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Development of market-oriented architectural standards by means of standardized vehicle layouts

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Abstract

Commercial vehicles serve a wide range of operational purposes so that a broad spectrum of conceptual configuration options, for example the number of axles or wheelbase and overhang, has to be offered to the customer. Resulting from the demanded range of configuration options, the installation space for chassis mounted parts varies extensively. This leads to a high variance in positioning for chassis mounted parts. In previous research, a generic package space decomposition and layout patterns of chassis mounted parts were introduced to reduce said complexity. However, a portfolio with layout patterns will only retain its stability as long as the portfolio does not undergo any major changes. Should internal or external causes lead to e.g. an alteration in the dimensions of just one component during the 15 to 20 year product life cycle, new layouts might need to be defined, adding to the variance. The main purpose of this paper is to methodically develop robust architectural standards in the form of standardized layouts regarding truck chassis components as an example for a complex technical system. The presented approach integrates customer- and company perspectives. Customer requirements are investigated retrospectively by means of a market basket analysis. The solution space is generated based on technical requirements. Market requirements and technical solution space are subsequently merged to generate standardized layouts.

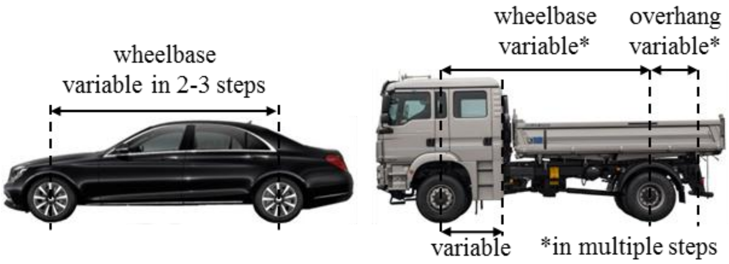
Keywords: ***Architectural standard, commercial vehicle design, modularization, variant management, vehicle layout***

1 Introduction

Over the last decades, the international commercial vehicle industry developed into a business catering for a broad variety of demands in the market. While car manufacturers further diversify their portfolio mainly due to differentiation and marketing reasons, the commercial vehicle sector is characterized by a multitude of customer applications. To offer fewer practical solutions for big number of market needs, a variable configuration system is necessary. For instance, heavy-duty construction is applicable for both rough road surfaces as well as long-haul transport on well developed roads. The carrying structure of heavy goods vehicles (HGVs), the chassis, is realized as a ladder frame by a modular tool kit consisting of longitudinal and cross profiles. It enables a variable configuration concerning different application characteristics within the design process. By looking at the chassis mounted parts and their carried over mounted positions onto portfolios, we can notice a seemingly unmanageable amount of mounting positions and component variants which evolved historically. In order to economically realize the demanded diversity of their products, manufacturers of HGVs need to apply practices from the field of variant management to their complex product structures. In the following, a market-oriented approach is presented, which aims to cater that need in the specific context of component- and positioning variance.

1.1 Background: Difference of variant products in automobile- and HGV industry

The issue of variance differs fundamentally between cars and HGVs. While a car customer selects his vehicle within a certain segment based on the body style, the wheel base is already determined by the manufacturer, except for a few long versions. However, the HGV customer solely chooses a product line to start with, then choosing from a considerably greater set of configuration options in terms of the number of axles, the wheelbase, the overhang and the cab size. The HGV customizability of wheelbase and overhang provides a basis for adapting the transportation capacity, the axle load distribution as well as the installation space between the axles. The space is needed for vehicle components, e.g. the fuel tank, or for body work related components, e.g. a compressor. Figure 1 shows some of the differences in configuration options defined by the customer.



Orderable Features	Car	HGV
Wheelbase	(Yes)	Yes
Overhang	No	Yes
Number of axles	No	Yes
Fuel tank volume	No	Yes
Battery capacity	No	Yes
Free installation space	No	Yes
Cab length	No	Yes

