NordDesign 2018
August 14 – 17, 2018
Linköping, Sweden

Efficient Module Design for Chassis-Mounted Components of Commercial Vehicles

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Abstract

Commercial vehicle manufacturers have to offer mass customized products in order to serve a wide range of customers from various industries respectively their applications. Since each branch has specific needs at comparatively low sales volumes, manufacturers strive for standardization. Varying drivetrain configurations, wheelbases, rear overhangs and therefore chassis types cause varying available installation spaces and arrangements, so called layouts, for the chassis-mounted components, such as fuel tank, battery case or exhaust system. Especially between the vehicle, its chassis mounted components and the truck body work many interfaces exist, which have to be considered in the early design phase (Förg, Kreimeyer, & Lienkamp, 2014; Förg, Wolter, Kreimeyer, & Lienkamp, 2014).

The varying available installation spaces make it difficult to identify combinations of components, so called modules, to be used portfolio-wide, since the number of components to be considered during packaging changes due to technical reasons.

Existing modularization approaches in literature either strategically approach the modularization problem and try to develop modules which can be shared by many products or they consider the problem as a technical problem and develop modules from components which are highly connected with each other. Some authors have tried to combine both approaches and tried to identify modules, which fulfil both considerations at the same time. However, it has always became a problem to decide how many components should be included in modules, as there are always components which are somewhat connected with identified modules. In most cases, due to some small differences, some components have been excluded from modules or included in them. Furthermore, restricted packaging spaces in different products of a product family have mostly been ignored, and hence, available packaging spaces could not be optimally used.

This paper proposes a two-step approach through which efficient modules for chassis-mounted components can be developed. In the first step, module alternatives are decided by using an algorithm which is based on the strategic and technical requirements for developing modules from chassis-mounted components. In the second step, final module selection is done by considering the available packaging spaces in vehicles. Among the considered module alternatives, the ones enabling the highest standardization levels are selected. Hence, the decision for the included component number in modules becomes more goal-oriented. The proposed methodology is validated with a Use Case.

In this way, efficient modules, which consist of highly connected components, which can be shared by many vehicles with different topologies, and which enable high standardization levels, are identified. This further helps to obtain reduced lead times, reusability, pre-assembly of the components, and to shorten cables and pipes in system.

Keywords: Modularization, Standardization, Module Design, Portfolio Management, Commercial Vehicles

1 Introduction

In contrast to car manufacturers, commercial vehicle manufacturers deal with higher complexity as they have to adapt their product topology specifically to customer applications. While car manufacturers offer only a few wheelbase options, customers of commercial vehicle manufacturers have more configuration options since wheelbase and rear overhang determine transportation capacities, load distributions, and installation space sizes near and in the middle of the chassis, which are used to install components such as fuel tank, exhaust system, and battery carrier (Stocker, Schmidt, Kreimeyer, & Lienkamp, 2016). Moreover, higher transportation capacities require powerful drive lines such as the all-wheel-drive, which further restrict installation space sizes especially in the middle of the chassis. To deal with this complexity and fulfil customer requirements with less effort, commercial vehicle manufacturers strive for positional standardization of components in vehicles.

2 State of the Art

Increasing customer-specific requirements for product layouts have forced manufacturers to find ways to control and manage the complexity in design and production processes efficiently. This consequently led to analyze product architectures, since it has been considered to be a tool to manage complexity.

Many researchers suggested the use of modularity to obtain a good product architecture (Erixon, 1998). However, there is no unique definition of it. Ulrich (1995) approached it by mapping functional elements to physical components, while Erixon (1998) also took customer requirements into account. Martin and Ishii (2002) strategically approached the problem and tried to reduce the design efforts for future products while building modules. Many researchers defined the modularization as “building larger assemblies by bringing sub-assemblies together”., Simplified product architectures through modularization allow today the OEM’s and suppliers to simultaneously develop their products (Koppenhagen, 2014).

Researchers have considered the modularization problem either as a technical problem (Lindemann, Maurer, & Braun, 2008; Martin & Ishii, 2002) and used matrices such as the design structure matrix (DSM) or as a strategic problem (Erixon, 1998), for which a solution should be found by considering all strategic issues about the problem. Some researchers combined both of these approaches (Blees, 2011; Borjesson & Hölttä-Otto, 2014; Koppenhagen, 2014). The technical approaches aimed to obtain independent modules in order to reduce overall lead time (Borjesson & Hölttä-Otto, 2014). The strategic approaches tried to create modules that can be shared by many product variants in a product family. This helps to create economies of scale in the company (Borjesson & Hölttä-Otto, 2014). Limited packaging spaces, on the other hand, have mostly been ignored by the authors while developing their modules (Förg, Stocker, Kreimeyer, & Lienkamp, 2014).

