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Enabling modularisation potentials by standardized vehicle layouts

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Abstract

Resulting from a high variety of customer utilization scenarios, a high variant spectrum at comparatively low production volumes is characteristic for commercial vehicle manufacturers. Within a product lifecycle of around 15 to 20 years, the vehicle portfolio and its component building blocks need to be revised cyclically and fundamentally to comply with new legislation and meet changing customer requirements. The outcome is evolutionary growth of the diversified portfolio. Negative consequences are high inner variance, strong interconnectedness of many components and hardly predictable change distribution. This paper focuses on modular design for commercial vehicles and existing approaches to modularisation are presented. However, these do not refer to all aspects necessary for the modularisation of commercial vehicles. A model for generic package space decomposition is introduced, which supports the creation of essential synergetic effects by identifying hot spots for modularisation potentials. Focusing on one specific package sector, different layouts and their characteristics are compared and evaluated in order to reduce internal variance without reducing the market-related external variance.

Keywords: ***Commercial vehicle design, modularisation, product architecture, standardisation, vehicle layout, generic package space decomposition***

1 Introduction

A steadily growing vehicle portfolio enables the German commercial vehicle manufacturer MAN Truck & Bus AG (hereinafter: MAN) to offer small, medium and heavy duty commercial vehicles for a wide range of customer needs. In the past, the number of basic vehicle configurations (implying only 11 very basic attributes) reached more than 15,000 variants – not including a high number of configuration options. In order to satisfy all customer needs and to reduce costs at the same time, the objective of a high external variety has to be harmonized with striving for the lowest possible internal variance [1]. In order to benefit from this modularisation, focusing on the definition of standards and stable interfaces within the future product portfolio is an important prerequisite [2]. However, interfaces and installation spaces initially designed within the vehicle may not continue for the whole product lifecycle due to external influences, e.g. laws concerning emissions standards or knock-on changes across the product. In order to enable flexibility concerning future changes, the vehicle design needs to be highly modular [3]. The topology of commercial vehicles makes it impossible to hold one and solely one installation space available for each

component within the overall package space of the vehicle portfolio. The available package space for mounting components to the frame between front and rear axles depends on the actual customer order configuration, i.e. which specific component variants are attracted in the simultaneity of a vehicle context. Components switch places across different vehicle configurations as customers demand different installation spaces depending on the transportation task. To meet specific customer requirements, e.g. high fuel tank volume for a certain driving range, it is necessary to divide the available space between the block-like components and displace subordinate components to enable e.g. maximum tank volume.
This research follows the concept of standardized vehicle layouts to reduce the impact of knock-on effects on changes and promotes the reuse of components. Standardized interfaces enable a high percentage of common parts and help decrease change distribution, which would be the consequence of dissociated optimisation of individual vehicles without the whole vehicle portfolio in mind. The objective of systematically designed vehicle layouts, to be established in the early concept phase, is to ensure a standardized arrangement of components for at least a majority of about 80% vehicle variants overall. On the one hand, this facilitates necessary changes of components and their effects within the product lifecycle by standardized layouts documenting all variants transparently. On the other hand, coordination in production and assembly is facilitated and a reduction of internal variance allows for potential cost savings. The 20% of vehicles remaining are not based on standardized layouts (company-internal estimate) and refer to specialised customer requests with small sales volumes and offer a high degree of flexibility for profound customisation. Hence, the business case for the design effort to standardize such layouts is not given.

1.1 Background and context: MAN Truck & Bus AG

The primary niche MAN occupies is that of mass customization for specialized markets. As such, MAN vehicles are built on a highly modular architecture that supports a wide range of applications, e.g. trucks for different market segments (long-haul, distribution or traction) and uses (e.g. logging, garbage disposal, military; cf. Figure 1).