Figure 1. Differences between car and truck

1.2 Problem description

As a result of the customers' impact on chassis design, truck manufacturers need to package many variants of components into the limited installation space provided by the wheelbase and overhang. This conflict induces mutual influence of both **part variance** and **positioning variance** of components. For example, fuel tanks are available in different volumes, according to customer requirements. They are usually fitted between front and rear axles among other chassis mounted components, such as the battery box and the spare wheel. As long as the wheel base allows the combination of all required variants in their optimal positions, no additional variants are induced compared to those directly demanded by the customer. As soon as the installation space becomes too small for all the components to fit in their original positions, the components' positions need to be swapped (adding positioning variance) or their design needs to be altered (adding component variance). One such change, or rather one additional variant, can cause several other changes to other components, in terms of both their positioning and design. These cause-effect-circles in variance propagation lead to exponential growth of variance in the manufacturer's solution space over time. Tracking or breaking this circular growth and eliminating customer-irrelevant variance yields a high cost reduction potential. To achieve this goal, the method requires a pragmatic, yet systematic solution to ascertain keeping customer-relevant variance, while significantly reducing customer-irrelevant variance.

1.3 Research methodology

The research methodology is based on three pillars: a methods group for modular systems at the company counting two researchers and two product architecture experts, a technical expert group with a member of each department for frame attachment components, and an interdisciplinary group for vehicle concepts at university. Within the methods group, a systematic procedure for planning standardized vehicle layouts was derived. The methodology was discussed with the experts group for frame attachment components concerning misconceptions and risks within the implementation process at the company.

2 State of the Art

2.1 Existing Approaches to Variant Management and Modularization

The field of **variant management**, which embraces the challenge of economically serving a variety of individual market needs, has been investigated thoroughly over the past decades. The role of product structure is seen as key for efficiently serving diverse market demand, i.e. external variance, while utilizing a relatively low number of configurable technical solutions, i.e. internal variance (Ericsson & Erixon, 1999; Erixon, 1998). Product structures comprising of platforms and modules or of modular kits as basis for whole product families have shown to leverage economic effects in product development and -manufacturing by reducing complexity (Blees & Krause, 2008; Gershenson, Prasad, & Zhang, 2003). A multitude of methods for **modularization** of product structures has been developed over the years, of which only the most relevant ones are mentioned here. Pertaining to the definition of product architecture, which comprises the mapping a product’s functional structure to its physical structure, such approaches follow the basic procedure of defining and decomposing product functions based on market requirements, relating functions to physical elements of the product, and subsequently creating modules by clustering related elements (Pimmler & Eppinger, 1994). An enhanced approach is Modular Function Deployment by ERIXON (Erixon, 1998), which includes mapping of module drivers to the product’s elements, thereby considering stakeholders from all phases of the product’s lifecycle in the process of defining modules in the product structure. BLEES and KRAUSE (Blees & Krause, 2008) add to these approaches by discussing the limited applicability of most modularization methods in cases of highly complex products. Furthermore, they pay attention to the fact that in most industrial product development settings, previous product generations serve as basis for evolutionary design. Radical reengineering is not always feasible when trying to achieve a modularized product architecture. Therefore, existing design information, also in terms of shape and geometrical attributes in general, can and often must be regarded for the purpose of modularizing a product. The methodology presented by HARLOU (Harlou, 2006) focuses on visualizing the variance of an existing product family – rather than a single product – from an architectural perspective. Functional relations and product structures are modeled, indicating the usage of functional or physical elements across the product portfolio. Recurring patterns in the product family architecture can be defined as so-called standard designs, ready for reuse across several or all products of the product family. The aim of this approach is similar to the definition of **modular kits**: Reuse of designs or building blocks across a whole product family to create a high number of external variants with a much lower number of internal variants (Pahl, Beitz, Feldhusen, & Grote, 2007). A crucial component of modular kits are architecture standards and guidelines, which determine how standardized and non-standardized building blocks can be combined to create the external variance required by the market from a set of recurring design elements (Förg, Stocker, Kreimeyer, & Lienkamp, 2014).