The strategic considerations include determination of module drivers which show how appropriate components are for building modules. The approaches developed by Erixon (1998) and Blees (2011) focused on finding module drivers by considering all stakeholders about the

product. Modules enabled them to easily deal with components at different stages of their product life-cycles, as they grouped components, fulfilling same module drivers, together.
Chassis-mounted components of commercial vehicles have less interfaces with each other compared to the other examples in literature. Many of the module drivers proposed by Erixon (1998) are not applicable for them. For example, they cannot be differentiated according to their needs for "separate testing", as all chassis-mounted components can already be tested separately. They can be easily assembled or disassembled and already handled well at different stages of their product lifecycles. Hence, the module drivers should be adapted for commercial vehicles and new module drivers should be defined accordingly to gain strategic advantages.

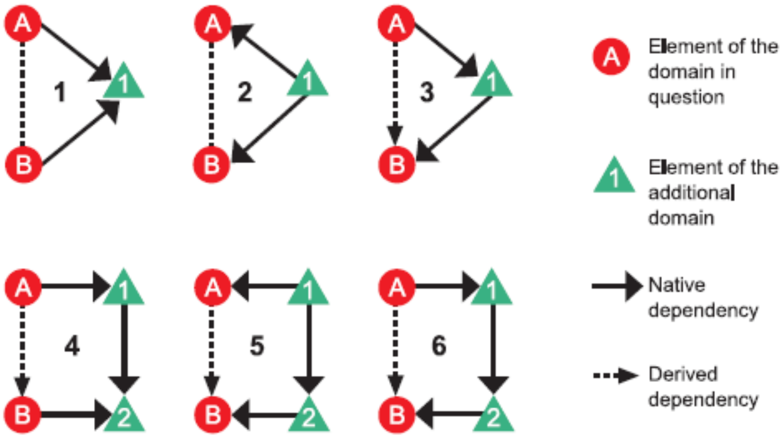


Figure 1. The six deduction logics for the indirect dependencies (Lindemann et al., 2008)

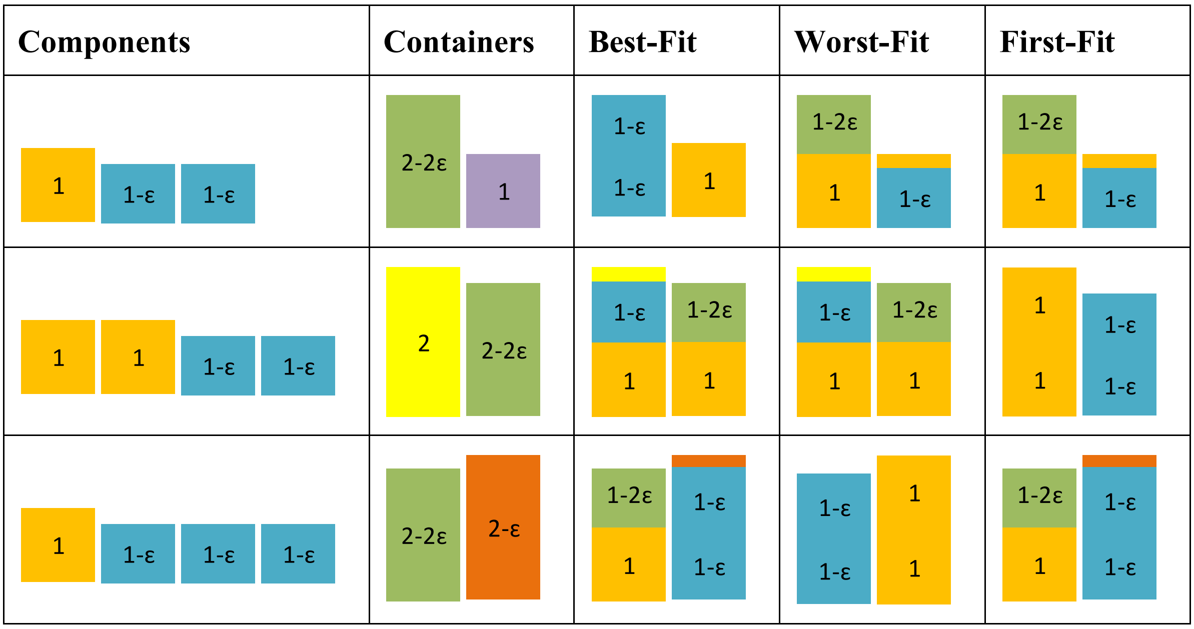
Secondly, the Design Structure Matrix (DSM) is considered to be a powerful tool to deal with the technical relations in a product. Lindemann et al. (2008) showed a method to derive indirect dependencies in a system and also used them in contrast to the other DSM approaches which are mostly based on only direct dependencies, because for some systems, like the chassis-mounted components, number of the direct dependencies might be very low, which cannot be analyzed further, as the DSM methodology requires more dependencies. Figure 1 shows the six deduction logics for deduction of indirect dependencies according to Lindemann et al. (2008). According to them, two components are dependent on each other, if they are connected with a common component or with two components, which are connected with each other.
Thirdly, geometrical limitations in the products have been mostly ignored by researchers while developing modules. The component-loading, knapsack and bin-packing problems in literature deal with the packaging issue. There are mathematical, metaheuristic and heuristic models for these problems which try to find the optimum packaging solutions for components according to given criteria. The heuristic algorithms are popular for solving complex problems, as they can find quick and efficient solutions for the cases which cannot be solved by mathematical and metaheuristic models. While the bin-packing algorithms deal with the allocation of components into the bins, the algorithms for the component-loading problem rather try to find the best position of components in large spaces. As commercial vehicles include many non-connected installation spaces, this paper focuses on the bin-packing algorithms.
As explained by Burke et al. (2006), the heuristic algorithms for the bin-packing problem are as follows:

