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Automated Development of Modular Systems for the Vehicle Front of Passenger Cars

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List of Abbreviations

ADAC	Allgemeine Deutsche Automobil-Club
AIS	Available Installation Space
AMS	Auto Motor und Sport
ASM	Asynchronous Machine
BEV	Battery Electric Vehicle
BOF	Ball-of-Foot
CAD	Computer-Aided Design
DC	Length of the Dimensional Chain
FCEV	Fuel Cell Electric Vehicle
GCIE	Global Car Manufacturers Information Exchange
GUI	Graphical User Interface
HEV	Hybrid Vehicle
ICEV	Internal Combustion Engine Vehicle
LDS	Longitudinal Dynamics Simulation
MLB	“Modularer Längsbaukasten“
MLBevo	“Modularer Längsbaukasten“ in the second generation
MSM	Modular Systems Matrix
MVCDP	Multiple Vehicle Concept Development Process
nMAE	Normalized Mean Absolute Error
OOST	Out-of-Sample Test
PACE	Parametric Automotive Concept Engineer
PHEV	Plug-In Hybrid Vehicle
PSM	Permanent Synchronous Machine
RCAR	Research Council for Automobile Repairs
SgRP	Seating Reference Point
SOP	Start of Production
VCDP	Vehicle Concept Development Process

List of Definitions

The following provides a list of the most important terms of this thesis and the authors definition and use of them.

Cross-vehicle module	Component variant, which finds application in multiple vehicle models and vehicle variants
Dimensional chain	Chain of component sizes and distances between ambient components within a start and end point along a defined coordinate direction
External variance	Total number of vehicle models and vehicle variants offered by an automotive manufacturer
Geometric substitute model	Empirical and semi-physical model, which converts requirements into component sizes and distances between components
Internal variance	Total number of component variants and position variants used by an automotive manufacturer
Method and tool	Development approach/procedure and the implementation in a software tool
Modular system	Set of different vehicle models with various vehicle variants, that share unified architectural standards and use cross-vehicle modules
Unified architectural standard	Element of the vehicle architecture standardized among multiple vehicle models and vehicle variants
Vehicle architecture	Body structure as well as dimensions and installation positions of the largest and for the functionality most important components
Vehicle concept	Preliminary representation of a vehicle which fulfills the requirements demanded
Vehicle model	A vehicle, as one combination of vehicle segments and body types
Vehicle variant	Variant of a vehicle model with one combination of performance classes, drive types, and drivetrain types

List of Symbols

Symbol	Unit	Description
α		Constant term
A_A	m^2	Vehicle front surface
$AIS_{EC/X}$	mm	Available installation space of the engine compartment in the x-direction
$a_{max,T}$	m/s^2	Maximum acceleration due to traction limit
a_{min}	m/s^2	Minimum acceleration
$a_{V,t}$	m/s^2	Acceleration at the current time step
β_i		Gradient term
b	mm	Bore diameter
γ_i		Gradient term
cs	mm	Cylinder spacing
c_W	-	c_W-value
c_{RR}	-	Rolling resistance
δ_i		Gradient term
D		Dependent variable (dimension)
$d_{BB-CS/x}$	mm	Distance between the bumper beam and the cooling system in the x-direction
$d_{CS-E/x}$	mm	Distance between the cooling system and the engine in the x-direction
$d_{E-BW/x}$	mm	Distance between the engine and the bulk wall in the x-direction
$DC_{EC/X}$	mm	Length of the dimensional chain over the engine in the engine compartment
$d_{PP/x}$	mm	Pedestrian protection distance in the x-direction
OH	mm	Front overhang of the vehicle
g	m/s^2	Force of gravity
i_{G_1}	-	Transmission ratio of the first gear speed
i_{G_a}	-	Minimum transmission ratio for minimum acceleration
$i_{G_{cl}}$	-	Minimum transmission ratio for climbing