2.2 State of the Art in variant management at MAN Truck & Bus

MAN as a commercial vehicle manufacturer faces the challenge of a highly diverse product family, which is contrasted by a comparably low market volume (in terms of sales figures) as a characteristic of the commercial vehicle industry. This challenge requires an effective variant management, which is met by **modular kits at two levels** on the side of MAN's product structure. At full vehicle level, cross-product configuration of main components is realized in a modular kit. At component level, single modules such as axles, cabin or frame are designed as modular kits for themselves, comprising sub-components and configuration rules (Förg et al., 2014; Kreimeyer, Förg, & Lienkamp, 2013). Variant management is furthermore embodied as an early phase in development processes. The so-called process of component variant planning focuses on single components of the full vehicle modular kit (Schumacher, Märkl, Gilbert, & Kreimeyer, 2015). Market requirements are translated into variant driving product characteristics, which are configurable by the customer (external variance). These customer requirements together with technical restrictions are multiplied into the required number of variants for each component (internal variance). This variant planning process creates an overview of internal variants per component in early development stages. However, many interrelations and dependencies from a technical, and especially the geometrical point of view, remain uncovered by this process. This is especially problematic for frame attachment components. These components are relatively independent from one another looking from the functional side. For example, fuel tanks, battery boxes and spare wheels do not show any functional correlations other than being packaged into the same segment of the vehicle. Thus, by means of classical modularization approaches, these components are fairly modular. Internal component variance still strongly exceeds market-required external variance due to geometrical, i.e. positioning/packaging conflicts. First steps into solving the interdependency of component- and positioning variance were taken by defining the previously mentioned generic package space decomposition (see Figure 2) and the concept of layouts for frame attachment parts (Förg et al., 2014).

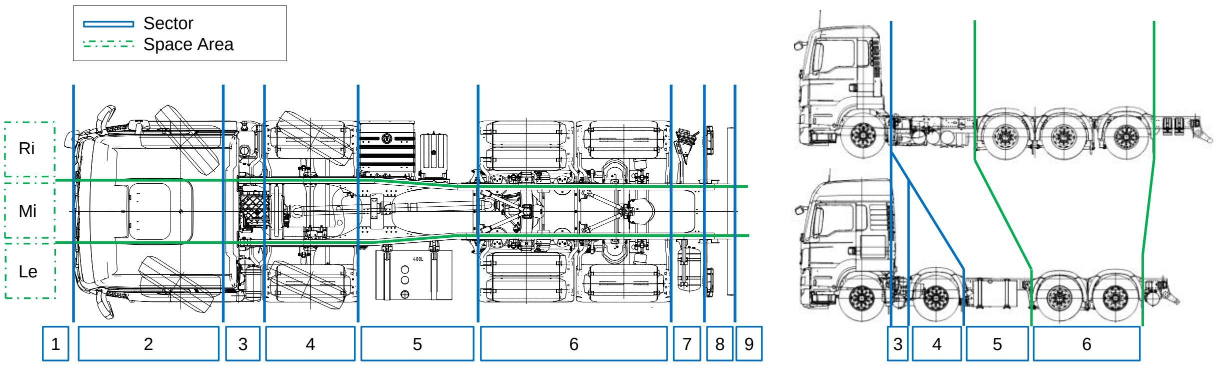


Figure 2. Generic package space decomposition at MAN. Highlighted sectors 3, 5 and 7 show possible installation space for chassis mounted parts.

Based on the structure of the generic package space decomposition, unified geometrical references can be made for chassis mounted components. The relevant sectors (3, 5 and 7 are possible for those components) can furthermore be parametrized in size depending on axle- and wheel base configurations. The term layout denotes a valid combination of attachment components, i.e. a set that can be configured and fitted into the vehicle altogether, and their positioning. Subsequently, it becomes possible to generate a holistic view on attachment components configured as a combination into e.g. sector 5, and to prescribe architectural standards such as standardized layouts and positioning standards. However, the sheer variety of influences on and interdependencies of component and positioning variance of attachment components could not yet be tackled by means of classical modelling and modularization approaches.

2.3 Intermediate conclusion and research gap

Existing approaches to economically balance internal and external product variance, both from the literature and from industry, show deficits when it comes to evolutionarily designed products with high complexity and variance. As the present case of chassis mounted truck components shows, even functionally independent building blocks of a modular kit need to be enhanced by architecture standards to break the circular dependency of component- and positioning variance. Such architecture standards for evolutionary product development need to comprise geometrical dependencies within the modular kit. Furthermore, it is necessary to retain the variance demanded by the market, which calls for consideration of customer requirements. Existing modularization approaches lack practical applicability in complex industrial settings when combined to a holistic approach that meets the abovementioned requirements. Hence, a new approach is presented to systematically define architecture standards, which also include geometrical standards such as positioning schemes and layouts. The effectiveness of modular kits as a form of variant management is expected to be enhanced by standardizing the interplay of modules and other components within such modular kits.