- Best fit: It puts the component into the fullest bin. If more than one options are available, the left-most one is chosen. A new bin is only opened when no other option is available.
- First fit: It is similar to the best fit algorithm, but it puts the component into the left-most bin.

- Worst fit: It puts the component into the emptiest bin. If more than one options are available, the left-most one is chosen. A new bin is only opened when no other option is available.
- Almost worst fit: It puts the component into the second-emptiest bin. If more than one options are available, the left-most one is chosen. A new bin is only opened when no other option is available.
- Next fit: It puts the component in the right-most bin and opens a new one if no bin is available.

In literature, there are many papers where components are installed in descending order according to their volumes (Garey, Graham, & Ullman, 1972; Haessler & Talbot, 1990; Johnson, 1974; Lim, Rodrigues, & Yang, 2005). Garey and Graham (1972) proved why the first-fit and best-fit decreasing algorithms outperform the others. Johnson (1974) even showed that the worst-fit decreasing can also be as good as the first-fit and best-fit decreasing algorithms.

Table 1. Comparison of the modifications of the bin-packing heuristics



Components	Containers	Best-Fit	Worst-Fit	First-Fit
1 1-ε 1-ε	2-2ε 1	1-ε 1-ε 1	1-2ε 1 1-ε	1-2ε 1 1-ε
1 1 1-ε 1-ε	2 2-2ε	1-ε 1 1-2ε 1	1-ε 1 1-2ε 1	1 1 1-ε 1-ε
1 1-ε 1-ε 1-ε	2-2ε 2-ε	1-2ε 1 1-ε 1-ε	1-ε 1-ε 1 1	1-2ε 1 1-ε 1-ε

Table 1 compares the three modifications of the bin-packing approaches if it is assumed that components should be packaged in a given number of containers. As seen, there are cases, where each algorithm can be better than the others. The first two cases are adapted from the paper written by Garey and Graham (1972), while the last one is adapted from the paper of Johnson (1974). They also proved that the limit of the ratio of the number of the needed bins for each algorithm to the optimum number of the needed bins lies between 11/9 and 5/4. One should note that the modified best-fit approach always guarantees the optimum solution if the number of components is one higher than the number of containers, whereas the other two modified algorithms would find non-optimum solutions in these cases.

This paper combines the strategic and technical module development approaches by using the MDM methodology and tries to select appropriate modules for chassis-mounted components of commercial vehicles according to available packaging spaces by using the bin-packing algorithms instead of trying to find the cluster with the highest interaction in the MDM.

3 Methodology

This paper proposes a method to design efficient modules through which both strategic and technical advantages can be gained. Chapter 3.1 introduces the strategic factors to be considered for chassis-mounted components, while Chapter 3.2 introduces the technical factors. Chapter 3.3 presents a method which combines both strategic and technical aspects. The method can also be supported by a clustering algorithm. At the end, the final module selection is conducted based on the available packaging spaces in vehicles.

3.1 Strategic Module Design

Erixon (1998) developed the Module Indication Matrix which was later used by many other authors. The chassis-mounted components are individual components having their own roles in a vehicle. They are in a competition with each other for installation spaces and have many configuration possibilities. Hence, they have less dependencies with each other compared to the examples in literature and can already be handled well at different stages of their product lifecycles. Due to this reason, the need for many module indicators in the MIM is eliminated for the chassis-mounted components. The adapted requirements are as follows:

1. **Variance**: Some of the chassis-mounted components have big differences in terms of their designs to overcome various installation space, customer, and legal limitations. Components with high dimensional variance are difficult to modularize, as for each variant, new component arrangements in the modules should be defined. For example, the fuel tank cannot build modules so easily as it has many variants with different dimensions. A module in a vehicle cannot necessarily be used in another vehicle due to its sizes. Thus, standardization of layouts would be difficult.

