02",
                      "name": "Austria"
                    }
                  ],
                  "operatorType": "OR"
                }
              ],
              "operatorType": "AND"
            }
          ],
          "operatorType": "AND"
        },
        "version": "A",
        "versionSortId": 1,
        "status": "Released",
        "startPP": "PP201801",
        "endPP": "PP203001"
      }
    ]
  },
  {
    "@type": "KVNode",
    "id": "KVNode12",
    "name": "First Aid Box Basic, label Portuguese",
    "children": [
      {
        "@type": "LENode",
```

```
    "id": "LENode10",
    "name": "First Aid Box Basic, label Portu
     guese",
    "children": [
      {
        "@type": "TNode",
        "id": "TNode14",
        "name": "First Aid Box Basic, label Portu
        guese",
        "oid": "TNode14",
        "container": "Elementary Example",
        "selectionRuleVersions": [

        ]
      }
    ],
    "oid": "LENode10",
    "container": "Elementary Example",
    "manNumber": "81#0993-003-SE01",
    "selectionRuleVersions": [

    ]
  }
],
"oid": "KVNode12",
"container": "Elementary Example",
"manNumber": "81#0993-003",
"tarVersions": [
  {
    "id": "81#0993-003-TAR",
    "ruleTree": {
      "@type": "OperatorNode",
      "children": [
        {
          "@type": "AtomicTermNode",
          "id": "PMChoice05",
          "name": "Brazil"
        }
      ],
      "operatorType": "AND"
    },
    "version": "A",
    "versionSortId": 1,
    "status": "Released",
    "startPP": "PP201801",
    "endPP": "PP203001"
  }
],
"id2": "81#0993-003",
"selectionRuleVersions": [
  {
    "id": "81#0993-003-TAR",
    "ruleTree": {
      "@type": "OperatorNode",
      "children": [
        {
```

```
                "@type": "AtomicTermNode",
                "id": "PMChoice05",
                "name": "Brazil"
              }
            ],
            "operatorType": "AND"
          },
          "version": "A",
          "versionSortId": 1,
          "status": "Released",
          "startPP": "PP201801",
          "endPP": "PP203001"
        }
      ]
    },
    {
      "@type": "KVNode",
      "id": "KVNode13",
      "name": "First Aid Box Fully loaded, label Portu
      guese",
      "children": [
        {
          "@type": "LENode",
          "id": "LENode11",
          "name": "First Aid Box Fully loaded, label Por
           tuguese",
          "children": [
            {
              "@type": "TNode",
              "id": "TNode15",
              "name": "First Aid Box Fully loaded, label
              Portuguese",
              "oid": "TNode15",
              "container": "Elementary Example",
              "selectionRuleVersions": [

              ]
            }
          ],
          "oid": "LENode11",
          "container": "Elementary Example",
          "manNumber": "81#0993-004-SE01",
          "selectionRuleVersions": [

          ]
        }
      ],
      "oid": "KVNode13",
      "container": "Elementary Example",
      "manNumber": "81#0993-004",
      "tarVersions": [
        {
          "id": "81#0993-004-TAR",
          "ruleTree": {
            "@type": "OperatorNode",
            "children": [
```

```
            {
              "@type": "OperatorNode",
              "children": [
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice17",
                  "name": "FA_fullyLoaded"
                },
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice05",
                  "name": "Brazil"
                }
              ],
              "operatorType": "AND"
            }
          ],
          "operatorType": "AND"
        },
        "version": "A",
        "versionSortId": 1,
        "status": "Released",
        "startPP": "PP201801",
        "endPP": "PP203001"
      }
    ],
    "id2": "81#0993-004",
    "selectionRuleVersions": [
      {
        "id": "81#0993-004-TAR",
        "ruleTree": {
          "@type": "OperatorNode",
          "children": [
            {
              "@type": "OperatorNode",
              "children": [
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice17",
                  "name": "FA_fullyLoaded"
                },
                {
                  "@type": "AtomicTermNode",
                  "id": "PMChoice05",
                  "name": "Brazil"
                }
              ],
              "operatorType": "AND"
            }
          ],
          "operatorType": "AND"
        },
        "version": "A",
        "versionSortId": 1,
        "status": "Released",
        "startPP": "PP201801",
```