3 Proposed methodology for deriving architecture standards in forms of standardized layouts and positioning standards

To methodically develop and define architectural standards for a modular kit, a portfolio-wide approach is necessary. The modular kit under regard consists of the chassis mounted parts for all heavy trucks in the company's portfolio. In a preparation step, the portfolio was divided into clusters based on vehicle characteristics relevant to the layout of chassis mounted parts.

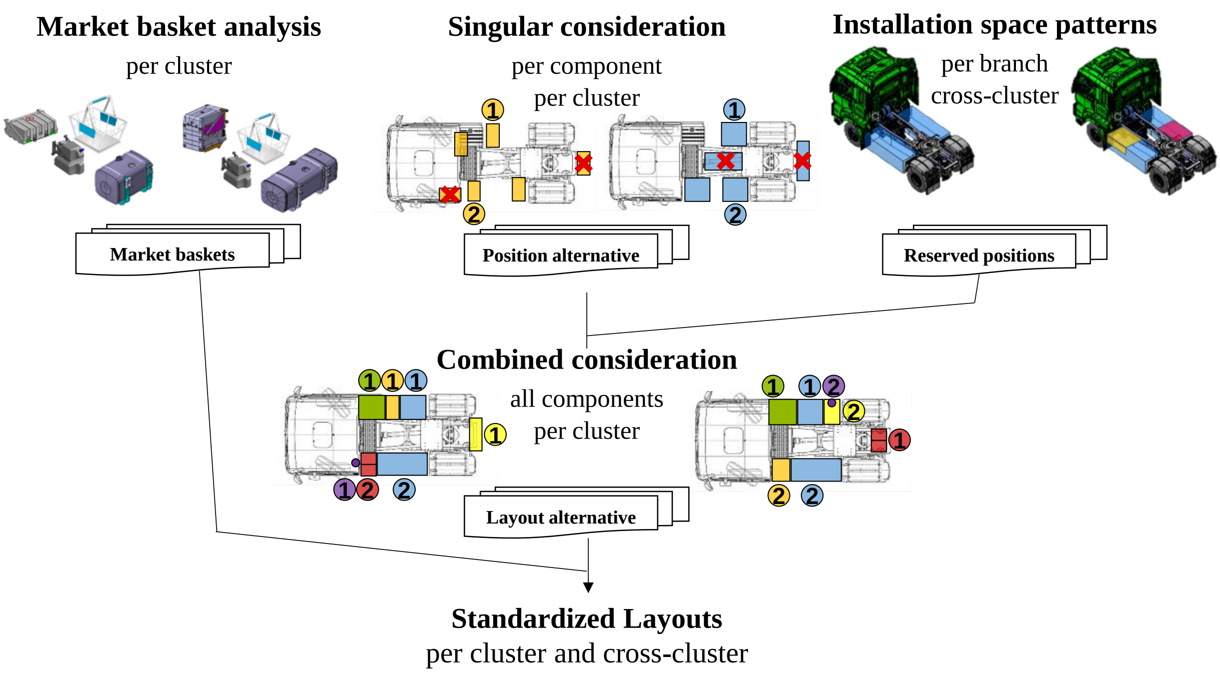


Figure 3. Methodology for deriving standardized layouts

Going from there, a retrospective market basket analysis of all produced vehicles in the past years is conducted, with the goal to ascertain that the most commonly used combinations of chassis mounted parts are reflected for layout standardization. In parallel, the layout-specific requirements of each industry sector are recorded and translated into technical specifications using branch-specific installation space patterns. The company perspective is generated by singular consideration of each component of the regarded modular kit. Per component, all technically possible mounting positions are collected and subsequently prioritized or eliminated based on technical criteria, which subsume functional aspects of the components, cost and risk as well as production- and user-related factors. By combining superposed singular position alternatives with branch-specific reserved positions, several layout alternatives are generated. After defining the basic vehicle containing chassis, cab, engine, drivetrain and axles, the possible solution space in form of the layout alternatives is filled with the demanded component combinations, i.e. the market baskets. With this information, standardized layouts are derived, which allow to serve market demand with minimal company-internal positioning and component variance. Figure 3 gives an overview of the steps covered in the methodology as well as the information artefacts that are produced.