2. **Common unit:** According to Erixon (1998), there are components which are used for all product variants. In contrast to the customization components, these components can take part in the same modules. In contrast, customization components can be only used with the components which fulfil distinctive features. According to Kipp (2013) distinctive features should be fulfilled with exactly one component or component group (module). Therefore, the components, which fulfil distinctive features, should not be used with the common unit components in the same modules. For example, a hydraulic auxiliary drive is not a common unit for all vehicles. Thus, building a module from its components can reduce standardization in portfolio.

3. **Space requirement**: Another factor, that affects the module sharing across different product variants, is the space requirement. Commercial vehicles have limited installation spaces. Moreover, different vehicle variants have different volumes of free installation spaces. To be able to generate modules from chassis-mounted components and to be able to use these modules in all vehicle variants, especially in the chassis middle, a low degree of space requirement by the components is required. For example, fuel tanks are not appropriate to build modules since they already have a large cross-sectional area.

4. **Customer requirement:** Commercial vehicle manufacturers offer products for a broad spectrum of industries, which lead to varying customer requirements for the same vehicle types. For some components, such as the fuel tank, customers prefer to specify the installation positions. Sometimes, these positions are even determined by legal regulations. For example, Component A should be mounted in the front part of the chassis while for

Component B other positions can be specified by customers. In such cases, they are not appropriate to build modules together.

In the next stage, components should be evaluated based on these requirements. Components, which fully fulfil a strategic requirement, are evaluated with "1", while components, which partly fulfil a strategic requirement, are evaluated with "0.5". Moreover, "0" point is given to the components for a strategic requirement, if the component does not fulfil it. At the end, by combining the answers for each component and strategic requirement, a component-to-strategic requirement Domain Mapping Matrix (DMM) is obtained. The upper branch in Figure 3 represents the strategic module development, which starts with the DMM.

3.2 Technical Module Design

Building independent modules brings many advantages to manufacturers. For example, by placing all electrical components together, one can reduce the total cable length in a system and obtain a product which looks cleaner. One can also minimize the total pipe length by focusing on the material flows. Furthermore, this would enhance simultaneous development of the components and pre-assembly.

Only three of the four interactions in terms of energy, material, and information will be used in context of this paper. The spatial interactions are not required in the technical module design, as the chassis-mounted components can be positioned at various positions in the vehicles. Moreover, material or energy flows between components already reveal this information. For chassis-mounted, only material, energy, and information flows result in a requirement for spatial closeness. For example, two chassis-mounted should not be installed side by side for mechanical power transmission.

In a component-to-component DSM, the cells, which correspond to a technical flow, will be marked by "1" and the rest will be left "0". The lower branch in Figure 3 represents the technical module development and starts with the DSM.

3.3 Combination of the Technical and Strategic Considerations

Lindemann et al. (2008) introduced the Multiple Domain Matrix, which enables to deal with more than one domain. The MDM for the chassis-mounted components is given in Figure 2. The DMM should be replaced by the strategic matrix, while the DSM should be replaced by the technical matrix. It was assumed that the module drivers are not related with each other. Hence, the cells on the diagonal are marked by "1"and the other cells are marked by "0".

Next, the indirect dependencies should be deducted for the DSM, as component pairs are tried to be found at the end. For the deduction of the indirect dependencies, only the directed dependencies will be considered, which refer to the case 3 and case 6 in Figure 1. There are two main reasons for that:

- There are only two domains. Thus, the consideration of the six cases is not required, since they would give similar results.
- The MDM is highly symmetric.

Moreover, the indirect dependencies until the third-degree are considered in this paper, as throughout the case studies, following degrees of connectivity were observed for the chassis-mounted components, if the considered degrees of dependency are changed:

- A degree of connectivity of 0.11 was obtained, if only direct dependencies are considered.
- A degree of connectivity of 0.27 was obtained, if dependencies until the second-degree are considered.

- A degree of connectivity of 0.38 was obtained, if dependencies until the third-degree are considered.

The optimization algorithms require ideally a degree of connectivity, which is higher than 0.30, as shown by Schweigert et al. (2017).