$i_{G_{cr}}$	-	Minimum transmission ratio for creep velocity
i_{G_n}	-	Transmission ratio of the engaged gear speed (with differential)
i_{G_p}	-	Maximum transmission ratio for producibility
i_{G_t}	-	Maximum transmission ratio for traction limit
λ	-	Rotational inertia factor
L_{CB}	mm	Cylinder block length
L_{OH}	mm	Engine overhang length
L_E	mm	Engine length
$m_{V,L}$	kg	Loaded vehicle weight (varies according to scenario)
$m_{V,0}$	kg	Vehicle curb weight
η_{dr}	-	Efficiency of the drivetrain
η_{Mod}	-	Level of modularization
n_C	-	Number of cylinders
$n_{c,Max}$	-	Maximum number of components
$n_{E,Min}$	1/min	Idle speed of the engine
n_{Mod}	-	Actual number of modules
$n_{Mod,Min}$	-	Minimum number of components
ρ_A	kg/m^3	Air density
PM	mm	Prestige measure
$P_{v_{max}}$	kW	Required engine power for maximum velocity
q	°	Slope angle (varies according to scenario)
r_{dyn}	m	Dynamic rolling radius
r_{SB}	-	Stroke-bore ratio
s	mm	Stroke
$s_{BB/x}$	mm	Bumper beam thickness in the x-direction
$s_{BW/x}$	mm	Bulk wall thickness in the x-direction
$s_{CS/x}$	mm	Cooling system thickness in the x-direction
$s_{E/x}$	mm	Engine length in the x-direction
$s_{LCP/x}$	mm	License plate thickness in the x-direction
$s_{PE/x}$	mm	Pedal system size in the x-direction
$T_{E,Max}$	N m	Maximum torque of the engine
$T_{E,t}$	N m	Engine torque at the current time step

V_{OC}	cm³	Optimal cylinder swept volume
V_C	cm³	Cylinder swept volume
v_{Cr}	m/s	Creep velocity
$V_{B,j}$		1 to j binary explanatory variables
V_{ED}	cm³	Engine displacement volume
$V_{ED_{NAG}}$	cm³	Engine displacement volume of gas naturally aspirated engines
$V_{ED_{SCD}}$	cm³	Engine displacement volume of diesel supercharged engines
$V_{ED_{SCG}}$	cm³	Engine displacement volume of gas supercharged engines
v_{max}	m/s	Maximum velocity
$V_{M,i}$		1 to i metric explanatory variables
$v_{tol,L/U}$	m/s	Lower/upper tolerance velocity
$v_{v,t}$	m/s	Velocity at the current time step

1 Introduction

1.1 Research Motivation

The automotive industry has come a long way since FORD said in 1922 “Any customer can have a car painted any color that he wants so long as it is black” [1, p. 72]. Following the megatrends of globalization, mass customization, and environmental protection, automotive manufacturers nowadays offer their customers a high number of product variants [2, p. 2, 3, p. 115, 4, p. 12, 5, pp. 19-20]. The vehicles, for example, differ in their segments and body types, performance classes as well as drivetrains (Figure 1.1).

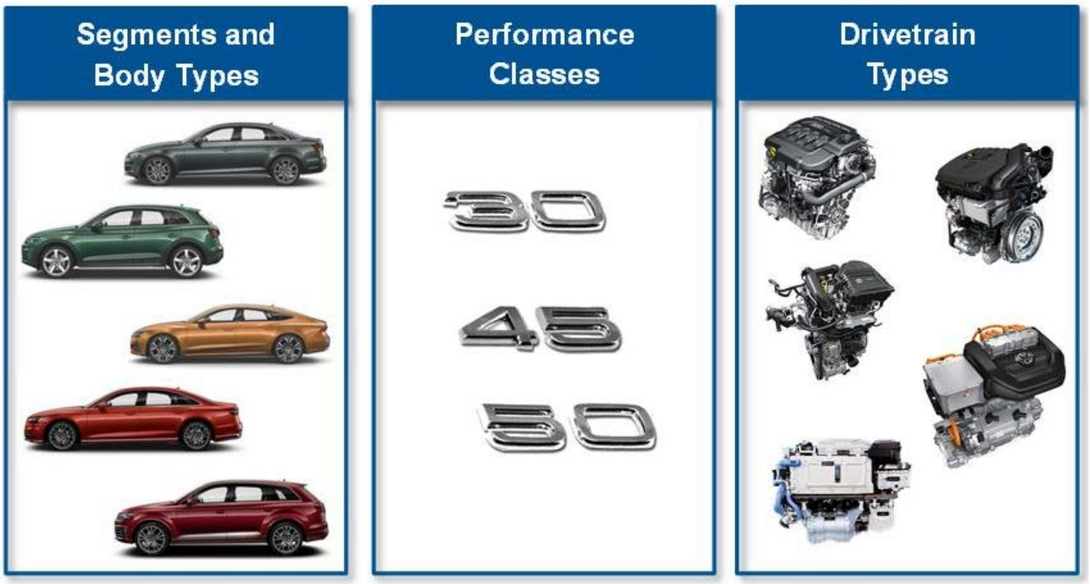


Figure 1.1: Examples of different segments and body types, performance classes, and drivetrain types (Image Sources: [6–12])