3.1 Identifying required component combinations from customer perspective

Market basket analysis

A market basket analysis is applied to obtain a profile of customer requirements to be used as input data for the layout-standardization. The analysis allows an in-depth view into the actually sold component combinations that need to be realized in the available solution space. The components considered are the exhaust system, the diesel tank, the AdBlue-tank and the battery box. The hydraulic tank and the spare wheel lift as optional components must be considered as well, since these components require a considerable amount of space. Compressed air tanks are not considered in the market basket analysis because the required volume of compressed air is directly defined by the number of axles. In further steps of the layout definition methodology, compressed air tanks are indeed considered.

The available installation space for chassis mounted parts depends on the number of axles, wheelbase and overhang. For layout-planning purposes, the vehicle portfolio is subdivided into clusters according to the available sectors: cluster "sector 5 only", cluster "sectors 5 and 7", and cluster "sectors 3 and 5". Sector definitions are derived from the generic package space decomposition model at MAN (Figure 2). The following approach is based on the data mining concept of BENSBERG (Bensberg, 2001). A market basket analysis, also referred to as association analysis, is used to extract/discover unknown and beneficial information from large sets of transaction data (Agrawal, Swami, & Imielinski, 1993). The desired outcome is the frequency distribution of item-combinations.

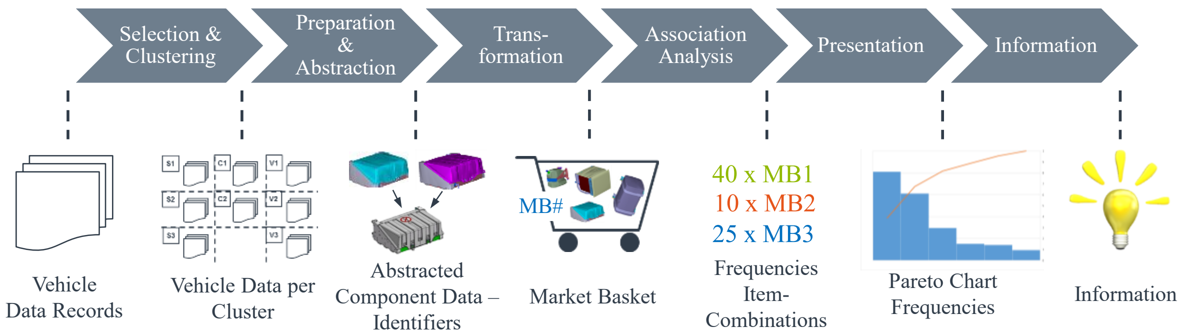


Figure 4. Market basket analysis procedure for HGVs at MAN

In the first phase of the procedure depicted in Figure 4, selection & clustering of the relevant data takes place. A set of sold vehicle data is chosen, which is then subdivided in accordance with the clustering concept described above. Subsequently, the preparation & abstraction step is conducted, which includes the analysis of data quality and an abstraction of the regarded components. Abstraction means that each variant of the regarded components is represented by an identifier. The components denoted by their identifiers are called "items" in the analysis. The actual market basket analysis is undertaken with the preprocessed data base. An exemplary application of a market basket analysis for HGVs at MAN is described in the following. Figure 5 shows the analysis results for vehicles sold in 2015 assigned to the cluster "Sector 5".

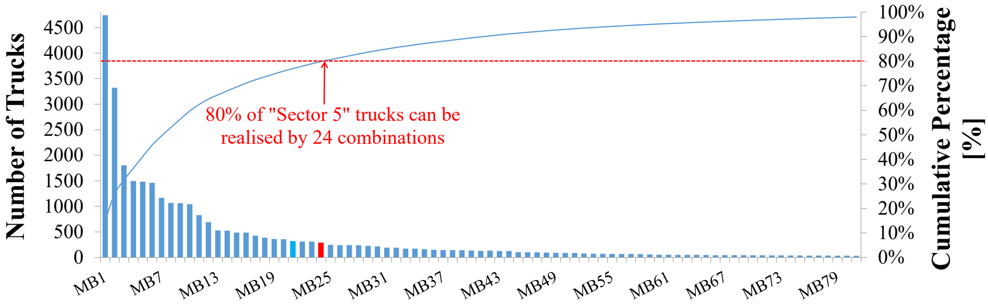


Figure 5. Frequencies of six-item-combinations in market baskets for cluster Sector 5

The Pareto chart outlines the frequencies of sold six-item-combinations in vehicles. It provides information about customer needs as a basis for layout standardization. These include the frequencies of all requested six-item-combinations, the cumulative percentage graph, the 80%-limit and the number of combinations which cover 80% of vehicles sold in this cluster. The most frequent combination "market basket 1 (MB1)" is composed of an AdBlue tank holding 80 l, a compact battery box, a double fuel tank with twice 580 l capacity, an exhaust system compliant to the EURO-6-norm, and no hydraulic tank or spare wheel lift.