```
                        "endPP": "PP203001"
                      }
                    ]
                  }
                ],
                "crossTreeUid": "81#0993",
                "oid": "81#0993",
                "id2": "0993"
              }
            ]
          }
        }
      ]
    }
  ]
}
```

8.2 The requests and responses of the validation services

In this chapter, the requests and responses of the algorithmic validation services are displayed, as used in the real-world case example.

8.2.1 The first consistency validation task – request and response

Request


```
{
      "preAssignments": {
            "expression": {
                  "@type": "and",
                  "andExps": []
            },
            "range": {
                  "from": "PP201801",
                  "to": "PP202110"
            }
      },
      "productKey": {
            "relativeFilePath": "example_2.json",
            "preferNumericId": true
      },
      "version": "0.0",
      "@type": "MANBasicValidationRequest",
      "correlationId": 42,
      "checkRange": {
            "from": "PP201801",
            "to": "PP202110"
      }
}
```


Response


```
{
    "@type": "MANBasicValidationResponse",
    "correlationId": 42,
    "invalidChoices": [
        {
            "expression": {
                "@type": "symbol",
                "codeId": "AA013",
                "domainId": "AA01"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        },
        {
            "expression": {
                "@type": "symbol",
```

```
                "codeId": "AA014",
                "domainId": "AA01"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        },
        {
            "expression": {
                "@type": "symbol",
                "codeId": "AA015",
                "domainId": "AA01"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        },
        {
            "expression": {
                "@type": "symbol",
                "codeId": "AA061",
                "domainId": "AA06"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        },
        {
            "expression": {
                "@type": "symbol",
                "codeId": "AA122",
                "domainId": "AA12"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        },
        {
            "expression": {
                "@type": "symbol",
                "codeId": "AA112",
                "domainId": "AA11"
            },
            "range": {
                "from": "PP201801",
                "to": "PP201907"
            }
        }
    ],
    "invalidEffectivities": [],
    "version": "0.0"
}
```

8.2.2 The bijectivity validation task – request and response

Request


```
{
  "@type": "MANValidInSchemaRequest",
  "version": "0.0",
  "productKey": {
    "relativeFilePath": "example_2_ex_1.json",
    "preferNumericId": true
  },
  "correlationId": 42,
  "preAssignments": {
    "@type": "and",
    "andExps": []
  },
  "schema": ["AA03","AA04","AA05"],
  "checkRange": {
    "from": "PP201801",
    "to": "PP202110"
  },
  "withRange": false
}
```


Response


```
{
    "@type": "MANValidInSchemaResponse",
    "correlationId": 42,
    "validCombinations": [
        {
            "values": [
                {
                    "codeId": "AA041",
                    "domainId": "AA04"
                },
                {
                    "codeId": "AA051",
                    "domainId": "AA05"
                },
                {
                    "codeId": "AA032",
                    "domainId": "AA03"
                }
            ]
        },
        {
            "values": [
                {
                    "codeId": "AA041",
                    "domainId": "AA04"
                },
                {
                    "codeId": "AA051",
```

```
                "domainId": "AA05"
            },
            {
                "codeId": "AA033",
                "domainId": "AA03"
            }
        ]
    },
    {
        "values": [
            {
                "codeId": "AA041",
                "domainId": "AA04"
            },
            {
                "codeId": "AA052",
                "domainId": "AA05"
            },
            {
                "codeId": "AA031",
                "domainId": "AA03"
            }
        ]
    },
    {
        "values": [
            {
                "codeId": "AA041",
                "domainId": "AA04"
            },
            {
                "codeId": "AA052",
                "domainId": "AA05"
            },
            {
                "codeId": "AA032",
                "domainId": "AA03"
            }
        ]
    },
    {
        "values": [
            {
                "codeId": "AA042",
                "domainId": "AA04"
            },
            {
                "codeId": "AA051",
                "domainId": "AA05"
            },
            {
                "codeId": "AA032",
                "domainId": "AA03"
            }
        ]
    },
```