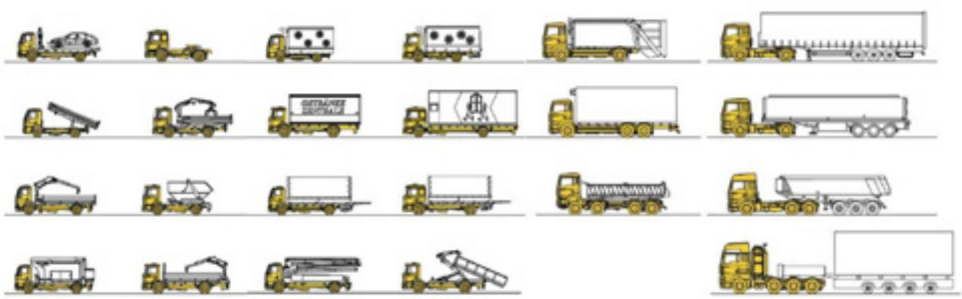


Figure 1: Typical commercial vehicle portfolio spread (yellow: responsibility of OEM) [4]

At a high level, the products within the portfolio are differentiated e.g. by the number of axles, the wheelbase, and the type of the cabin. At a more detailed level, the gross vehicle weight, the emissions standard, the engine power, the type of suspension, the steering arrangement and the overhang differentiate variants further.
In turn, the available space at the frame (being the central component) varies significantly. In the past, for requests not available within the standard portfolio, a vehicle layout was customized individually, which led to a massive increase in the variants offered over the product lifecycle. Therefore, a more targeted product architecture planning process was introduced to enable – inter alia – modularisation potentials to be realized through standardized vehicle layouts.

1.2 Problem description

The trend of mass customization challenges many companies to offer individual customer solutions [5]. Hence, the vehicle portfolio contains a large number of product variants. However, a growing number of product variants also constitute a risk: the variety has a cost-increasing effect, i.e. the overheads and administration necessary to ensure that new components fit into the existing variant spectrum (with regard to "form, fit and function"). These minor transparent costs are difficult to assess and assign to specific parts of the product. In this manner, the costs of creating and managing the large number of variants are potentially higher than the profit [6]. Often, the consequences of additional variants are underestimated and only seen in the need to manage additional drawings and bills of materials in the departments of design and operations scheduling [7].

The reasons for variety in companies can be divided into external and internal causes. External causes include customer requirements, changes in markets and competitors, as well as other conditions such as laws, regulations and further technological development. In-house causes of variety, however, can be mainly attributed to the undirected, arbitrary continuation of product variants due to methodological and organisational deficits.

The determination of costs caused by variety and the associated portfolio complexity is difficult. As a consequence, decisions on the introduction of further variants are often evaluated unilaterally in terms of a short-term increase in sales. The simultaneous need to take effective measures to control the variance of products and parts is misconceived [7]. Due to a lack of transparency about existing technical solutions, unnecessary new designs are developed. This leads to a further decrease in transparency [8].

EHRLENSPIEL [6] refers to this phenomenon as "complexity trap": Companies expand their product range through niche products and special versions to increase the revenue. The increase of complexity compared to no significant increase in market share results in disproportionately high costs and low revenues. In order to increase the profit, the internal variance needs to be reduced while the external variance is still offered. The modularisation of components mounted to the ladder frame therefore represents the major target for future development, as component variants can be generated by a sophisticated break down of components.

Instead of using different fuel tanks (e.g. 200, 300, 400, 600, 800 and 1000 litres), the tank could be sectioned into front wall, middle section and rear wall. Using different numbers of middle section parts (e.g. each middle section has a volume of 100 litres), every tank could be manufactured modularly. The internal variance decreases as the external variance stays constant. To tighten the product portfolio with a lean modular kit of component building blocks, this paper focuses on modularisation potential of commercial vehicles.

2 Modularisation – state of the art in commercial vehicle development

To counteract the problems described by an increase in the number of variants, various approaches have been developed to achieve a reduction in complexity [9] and thus to offer the customer-requested variance efficiently with the smallest possible number of parts.

A well-known approach to structuring and increasing efficiency in design and manufacturing is the development of **series**. A series contains technical structures, fulfilling the same function with the identical principle, in several grades of size in a wide range of applications, e.g. a fuel tank with one cross-section and different length for different volumes. According to BLEES [10], the advantage of a series can be found in its reduced design effort.