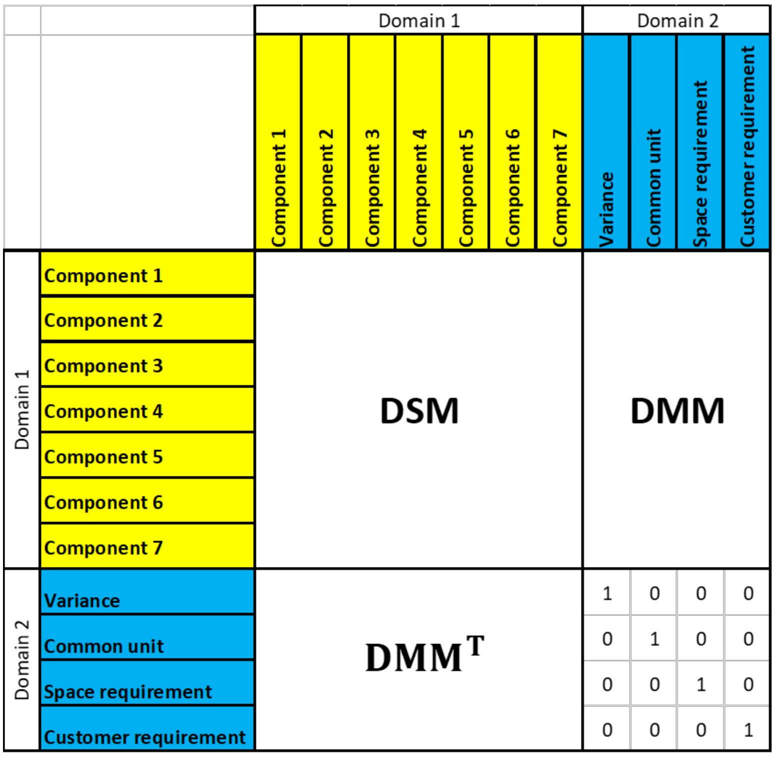


Figure 2. The MDM for chassis-mounted components

Case 3 in Figure 1 gives the second-degree dependencies and they are calculated by Eq. (1). It can be rewritten as follows:

$$DSM_{second-degree} = \underbrace{(DSM \times DSM)}_{\boxed{DSM_{2nd-deg-technical}}} + \underbrace{(DMM \times DMM^T)}_{\boxed{DSM_{2nd-deg-strategic}}} \tag{1}$$

Case 6 refers to the directed third-degree dependencies and they are calculated by Eq. (2). The Eq. (2) can be rewritten as follows:

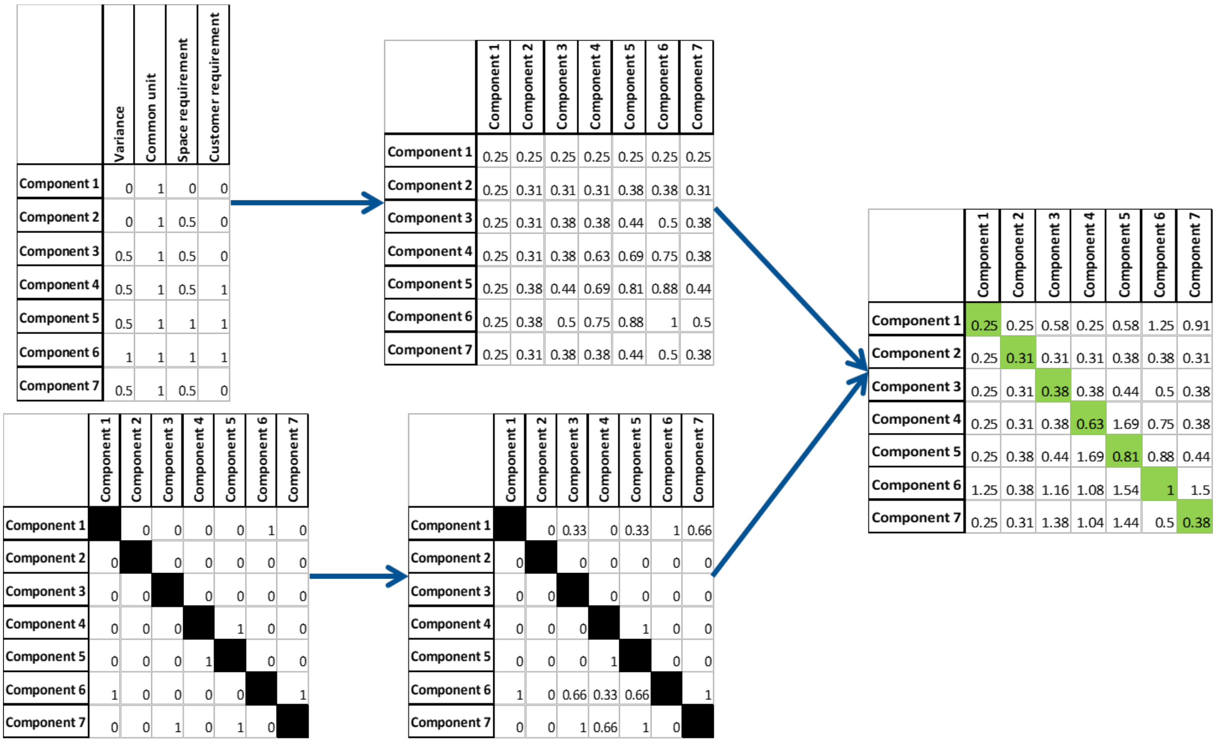
$$DSM_{third-degree} = \underbrace{(DSM \times DSM \times DSM)}_{\boxed{DSM_{3rd-deg-technical}}} + \underbrace{(DMM \times I \times DMM^T)}_{\boxed{DSM_{3rd-deg-strategic}}} \tag{2}$$

One can observe that the strategic parts of the DSMs in Eq. (1) and (2). are equal. Thus, it is enough to calculate the $DSM_{2nd-deg-strategic}$.