```
        {
            "values": [
                {
                    "codeId": "AA042",
                    "domainId": "AA04"
                },
                {
                    "codeId": "AA051",
                    "domainId": "AA05"
                },
                {
                    "codeId": "AA033",
                    "domainId": "AA03"
                }
            ]
        },
        {
            "values": [
                {
                    "codeId": "AA042",
                    "domainId": "AA04"
                },
                {
                    "codeId": "AA052",
                    "domainId": "AA05"
                },
                {
                    "codeId": "AA031",
                    "domainId": "AA03"
                }
            ]
        },
        {
            "values": [
                {
                    "codeId": "AA042",
                    "domainId": "AA04"
                },
                {
                    "codeId": "AA052",
                    "domainId": "AA05"
                },
                {
                    "codeId": "AA032",
                    "domainId": "AA03"
                }
            ]
        }
    ],
    "version": "0.0"
}
```

8.2.3 The second consistency validation task – request and response

Request


```
{
    "preAssignments": {
        "expression": {
            "@type": "and",
            "andExps": []
        },
        "range": {
            "from": "PP201801",
            "to": "PP202110"
        }
    },
    "productKey": {
        "relativeFilePath": "example_2_ex_1.json",
        "preferNumericId": true
    },
    "version": "0.0",
    "@type": "MANBasicValidationRequest",
    "correlationId": 42,
    "checkRange": {
        "from": "PP201801",
        "to": "PP202110"
    }
}
```


Response


```
{
    "@type": "MANBasicValidationResponse",
    "correlationId": 42,
    "invalidChoices": [],
    "invalidEffectivities": [],
    "version": "0.0"
}
```

8.2.4 The Bill-of-Materials validation task – request and response

Request


```
{
  "version": "1.0",
  "@type": "MANBomElementCheckRequest",
  "productKey": {
    "relativeFilePath": "example_2_ex_1.json",
    "preferNumericId": true
  },
  "correlationId": 100,
  "bomElementIds": [],
  "checkRange": {
    "from": "PP201801",
    "to": "PP202110"
  },
  "preAssignments": {
    "@type": "and",
    "andExps": []
  },
  "validateLEsAndTransformations": false,
  "nrOfExamples": 2
}
```


Response


```
{
  "@type": "MANBomElementCheckResponse",
  "correlationId": 100,
  "bomErrors": [
    {
      "ambiguousBomElements": [
        {
          "ambiguousId1": "81#0993-004",
          "ambiguousId2": "81#0993-003",
          "ambiguousCombinations": [
            {
              "expression": {
                "@type": "and",
                "andExps": [
                  {
                    "@type": "or",
                    "orExps": [
                      {
                        "@type": "symbol",
                        "codeId": "AA063",
                        "domainId": "AA06"
                      }
                    ]
                  },
                  {
                    "@type": "or",
                    "orExps": [
```

```
                {
                  "@type": "symbol",
                  "codeId": "AA015",
                  "domainId": "AA01"
                }
              ]
            }
          ]
        },
        "range": {
          "from": "PP201801",
          "to": "PP202110"
        }
      }
    ]
  },
  {
    "ambiguousId1": "81#0993-003",
    "ambiguousId2": "81#0993-000",
    "ambiguousCombinations": [
      {
        "expression": {
          "@type": "and",
          "andExps": [
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA015",
                  "domainId": "AA01"
                }
              ]
            },
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA061",
                  "domainId": "AA06"
                }
              ]
            }
          ]
        },
        "range": {
          "from": "PP201801",
          "to": "PP202110"
        }
      }
    ]
  }
],
"ambiguousBomElementsWithEmptyExpression": [],
"bomElementId": "K_0993",
```