Modularisation is another instrument to reduce complexity. Modules are independent, exchangeable subsystems, which are connected with other modules or the rest of the system via standardized interfaces. The aim of the module approach is to reuse subsystems without changing them. Therefore, effort can be saved in design and economies of scale can be achieved in purchasing. Furthermore, through the decomposition of the product into stand-alone subsystems, complexity can be controlled more easily [11]. The ladder-frame contains box-like open spaces on the left and right side between front and rear axle, in which the various modules can be mounted. Therefore, the free space on the frame allows flexible sizing of components to be mounted according to the customer's requirement (e.g. large tank only with battery box compact vs. small tank with standard battery box). To enable this, the ladder-frame needs to be flexibly useable, and particular attention must be paid to the fulfilment of all potential customer requirements already in the design phase.

Another way to control the variance is the application of **product platforms**. They describe a set of related components and parts which form a common structure, based on which a number of different products can be developed, produced and configured [12]. The platform concept represents a special application of the modularisation concept on product and part level and can be seen as a special type of modular kit [13]. It allows for a high degree of common parts across different products, since the platform elements are used for different variants [11]. By unifying product package areas with low direct customer relevance, cross-product synergies can be realized without restricting external variance, which is perceptible by the customer. However, a platform strategy only influences a section of the vehicle, e.g. only the underbody, as it is designed for a specific scope of the product [11]. In the automotive industry for example, a platform can include the components of the power train.

The most suitable product structure for products with many variants is a **modular kit system**, which describes a system with a limited number of building blocks and a set of associated combination rules. By combining the building blocks, a plurality of different vehicles can be configured. According to FELDHUSEN [14] a modular kit is – compared to an individual solution – economically and technically reasonable if all or certain variants of a product range will only be sold in small numbers and can be realized by a few building blocks [15].

A platform strategy can hardly be applied to commercial vehicles, since platform strategies generate synergies of components only within one vehicle class. Module structures allow for synergies partly across vehicle classes through the use of modules. Best practice is a modular kit system, where synergies can be used over the whole vehicle portfolio by using standards and architectural guidelines [16].

To illustrate this: While the wheelbase, the power train (e.g. rear-wheel drive) and the chassis (e.g. ground clearance) for passenger cars would be identical within one vehicle class (when derived from one product platform) and only the body is different (e.g. sedan, wagon, coupe and convertible), commercial vehicles have to cover many different customer requirements resulting in almost full factorial combinability of wheelbases, power trains and chassis. The wheel base, for example, is a feature the customer chooses depending on the vehicle‘s transportation task. Since issues like size demand different lengths of components (e.g. drive-shafts), it is – in the classical sense of term – no longer a platform concept. The commercial vehicle manufacturer Volvo still uses the term product platform, but extends it to similar solution principles or technologies [17]. Other manufacturers call it a modular kit system [20,22]. At MAN, the series principle is applied to components, e.g. for the fuel tank (volume increases with different lengths at constant cross-section) while the cab or the axles are derived from a modular kit system. Not all components can be fully modularised or standardized. But for the majority of components different variants are determined and mounting spaces are defined. This provisional reservation of space provides the knowledge where the component will be mounted and is a first and necessary step for modularization.

Specialist literature already exists on the subject of modularisation, in which the theory of platform and modularisation strategies is described and reviewed in detail, e.g. [10, 18]. However, little is available on how to implement these approaches in industry, as such approaches are commonly perceived as competitive advantages.

According to PILLER [19], Scania uses a modular approach in a consistent manner. For each component, a limited predefined degree of flexibility and designated performance steps are carefully managed. Figure 2 illustrates this principle. At MAN modular kits exist on two levels (referred to as “multilevel modular kit development”) [20]: Both on the complete vehicle level (cross-product configuration of main components) and on component level primarily for single modules, e.g. axle, cabin and frame (increase of common parts within component variants). Mercedes Benz uses e.g. an engine platform for 6-cylinder engines and modular kits for axles and cabins [21].

Figure 2: Illustration of Scania‘s modular system and possible cab variants [19],[22]

Through the modular concept innovation can be easily introduced into products, since only individual modules have to be replaced while the rest of the architecture is stable. This modular kit enables Scania to offer variants highly efficiently, which satisfies customers’ needs concerning their specific transport task. In addition, the company follows the strict principle of refusing orders if they cannot be mapped within its modular product portfolio [23]. In this manner, an overflow of the variance is prevented. The strategic approach behind Scania‘s modular strategy is to link the individual components via standardized interfaces, which are stable over a long period of time. Simultaneously, the number of variants is checked continuously to ensure the entire modular system remains efficient [24].
The above mentioned approaches already help to reduce complexity within several component assemblies, but do not directly refer to the arrangement of components along the ladder frame.