Branch specific installation space patterns

MAN's truck portfolio is divided into three segments: long-haul, distribution, and traction. Each segment can be subdivided into branches with influence on the truck body work. Traction, for example, can be specified as construction, crane and loading systems, mining, logging and agriculture as well as heavy-duty and recovery. As mentioned earlier, installation patterns of chassis mounted parts vary greatly with conceptual vehicle characteristics such as wheelbase and number of axles. Per branch, it might be required that installation space within the chassis is reserved for body-specific components that are not provided by MAN itself as an OEM. As a result, the competitive struggle for installation space increases between vehicle's own and body-work-specific chassis mounted parts. To gain a portfolio-wide overview, all branches within the three segments were analyzed for their installation space patterns. The results are 15 general installation space patterns that can now be used in step 2 to generate layout alternatives.

3.2 Defining solution space for components in abstracted geometrical vehicle context

Singular consideration of components

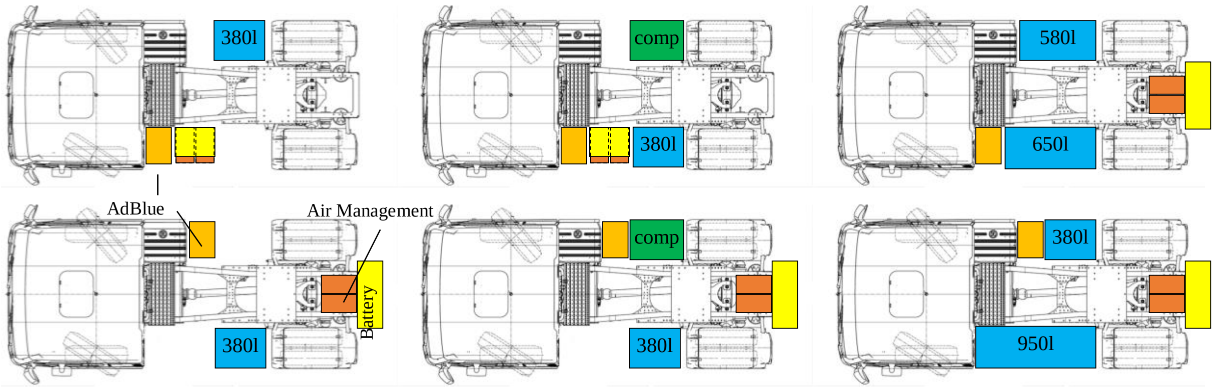
The previous steps so far covered the market perspective on required installation space and component combinations. Now, the possible solution space is generated from the company's perspective, i.e. based on functional and other criteria. Therefore, all possible installation positions are collected for each component that is also evaluated in the market basket analysis. This procedure is performed for every portfolio cluster. Subsequently, each possible position for each component is evaluated based on criteria from technical, financial and other relevant perspectives. Based on the evaluation, the theoretical solution space is reduced by elimination of unreasonable positions. The remaining positions are then ranked based on the pros and cons stemming from the criteria-based evaluation. Examples of criteria can be: Accessibility for refueling or maintenance procedures; Length/diameter and therefore costs of cables and wires; Flexibility of component volumes, e.g. fuel tanks or Cost and risk for new product development

Combined consideration of components and layout alternatives

After determining the first and second best positions for each component within each cluster, all components within one cluster are superposed to visualize the remaining installation space conflicts. At this point, the branch-specific installation space patterns are integrated. For example, free space for a compressor for the pneumatic discharge of dry bulk road tankers needs to be provided in some layout alternatives for sector 5. Altogether, a set of layout alternatives with and without restrictions from installation space patterns is generated. This set of alternatives serves as input for the next step, where information from the market basket analysis is used to determine required layouts.