```
    "incompleteCombinations": [
      {
        "expression": {
          "@type": "and",
          "andExps": [
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA013",
                  "domainId": "AA01"
                },
                {
                  "@type": "symbol",
                  "codeId": "AA014",
                  "domainId": "AA01"
                }
              ]
            },
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA062",
                  "domainId": "AA06"
                },
                {
                  "@type": "symbol",
                  "codeId": "AA063",
                  "domainId": "AA06"
                }
              ]
            }
          ]
        },
        "range": {
          "from": "PP201801",
          "to": "PP202110"
        }
      }
    ],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [],
    "bomElementId": "K_0990",
    "incompleteCombinations": [],
    "unusedBomElements": [
      {
        "bomElementId": "81#0990-002",
        "unusedPeriods": [
          {
            "from": "PP201801",
```

```
                "to": "PP202110"
              }
            ]
          }
        ]
      }
  ],
  "version": "0.0"
}
```

8.2.5 The geometry validation task – request and response

Request

```
{
  "version": "1.0",
  "@type": "MANBomElementCheckRequest",
  "productKey": {
    "relativeFilePath": "example_2_ex_2_2.json",
    "preferNumericId": true
  },
  "correlationId": 100,
  "bomElementIds": [],
  "checkRange": {
    "from": "PP201801",
    "to": "PP202110"
  },
  "preAssignments": {
    "@type": "and",
    "andExps": []
  },
  "validateLEsAndTransformations": true,
  "nrOfExamples": 2
}
```

Response

```
{
  "@type": "MANBomElementCheckResponse",
  "correlationId": 100,
  "bomErrors": [
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [],
      "bomElementId": "K_0990",
      "incompleteCombinations": [],
      "unusedBomElements": [
        {
          "bomElementId": "81#0990-002",
          "unusedPeriods": [
            {
              "from": "PP201801",
              "to": "PP202110"
            }
          ]
        }
      ]
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "81#0993-004-SE01"
      ],
      "bomElementId": "81#0993-004",
```

```
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "81#0993-003-SE01"
      ],
      "bomElementId": "81#0993-003",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "81#0993-002-SE01"
      ],
      "bomElementId": "81#0993-002",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "81#0993-001-SE01"
      ],
      "bomElementId": "81#0993-001",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode15"
      ],
      "bomElementId": "81#0993-004-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode14"
      ],
      "bomElementId": "81#0993-003-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode13"
      ],
      "bomElementId": "81#0993-002-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
```

```
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode12"
      ],
      "bomElementId": "81#0993-001-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "81#0992-001-SE01"
      ],
      "bomElementId": "81#0992-001",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [
        {
          "ambiguousId1": "TNode11",
          "ambiguousId2": "TNode10",
          "ambiguousCombinations": [
            {
              "expression": {
                "@type": "and",
                "andExps": [
                  {
                    "@type": "or",
                    "orExps": [
                      {
                        "@type": "symbol",
                        "codeId": "AA061",
                        "domainId": "AA06"
                      }
                    ]
                  },
                  {
                    "@type": "or",
                    "orExps": [
                      {
                        "@type": "symbol",
                        "codeId": "AA013",
                        "domainId": "AA01"
                      },
                      {
                        "@type": "symbol",
                        "codeId": "AA014",
                        "domainId": "AA01"
                      },
                      {
                        "@type": "symbol",
                        "codeId": "AA015",
                        "domainId": "AA01"
```

```
                    }
                  ]
                }
              ]
            },
            "range": {
              "from": "PP201801",
              "to": "PP202110"
            }
          }
        ]
      }
    ],
    "ambiguousBomElementsWithEmptyExpression": [],
    "bomElementId": "81#0992-001-SE01",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [],
    "bomElementId": "81#0991-001",
    "incompleteCombinations": [
      {
        "expression": {
          "@type": "and",
          "andExps": [
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA032",
                  "domainId": "AA03"
                },
                {
                  "@type": "symbol",
                  "codeId": "AA033",
                  "domainId": "AA03"
                }
              ]
            },
            {
              "@type": "or",
              "orExps": [
                {
                  "@type": "symbol",
                  "codeId": "AA042",
                  "domainId": "AA04"
                }
              ]
            },
            {
              "@type": "or",
              "orExps": [
                {
```