The following aspects can be taken as an intermediate conclusion:

- The chassis as the main “bus” (cf. “bus modularity” [25]) that links all components of a commercial vehicle needs specific attention to enable the modularisation of equipment attached to the vehicle; each item of equipment (e.g. a fuel tank or a battery case) ideally follows the idea of the modularised series, i.e. well-defined performance steps catering for customer needs and the best possible interface description to avoid knock-on changes
- A common platform for the whole vehicle portfolio of a commercial vehicle manufacturer is hard if not impossible to obtain, as the transport needs and the topology of the different vehicles across the total portfolio vary too much even in the high-level variance drivers (such as the wheel-base)

- Components of a vehicle will have different positions across the total vehicle topology. Therefore, not all components can be fully modularised or even standardized; a prioritisation of what component is standardized to what degree (position, interface, functions, etc.) is needed

3 Methods to enable further modularisation potentials

In order to provide the required large external variance, 15,000 basic vehicle variants exist within the portfolio of MAN, based on the following criteria: *market segment, tonnage, type of vehicle, wheel formula, engine, emissions standard, cabin type, right-/left-hand drive, wheelbase, overhang and type of suspension*. When ordering, the customer selects a basic vehicle and specifies it to a "100% vehicle" by selecting features. A high variety of selectable features translates into a multiplicity of package arrangement patterns for the components. In order to approach and reduce this internal variance, at first it is analysed based on a generic package space decomposition focusing on the sector proven to hold the most critical component variance. In a second step, standard layouts are identified and are made mandatory to sustainably enforce a more transparent and modular overall vehicle structure.

3.1 Generic package space decomposition

As a basis to enable the standardisation of the component positioning across a vehicle, it is necessary to denominate available installation spaces (referred to as "sectors") for components through a systematic and standardized nomenclature. For each sector the variance can be analysed and the planning of layouts is already possible at an early stage of the design process. In this way, discussions about the positioning of components and possible standardisation approaches can be purposefully supported and contribute to an increase in transparency. As part of this research, a model for generic package space decomposition has been developed and implemented (as works-standard specification), which is applied primarily in the early concept phase as a guideline and as a basis for discussion for the departments responsible for components (cf. Figure 3) as well as to enable rough planning for packaging strategies. Using the generic package space decomposition it is possible to assign every basic vehicle to an identical package space structure for independent consideration of the different sectors across the overall vehicle portfolio. As a result, the layout planning is only influenced by the wheelbase and conducted independently of the individual vehicle context (e.g. basic vehicle or customer's vehicle).

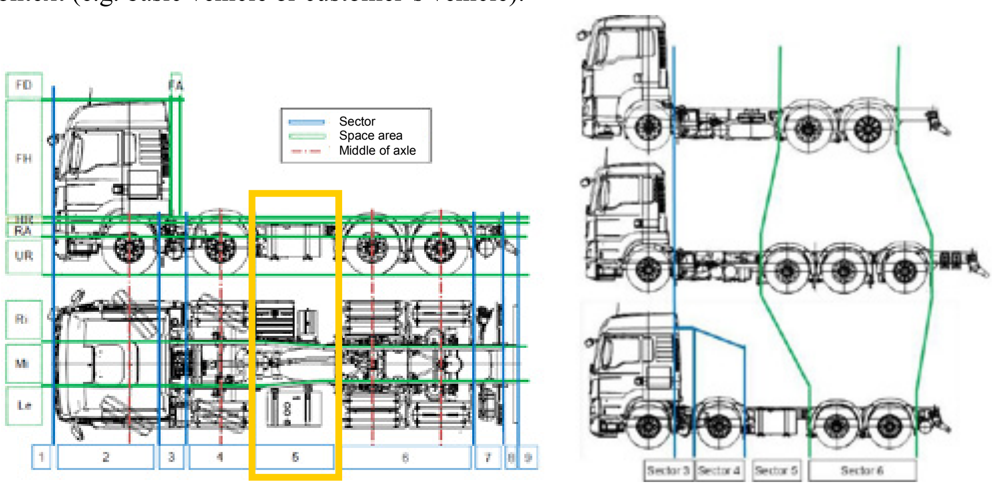


Figure 3: Generic package space decomposition

The description of sectors arises from parametrically defined collateral sector planes based on generic structuralizing vehicle elements (context-independently always appearing). Mainly the frame side members, the number and arrangement of axles (including fender) and the cab are important, as these determine the space for freely positionable components. Overall, the vehicle is split into 9 main sectors, vehicles with fewer axles accordingly into fewer sectors. A more detailed description of the generic package space decomposition is provided in [26].