The offered products and the global revenue share of the AUDI AG exemplify these trends and the increase in variance (Figure 1.2). While in 2006, only 13 vehicle models were available as a combination of a segment and body type, the number rose to 25 in 2016 [13, p. 145, 14, p. 152, 15, p. 112]. Comparing the revenue shares of the company within the same period shows the increasing globalization, as the revenue share decreased in Europe and increased in other regions such as North America and Asia [13, p. 202, 14, p. 245, 15, p. 241]. In a previous publication [16], the author provides further details about the product variants in the automotive industry.

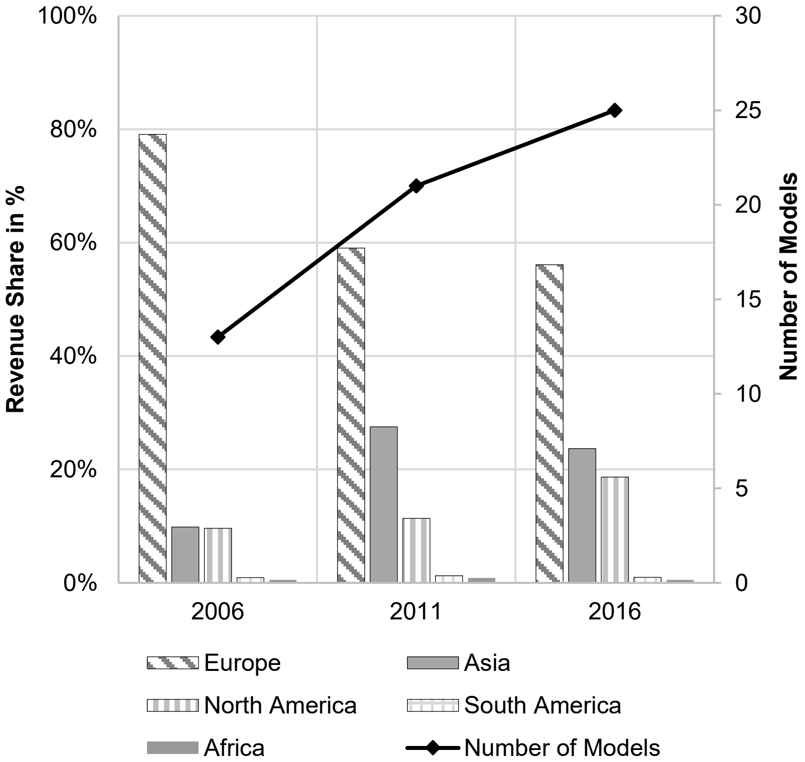


Figure 1.2: Transformation of the global revenue share and the number of vehicle models of the AUDI AG, based on [16, p. 2]

While the growing number of product variants attracts more customers and increases revenues, it also enhances the complexity in the development and production of vehicles. This ultimately leads to an increase in development and production costs [17, p. 156, 18, p. 284].

To overcome the high complexity as the downside of the variance, automotive manufacturers avoid the individual design of vehicles. Instead, they use methods which build different vehicles on the same foundation. This, on the one hand, allows a high external variance [18, p. 285, 19, p. 12, 20, pp. 22-23], meaning the variance selectable by the customers, such as the vehicle segment, the body type, the performance class, and the drivetrain type. On the other hand, it reduces the internal variance and thus the complexity in terms of the variance of components and installation positions not relevant to the customer.

A modular system is an approach used by most automotive manufacturers with a large number of product variants [21, p. 53]. It has the potential to cover a wide external variance while reducing the internal variance. Within a modular system, various vehicles of different segments have vehicle architectures that share unified architectural standards, such as the drive type, the engine installation position, and the chassis type [3, p. 120]. In this context, a vehicle architecture defines the body structure as well as dimensions and installation positions of the components [19, p. 18] most important for the overall vehicle functionality and with the largest dimensions. Examples of these components are the engine, the gearbox, the chassis, and the cooling system. Also within a modular system, some components such as engines are used across almost all vehicles as modules [19, p. 11]. However, other components and installation positions may vary between the different vehicles.