```
                  "@type": "symbol",
                  "codeId": "AA051",
                  "domainId": "AA05"
                }
              ]
            }
          ]
        },
        "range": {
          "from": "PP201801",
          "to": "PP202110"
        }
      }
    ],
    "unusedBomElements": [
      {
        "bomElementId": "81#0991-001-SE02",
        "unusedPeriods": [
          {
            "from": "PP201801",
            "to": "PP202110"
          }
        ]
      }
    ]
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "TNode09"
    ],
    "bomElementId": "81#0991-001-SE02",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [],
    "bomElementId": "81#0991-001-SE01",
    "incompleteCombinations": [],
    "unusedBomElements": [
      {
        "bomElementId": "TNode08",
        "unusedPeriods": [
          {
            "from": "PP201801",
            "to": "PP202110"
          }
        ]
      },
      {
        "bomElementId": "TNode07",
        "unusedPeriods": [
          {
            "from": "PP201801",
            "to": "PP202110"
```

```
          }
        ]
      },
      {
        "bomElementId": "TNode06",
        "unusedPeriods": [
          {
            "from": "PP201801",
            "to": "PP202110"
          }
        ]
      }
    ]
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "81#0990-004-SE01"
    ],
    "bomElementId": "81#0990-004",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "81#0990-003-SE01"
    ],
    "bomElementId": "81#0990-003",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "81#0990-001-SE01"
    ],
    "bomElementId": "81#0990-001",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "TNode04"
    ],
    "bomElementId": "81#0990-004-SE01",
    "incompleteCombinations": [],
    "unusedBomElements": []
  },
  {
    "ambiguousBomElements": [],
    "ambiguousBomElementsWithEmptyExpression": [
      "TNode03"
    ],
    "bomElementId": "81#0990-003-SE01",
```

```
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode02"
      ],
      "bomElementId": "81#0990-002-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
    },
    {
      "ambiguousBomElements": [],
      "ambiguousBomElementsWithEmptyExpression": [
        "TNode01"
      ],
      "bomElementId": "81#0990-001-SE01",
      "incompleteCombinations": [],
      "unusedBomElements": []
    }
  ],
  "version": "0.0"
}
```

8.2.6 The third consistency validation task – request and response

Request


```
{
  "preAssignments": {
    "expression": {
      "@type": "and",
      "andExps": []
    },
    "range": {
      "from": "PP201801",
      "to": "PP202110"
    }
  },
  "productKey": {
    "relativeFilePath": "example_2_ex_3.json",
    "preferNumericId": true
  },
  "version": "0.0",
  "@type": "MANBasicValidationRequest",
  "correlationId": 42,
  "checkRange": {
    "from": "PP201801",
    "to": "PP202110"
  }
}
```


Response


```
{
  "@type": "MANBasicValidationResponse",
  "correlationId": 42,
  "invalidChoices": [],
  "invalidEffectivities": [],
  "version": "0.0"
}
```


8.3 The case study example in the final, corrected version

In this section of the appendix, the final version of the case study example is shown. It consists of the same content as the original version, but all the identified portfolio errors have been corrected in this version. By comparison to the original file, the changes can be identified.

Corrected originale example


```
{
    "requirementTree": {
        "@type": "RequirementTree",
        "rootNode": {
            "@type": "RequirementRootNode",
            "children": [{
```