3.2 Focus on sector 5 between front and rear axles

In extensive workshops with concept development experts at the company, the entire vehicle was analysed in terms of the areas of highest variance. While the area under the cab was determined to be the most complex, the region between the front and rear axles was identified as the area with the highest variance with respect to component arrangement. This sector includes the space between the end of the last front axle and the beginning of the first rear axle (Figure 4). In this area, amongst others, the exhaust system (including exhaust after-treatment and particulate filter), battery case, AdBlue tank and one or two fuel tanks are installed. Depending on the vehicle context and the available installation space, compressor air tanks (usually under the standard battery case), spare tyre or wheel chocks are installed in this area, too. All the components mentioned above are available in different sizes and are mounted in variable positions due to different customer requirements. The battery cases are usually mounted on the left side of the vehicle, but can also be placed on the right side of vehicles of emission class EURO 6 in order to mount a large fuel tank on the left side. The size of the fuel tank depends on the fuel volume required by the customer and can vary in one to two tanks of different sizes. The container size for the AdBlue tank, which contains the urea required for exhaust after-treatment, depends on the fuel tank size. Furthermore the customer needs the possibility to choose options such as “empty space on right side” to allow for the mounting of additional components on the frame that are necessary for their transport task, e.g. a pump in a milk float. For vehicles with a short wheelbase, e.g. 3600 mm as used in long-distance tractor units, the space in sector 5 is restricted. However, especially for this type of vehicle an extensive fuel tank volume is required. As a result, a large number of layouts have been created to ensure all available space is used for maximum fuel tank capacity.
The area of sector 5 is subjected to instability within the product lifecycle due to many dependencies, e.g. in the design phase of vehicle concepts it is not possible to predict how emissions standards and therefore the size of the technical solution will be affected in the future. As a result and depending on the large set of configurable options, an almost unmanageable number of positions of the individual components emerge, which are linked to each other by packaging conflicts or technical dependencies.

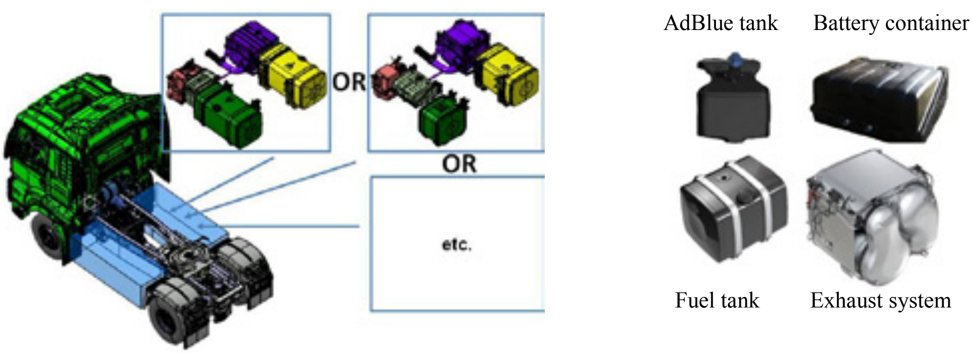


Figure 4: Sector 5 (blue boxes) with alternative possible layouts (left); components within layouts (right)

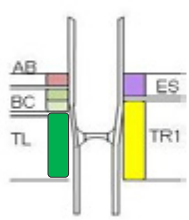
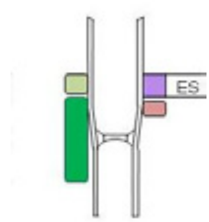
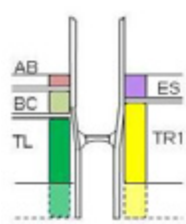
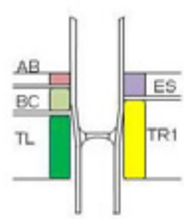
3.3 Layout breakdown

As the above sector 5 is complex in its cross dependencies through the topology of the components attached to the frame, a more “well sorted” arrangement could provide better and more consistent modularisation and thus component reuse, if it does not contradict any customer requirements.