3.3 Merging solution space and required combinations to create standardized layouts

As the last step of the proposed methodology, market- and technical information are merged. By comparing the set of layout alternatives with all market baskets, the goal to find market-required layouts can be reached. Starting with the smallest wheelbase for every portfolio cluster, each market basket in this cluster is checked for compatibility to the layout alternatives. Three different cases have to be distinguished: First, all component variants fit in perfectly; Second, the required installation space can be provided, but the arrangements have to be modified. For example instead of using two 580 l fuel tanks, they would need to split up into a 390 and a 770 l tank. Third, the observed market basket does not fit in and the component variants have to be changed to smaller sizes.



Basic layout Compressor layout Max. fuel capacity layout

Figure 6. Exemplary layouts produced by the presented methodology (bottom row) compared to original layouts of the current product generation (top row)

In several iterations, the positioning alternatives need to be compared within one cluster and across several clusters to determine which alternative layouts are necessary to serve the demanded external variance. The comparison is performed regarding the similarity of patterns, and by considering a metric for prioritized positions from customer- and technical perspective. Those layout alternatives with maximum cross-cluster similarity and with a minimal position-priority metric are defined as standard layouts. A standard layout can be valid for a wide range of the product portfolio or for a narrow segment, depending on more or less specific characteristics of those segments. In addition to standardized layouts, which are defined to describe the simultaneous positioning of a combined set of components, positioning standards for single components can be identified and defined as a byproduct of this methodology step. The top row of Figure 6 shows the current layout patterns of three exemplary tractor configurations. The left column illustrates a basic configuration. The middle column shows a configuration containing a compressor, and in the right column, a configuration with maximum fuel tank volume is represented. The main difference between both sets of layouts is that chassis mounted parts, which vary in their volume and therefore their size, are mounted right next to areas, where branch-specific free installation space is necessary. Parts, which are stable in their dimensions, are uncoupled by placing them at the vehicle‘s rear end. These arrangement principles are an example of architectural standards manifested in standardized layouts.

4 Conclusion and Outlook

This paper presents a methodology that aims to support variant management of engineering companies that need to address and reduce unwanted, unnecessary internal variance while retaining the external variance that is demanded by the market. For that reason, a holistic approach is designed, which incorporates not only a technical, solution-oriented perspective, but also a market perspective. To incorporate the market view into this methodology, a market basket analysis is applied, which allows a holistic view on configurations, i.e. combinations of several components bought by customers. The market-oriented information is enhanced by so-called branch-specific installation space patterns, which describe required installation space that ought to be unobstructed by the OEM. Both types of market-oriented information are merged with the technical solution space for chassis mounted components. The latter is obtained from balancing functional, financial and other constraints on theoretically possible installation spaces. By merging the solution space and the market requirements, candidates for standardized layouts are generated, which are iteratively optimized towards a minimization of internal component variants while retaining the required external variance. Together with standardized layouts, other architectural standards can be obtained by applying the presented methodology. The analyzed dataset is extensive, verified and statistically representative. However, this procedure only allows a retrospective view on market demand characterized by already offered variants. To this point, it remains unsettled whether or not the already offered variants perfectly match customer demand. The proposed standardized layouts that result from applying the presented methodology therefore should be seen as a solid foundation, which iteratively needs to be aligned with marketing- and sales information. As part of these iterations, necessary flexibility for long-term innovation can be identified and then manifested in product architecture via standardized layouts or adjacent standards. Another critical aspect is the fact that creating standardized layouts is a very complex multi-criterial optimization problem. These criteria include cost, benefits, technical constraints, user-friendliness, and several more aspects. The presented methodology provides a systematic, yet rather “hands-on” approach, which leads to good results with the right experts in the performing team for a limited scope of components. What remains to be detailed and validated is an optimization solution in form of a supporting tool utilizing a multi-criteria optimization algorithm. Alongside this optimization solution, the effects achieved in variant- and therefore cost reduction need to be transparently evaluated and visualized. According key performance indicators and the optimization solution are currently developed. Furthermore, to ensure long-term robustness of architecture standards, tool support and according processes need to be defined, so that the architecture standards can be documented and handled in a formalized way. In a multidisciplinary and distributed development environment, this is an essential part of implementing effective variant management.

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