To normalize the results to the 0-1 range, the second-degree-strategic DSM is divided by the number of module drivers, namely four.

$$DSM_{2nd-deg-strategic} = \frac{DMM \times DMM^T}{\#\ of\ module\ drivers} \tag{3}$$

The numbers in the cells $DSM_{2nd-deg-technical}$ and $DSM_{3rd-deg-technical}$ indicate, how many second-degree or third-degree dependencies exist in the system between two components. For larger systems, more than one indirect dependencies can exist between components.



	Variance	Common unit	Space requirement	Customer requirement
Component 1	0	1	0	0
Component 2	0	1	0.5	0
Component 3	0.5	1	0.5	0
Component 4	0.5	1	0.5	1
Component 5	0.5	1	1	1
Component 6	1	1	1	1
Component 7	0.5	1	0.5	0

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
Component 1	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Component 2	0.25	0.31	0.31	0.31	0.38	0.38	0.31
Component 3	0.25	0.31	0.38	0.38	0.44	0.5	0.38
Component 4	0.25	0.31	0.38	0.63	0.69	0.75	0.38
Component 5	0.25	0.38	0.44	0.69	0.81	0.88	0.44
Component 6	0.25	0.38	0.5	0.75	0.88	1	0.5
Component 7	0.25	0.31	0.38	0.38	0.44	0.5	0.38

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
Component 1	■	0	0	0	0	1	0
Component 2	0	■	0	0	0	0	0
Component 3	0	0	■	0	0	0	0
Component 4	0	0	0	■	1	0	0
Component 5	0	0	0	1	■	0	0
Component 6	1	0	0	0	0	■	1
Component 7	0	0	1	0	1	0	■

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
Component 1	■	0	0.33	0	0.33	1	0.66
Component 2	0	■	0	0	0	0	0
Component 3	0	0	■	0	0	0	0
Component 4	0	0	0	■	1	0	0
Component 5	0	0	0	1	■	0	0
Component 6	1	0	0.66	0.33	0.66	■	1
Component 7	0	0	1	0.66	1	0	■

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6	Component 7
Component 1	0.25	0.25	0.58	0.25	0.58	1.25	0.91
Component 2	0.25	0.31	0.31	0.31	0.38	0.38	0.31
Component 3	0.25	0.31	0.38	0.38	0.44	0.5	0.38
Component 4	0.25	0.31	0.38	0.63	1.69	0.75	0.38
Component 5	0.25	0.38	0.44	1.69	0.81	0.88	0.44
Component 6	1.25	0.38	1.16	1.08	1.54	1	1.5
Component 7	0.25	0.31	1.38	1.04	1.44	0.5	0.38

Figure 3. The strategic and technical module design

To simplify the method, the information of how many second or third-degree dependencies exist between components, will not be used. Moreover, it does not influence the fact at which dependency the components are connected with each other for the first time. It will be assumed that a first-degree dependency is always superior to a second-degree dependency and a second-degree dependency is always superior to a third-degree dependency.

Lastly, a new matrix will be generated which includes at which dependency two components are connected with each other for the first time.

A linear relationship is assumed, and the following values are used:

- 1, if two components are connected with a direct dependency.
- 0.66, if two components are not directly connected, but they are connected with a second-degree dependency.
- 0.33, if two components are not connected with a second-degree dependency, but they are connected with a third-degree dependency.
- 0, if two components are not connected even with a third-degree dependency.

At the end the results for the technical and strategic dependencies will be summed up. An example case is shown in Figure 3. In the upper branch, a strategic DMM is given and converted into a second-degree strategic DSM. Similarly, a technical DSM with only direct flows is given in the lower branch and converted into a technical second-degree technical DSM. A final matrix is obtained by summing up both DSMs.

3.4 Package-Oriented Final Module Selection

Lastly, the chassis-mounted components should be tried to be standardized in the chassis middle of the commercial vehicles as much as possible by also enabling optimum volume utilization, as these spaces vary too much from vehicle to vehicle and they cannot be efficiently used if no standardization exists there.