There are different ways of layout tailoring, but all of them pursue the same goal. By interviewing design, product management and sales experts at the company, it became obvious that layouts must provide a documented overview of all existing technical solutions, guarantee collision-free packaging and contribute to standardisation. Further, layouts must provide the ability to compare solutions clearly and allow the assignment of layouts to vehicle characteristics. Therefore the different types of layout definition were evaluated by the experts on a scale of double-plus to double-minus.

The overall goal is to reduce the number of different layouts in order to simplify the coordination in development, production and assembly and saving expenses. Different types of layouts (cf. Table 1) are rated by the criteria *straightforwardness of the total number of layouts developed*, *transparency over existing solutions*, *flexibility of layout adjustment*, *guarantee of collision-free packaging* and its *contribution to the standardisation* in the particular sector. *Straightforwardness* means how many different layouts exist according to the type of layout definition. For example, if one component is moved slightly to the ladder frame, it depends on the type of layout definition if therefore the layout is named differently. This would cause an increase in the total number of layouts. *Transparency* rates how easily designers can get an overview of all existing layout solutions, in order to estimate the influence of component changes to the whole product portfolio. The non-flexible layout was proven to be most suitable. An advantage of this type of tailoring is a layout which comprises specific dimensions and thus reliably defines the functional installation space. A disadvantage is the relatively large number of layouts, since no functional installation spaces are summarized.

Table 1: Different types of layout formalisations to be reviewed

<table>
<tr><th>(A) functional</th><th>(B) flexible</th><th>(C) partly-flexible</th><th>(D) non-flexible</th></tr>
<tr><td colspan="4">AdBlue Tank | Battery container | Exhaust system | Fuel tank left | Fuel tank right</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td>Components are placed inside of predefined functional spaces (maximum limits).</td><td>Positioning of only a subset of components is defined fix per layout.</td><td>Predefined installation spaces expand flexibly depending on the wheel base.</td><td>Positioning of all components is defined fix per layout.</td></tr>
</table>

A functional layout (A) only describes the limit of functional installation spaces. Components have to be placed within the limits, but may vary in position as long as they are smaller than the functional area giving the limits. Thus, in the design of these layouts technical solutions can be summarized, in which identical maximum dimensions can be defined for the design spaces. For example, two layouts can be summarized, which have an identical arrangement of components. However, one layout has a large and the other layout a small tank. Likewise,

identical layouts can be summarized, in which one of the layouts only has one tank, whereas the other layout provides two. Consequently, the dimensional limits are preserved in both. Flexible layouts (B) describe only a minority of parts of an overall technical solution. Thus, certain standards can be documented with a single layout, such as the arrangement of the exhaust system in one specific location, without limitations for all other components. This type of layout provides great flexibility. One disadvantage is that they do not provide an overview of existing solutions, but allow for a collision-free overall packaging. Another way of defining layouts is to predefine installation spaces for all components, but allow for their flexible growth with the wheel base (C) being the most important variant driver for sector 5 (e.g. fuel tank rear limit is depending on wheel base to allow for maximum tank volume). A certain number of layouts can be combined by a partly-flexible layout definition and the amount of layouts is easier to manage. Nevertheless, collision-free packaging can be guaranteed. Layout D describes a clear combination of functional installation spaces and their exact leading and rear edge. With a gradual deregulation of restrictions the layouts (B) and (C) emerge from layout D. The functional layout (A) constitutes a combination of the layout approaches B and D: on the one hand, every component is installed within a specified area, on the other hand it allows for flexibility within this area whenever the component is smaller than the considered installation area.
Figure 5 illustrates an example of three different, but standardized truck layouts for the sector in question. For example, if customers order a vehicle with no special configuration, they receive the basic configuration in which the smallest fuel tank is mounted. By choosing another tank volume, the empty space between the exhaust system and the smallest tank version is used to enlarge the fuel tank by the principle of a series mentioned above. Based on the smallest available space in sector 5, layouts can be configured in the future by setting up a basic configuration, which can be expanded by larger components according to the available package space. In this case the variance is deliberately allowed with an adjustable tank. Since there are no dependencies between the fuel tank size and the other mounted parts, the variance is easy to manage. A customized vehicle can be offered, which is profitable for the company by only one varying component.