```
                    "@type": "PMOptionCategory",
                    "id": "PMOptionCategory1",
                    "name": "Elementary example",
                    "children": [{
                            "@type": "PMOption",
                            "id": "PMOption1",
                            "name": "Country",
                            "children": [{
                                    "@type": "PMChoice",
                                    "id": "PMChoice01",
                                    "name": "Germany",
                                    "id2": "AA011",
                                    "type": "STANDARD",
                                    "numericValue": 0
                                }, {
                                    "@type": "PMChoice",
                                    "id": "PMChoice02",
                                    "name": "Austria",
                                    "id2": "AA012",
                                    "type": "STANDARD",
                                    "numericValue": 0
                                }, {
                                    "@type": "PMChoice",
                                    "id": "PMChoice03",
                                    "name": "Switzerland",
                                    "id2": "AA013",
                                    "type": "STANDARD",
                                    "numericValue": 0
                                }, {
                                    "@type": "PMChoice",
                                    "id": "PMChoice04",
                                    "name": "Ukraine",
                                    "id2": "AA014",
                                    "type": "STANDARD",
                                    "numericValue": 0
                                }, {
                                    "@type": "PMChoice",
                                    "id": "PMChoice05",
                                    "name": "Brazil",
                                    "id2": "AA015",
                                    "type": "STANDARD",
                                    "numericValue": 0
                                }
                            ],
                            "id2": "AA01",
                            "type": "STANDARD"
                        }, {
                            "@type": "PMOption",
                            "id": "PMOption2",
                            "name": "HazardousGoods",
                            "children": [{
                                    "@type": "PMChoice",
                                    "id": "PMChoice06",
                                    "name": "HG_with",
                                    "id2": "AA021",
                                    "type": "STANDARD",
```

```
            "numericValue": 0
        }, {
            "@type": "PMChoice",
            "id": "PMChoice07",
            "name": "HG_wo",
            "id2": "AA022",
            "type": "STANDARD",
            "numericValue": 0
        }
    ],
    "id2": "AA02",
    "type": "STANDARD"
}, {
    "@type": "PMOption",
    "id": "PMOption3",
    "name": "WheelBase",
    "children": [{
            "@type": "PMChoice",
            "id": "PMChoice08",
            "name": "R3600",
            "id2": "AA031",
            "type": "STANDARD",
            "numericValue": 3600,
            "unitOfNumericValue": "mm"
        }, {
            "@type": "PMChoice",
            "id": "PMChoice09",
            "name": "R5300",
            "id2": "AA032",
            "type": "STANDARD",
            "numericValue": 5300,
            "unitOfNumericValue": "mm"
        }, {
            "@type": "PMChoice",
            "id": "PMChoice10",
            "name": "R5900",
            "id2": "AA033",
            "type": "STANDARD",
            "numericValue": 5900,
            "unitOfNumericValue": "mm"
        }
    ],
    "id2": "AA03",
    "type": "STANDARD"
}, {
    "@type": "PMOption",
    "id": "PMOption4",
    "name": "FuelTank",
    "children": [{
            "@type": "PMChoice",
            "id": "PMChoice11",
            "name": "T_small",
            "id2": "AA041",
            "type": "STANDARD",
            "numericValue": 0
        }, {
```

```
                "@type": "PMChoice",
                "id": "PMChoice12",
                "name": "T_large",
                "id2": "AA042",
                "type": "STANDARD",
                "numericValue": 0
            }
        ],
        "id2": "AA04",
        "type": "STANDARD"
    }, {
        "@type": "PMOption",
        "id": "PMOption5",
        "name": "SpareWheel",
        "children": [{
                "@type": "PMChoice",
                "id": "PMChoice13",
                "name": "SW_with",
                "id2": "AA051",
                "type": "STANDARD",
                "numericValue": 0
            }, {
                "@type": "PMChoice",
                "id": "PMChoice14",
                "name": "SW_wo",
                "id2": "AA052",
                "type": "STANDARD",
                "numericValue": 0
            }
        ],
        "id2": "AA05",
        "type": "STANDARD"
    }, {
        "@type": "PMOption",
        "id": "PMOption6",
        "name": "FirstAidBox",
        "children": [{
                "@type": "PMChoice",
                "id": "PMChoice15",
                "name": "FA_wo",
                "id2": "AA061",
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"T_small"
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"AtomicTermNode",
                        "id":
"PMChoice25",
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large",
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Versions": [

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"T_large"
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```

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with integrated step tread",
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Versions": [
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Example",
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sions": [
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ple",
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"AND"
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Mounting positioning left",
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Bottle",
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ple",
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}
],
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ple",
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            }, {
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                "id": "PMChoice02",
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            }
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        }
        ],
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    }
    ],
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                        }
                    ],
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ple",
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}, {
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}, {
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