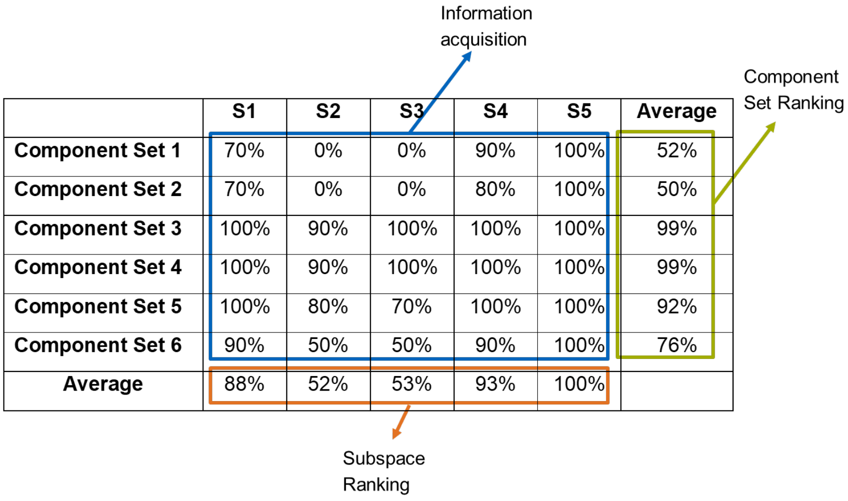
From the final matrix, which includes both strategic and technical dependencies, meaningful cluster alternatives should be generated. However, the decision for how many of the connected components should be included in modules should be based on a packaging heuristic, which tries to select the module with the highest standardization rate and the most efficient volume utilization in the vehicles. In that way, modules with strong technical dependencies can be designed, while enabling strategic advantages and optimum volume utilization.

The proposed packaging heuristic of this paper is based on the modified best-fit algorithm shown in Table 1. To enable the best volume utilization, the highest possible cluster alternative found by the first part of the methodology should be standardized in the smallest subspace. However, the smallest subspace is not easy to find, as they vary too much from one vehicle to another. Hence, average values will be used, and it will be assumed that a subspace is small if modules cannot be packaged there due to geometrical limitations.

Figure 4. Overview of the packaging solution

Figure 4 summarizes the proposed packaging solution for module selection. In the first step, meaningful subspaces, which are common for most of the vehicles, should be generated to be able to apply the packing heuristic. In the second step, the information, in how many vehicles the proposed modules can be packaged in the subspaces, must be found. Next, the considered module alternatives should be ranked according to their volumes in descending order, as suggested by many packaging heuristics. In the fourth step, the subspace, where the considered module alternative can be packaged with the highest rate, should be selected. If two subspaces enable equal rates, the one where other modules can be packaged there with less rates, should be selected, as it is smaller. Lastly, the module and the appropriate subspace for it should be decided.

Figure 5 shows the application of the proposed solution on an example case. In this case, Component Set 3 is the biggest module alternative, as it is the difficult to package. Subspace S5 offers the highest standardization rate for it.



	S1	S2	S3	S4	S5	Average
Component Set 1	70%	0%	0%	90%	100%	52%
Component Set 2	70%	0%	0%	80%	100%	50%
Component Set 3	100%	90%	100%	100%	100%	99%
Component Set 4	100%	90%	100%	100%	100%	99%
Component Set 5	100%	80%	70%	100%	100%	92%
Component Set 6	90%	50%	50%	90%	100%	76%
Average	88%	52%	53%	93%	100%	

Figure 5. Example application of the proposed heuristic

4 Results

The proposed modularization methodology has been applied on 24 chassis-mounted components to obtain meaningful component sets to be standardized in the chassis middle. A clustering algorithm has also been used to identify modularization possibilities under different assumptions.

From the algorithm results under different assumptions, it was observed that the three components "compressed air reservoir– 40L (CAR – 40L)", "air dryer (AD)", and "multi-circuit protection valve (MCPV)" have strong technical interactions with each other. As they are common units for all vehicles, are small, have only a few variants and have no specific positions, they also fulfil the strategic requirements very well. "Control board (CB)" has also technical interactions with the CAR – 40L and MCPV, and hence, it can be added to the other three components, as observed in the algorithm results.

The CAR – 40L can also be replaced by the "compressed air reservoir – 30L (CAR – 30L)", which requires less installation space, without any additional technical effort. However, it should be noted that the CAR – 30L is not common for all vehicles. These module alternatives are shown in Figure 6 with their technical flows.

Moreover, the prefuse boxes ATO and Power play central roles in the electronic system of the vehicles. They have many direct and indirect dependencies with each other. They also fulfil the strategic requirements very well.

After identifying the most promising module alternatives, the final selection should be based on the available packaging spaces in the vehicles. At this stage, it should be decided whether the red dotted alternatives should be realized or due to packaging concerns any other component in Figure 6 should be packaged with the red-dotted solutions.

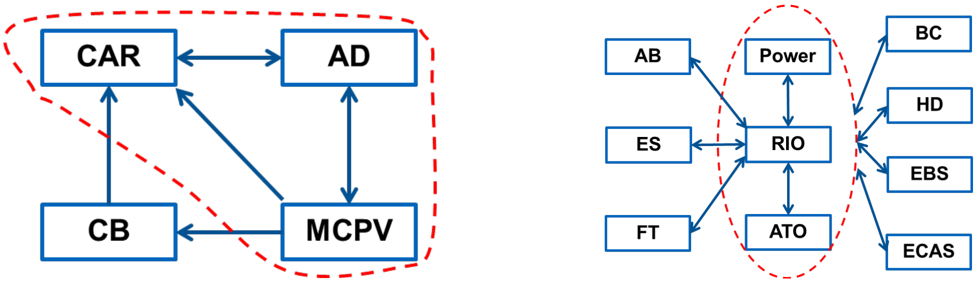


Figure 6. The proposed module alternatives for the air and electronic components

For that purpose, the proposed heuristic was manually applied on a portfolio of fourteen vehicles. As the first cross-beam and cardan shaft exist in all vehicles, they are used to define subspaces. Moreover, the space in the rear is also common for all vehicles.