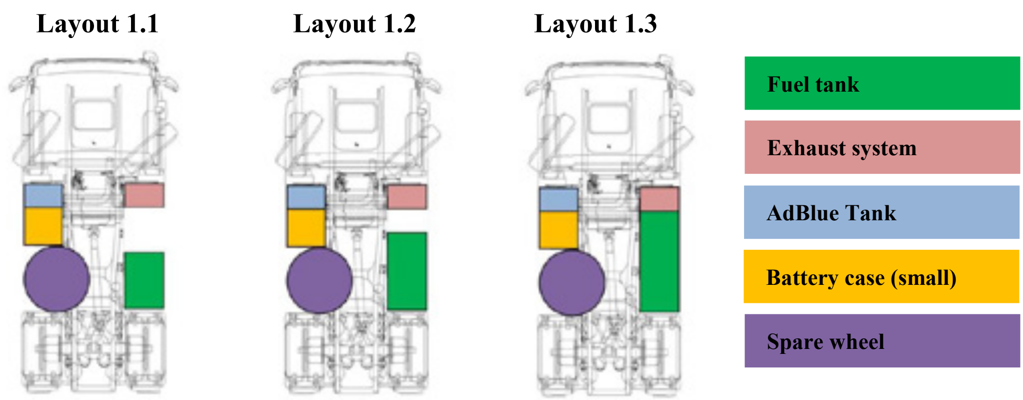


Figure 5: Exemplary standardized layouts with only one variable part (fuel tank)

So far, the presented method is a theoretical approach. It was conducted with ambitious use cases to evaluate its functionality. For the majority of vehicle configurations a layout was defined. Therefore every component was allocated to a certain area at the ladder frame. Combining all these functional areas, sample component arrangement patterns (layouts) were deduced. Referring to these layouts, it is possible e.g. for the design department to subdivide the vehicle and work already within certain guide rails, which are isolated independently by sector and mounting positions. Since all variants of components are already known at an early stage of design, peripheral devices, e.g. the cable harness, can be considered and optimized to fulfil all requirements with as little variants as possible.

4 Summary and conclusion

While the approach of offering niche products for a broad variety of customer needs is adopted by a portfolio of more than 15,000 basic vehicles, the cost aspect, i.e. to realize a given external variance at the lowest internal variance, becomes more important. To reduce the internal variance of products, several existing approaches for modularisation are presented. To make internal variance tangible for individual sectors and including their component arrangement patterns, a model for generic package space decomposition is developed. It allows for visualization of component positioning alternatives and the related requirements. The overall aim is to clarify internal variance not accounting directly for external variance, i.e. promoting the effectiveness of sales. Different layouts only add value, if they enable market-efficient product differentiation, i.e. achieving different customer requirements. As a result it is possible to standardize vehicle layouts without generating functional constraints (e.g. less available fuel volume for customer). Therefore, different layout approaches have been reviewed and compared with each other to find the most suitable approach for modularisation. Non-flexible layout formalisation is selected as it allows for best predictability of possible package spaces given that the completeness of all relevant components is part of the layout syntax. Consequently, series of the components to be mounted to the ladder frame can be derived and developed, which can reduce the number of existing layouts by systematic combination of different parts still satisfying customer requirements.

By designing new layouts at an early stage within the design process, it is possible to clarify potential fixed locations for components. Well designed and standardized interfaces increase transparency within the portfolio with positive effects for designers as well as logistics coordination by reducing the number of different mounting instructions. Non-flexible layouts also guarantee collision-free packaging and support the design of a lean modular kit of components. In the future all components will be analysed in this uniform manner in terms of their different characteristics (e.g. the number and step sizes of all fuel tanks offered). An optimal differentiation of step sizes is premised to fully exploit modularisation potentials on component level. By assigning sales figures to layouts, a statement on the demand of individual technical solutions and their priority, respectively, can be derived. This provides the basis for a future revision of the number of variants within the vehicle portfolio. With a manageably limited amount of standardized vehicle layouts made compulsory when designing or changing vehicles, a simplified, more transparent and modular overall vehicle structure will be sustainably enforced.

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