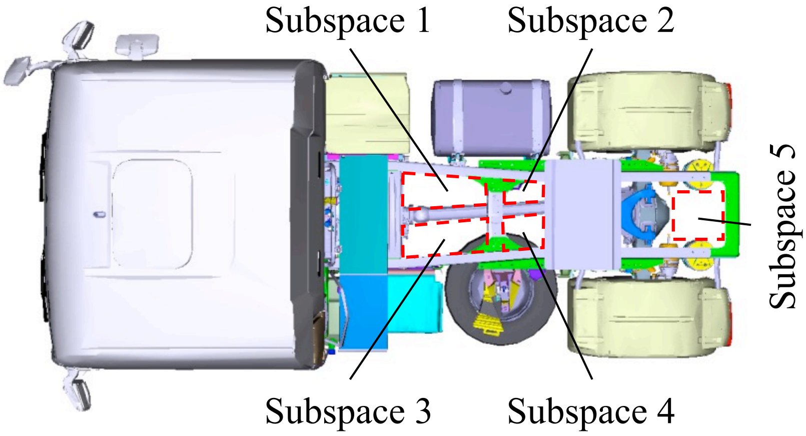


Figure 7. Subspace generation within a Semi-trailer tractor (Top view; Source: manted.de)

Analyses have shown that the free space in the rear is the only space which enables standardization of air components in the middle. Moreover, the module alternative with CAR – 40L is the biggest realizable alternative among the others. If there would be less space in the rear, one more component should have been removed from the suggested module. As “Control Board” requires access from outside, it cannot be standardized in the middle.

Secondly, after the standardization of a compressed air reservoir in the rear, there occurred a free space under the battery carrier, which has also cable connections with the three electronic components in Figure 6. In this way, a new module with higher technical interactions can be obtained.

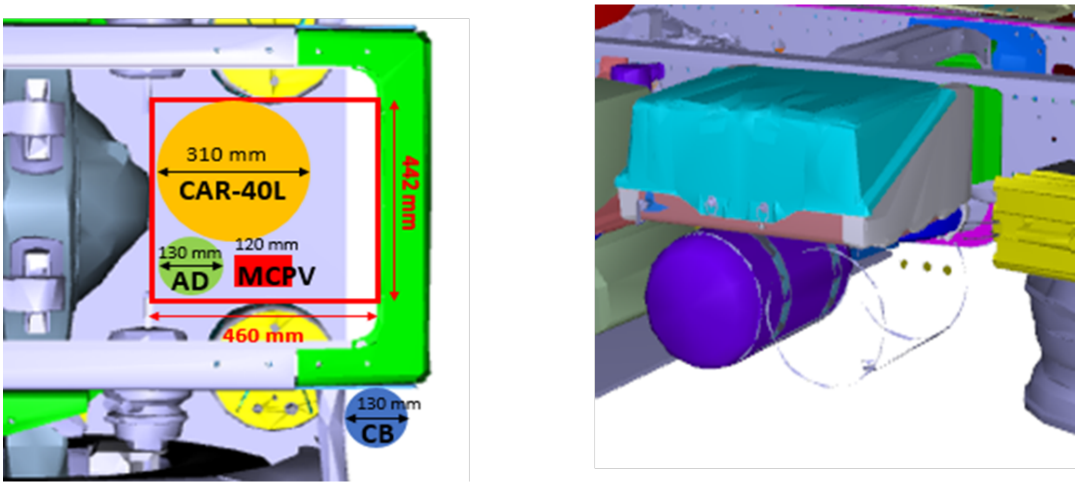


Figure 8. New module suggestions

5 Conclusion

To sum up, this paper proposes a new methodology to design efficient modules from chassis-mounted components of commercial vehicles. The proposed methodology considers both technical and strategic module development issues by using the MDM methodology. However, it is not only based on mathematical formulations and is supported by a packaging heuristic to be able to design modules regarding topological standardization and efficient use of packaging spaces. At the end, the proposed methodology has been applied on chassis-mounted components, and efficient modules, which have both technical dependencies and allow the reuse across different the vehicle variants at standard positions have been identified.

The methodology should be applied on more case studies to check its validity and the information acquisition step of the packaging heuristic should be automatized to be able to cover all vehicles in the portfolio.

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