An example of a modular system is the “*Modularer Längsbaukasten*” (MLB) lead developed by the AUDI AG. In the second generation (MLBevo), this modular system uses unified architectural standards, such as the longitudinal engine installation, the multi-link chassis, and the front- or all-wheel drive type. Modules exist as for example within the engines and gearboxes. The modular system covers over ten vehicles across three segments and five brands (Figure 1.3) [22, p. 15]. Hereby, the vehicle segments follow the designation of the AUDI AG and LIENKAMP [31, 1.0-58]

	B-Segment	**C-Segment**	**D-Segment**
AUDI	A4, A5, Q5	A6, A7, Q7, Q8	A8
Bentley		Bentayga	
Lamborghini		Urus	
Porsche		Cayenne	
Volkswagen		Touareg	

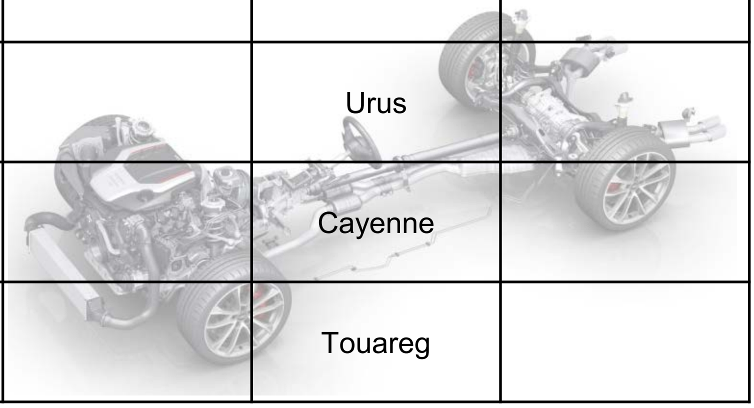


Figure 1.3: Vehicles of the “*Modularer Längsbaukasten*“ in the second generation (MLBevo) [22, pp. 4-5, 23, p. 10, 24] (Image Sources: [6, 25, 26])

The development of modular systems is part of the vehicle concept development and one of the earliest phases of the overall vehicle development process. Hereby, the task is to generate for multiple vehicles the vehicle architectures with unified architectural standards and cross-vehicle modules.

The first step of the process for the development of a modular system is, therefore, generating conceivable vehicle architectures for each vehicle [27, p. 2]. It is important to note that at this early stage, the solution space for the architectures is high. For each component, a multitude of alternatives is available, as for example, the in-line and V-type combustion engines. Similarly, there are various alternatives for the installation positions of components. Alternatives for engine installation positions are longitudinal and transversal installations. This leads to a large number of possible vehicle architectures. In the second step, concept engineers analyze whether, within the feasible architectures of the individual vehicles, unified architectural standards and cross-vehicle modules exist [27, p. 2]. If none are available, it is possible that the generated architectures did not contemplate any suitable component and position alternatives. Besides, there are conflicts of interests between the requirements, such as demanding performance requirements and limited exterior dimensions or between the external and internal variance. Solving these problems requires iterations with adjusted dimensions, vehicle architectures, requirements as well as a reduced variability of the vehicles.

In practice, the holistic development of modular systems is too complicated and time-consuming. Due to the large number of vehicles as well as the numerous component and position alternatives, concept engineers would need to generate hundreds of thousands of architectures. Consequently, automotive manufacturers limit the solution space of the modular system. Based on predecessor vehicles and benchmarks, some architectural standards and modules are predefined [27, p. 3]. This reduces the complexity as well as the required time for the development of the modular system. However, the process still requires time-consuming iterations to solve conflicts of interests. Furthermore, it is possible that with the limited solution space and the considered component or position alternatives only an inferior or no solution is available for the modular system.

In addition to the development of a modular system, automotive manufacturers make a financial assessment based on expected production and sales figures. However, this is not within the scope of this thesis.

1.2 Research Objective

Automotive manufacturers are only able to offer an increasing number of product variants due to the limitation of the internal variance with modular systems. However, the current process for the development of modular systems is time-consuming due to many iterations. Also, the process is not holistic, as it is too complex to consider all conceivable solutions.

The research objective of this thesis is to enable the rapid and holistic development of modular systems. Therefore, this thesis focuses on the development of a method and its implementation in a software tool to automatically generate hundreds of thousands of architectures and to identify unified architectural standards and cross-vehicle modules for multiple vehicle variants of different vehicle models. If no solution is available, fast iterations are possible.

The method is requirement-based and holistic, due to the use of continuous scalable geometric substitute models and the permutation of all conceivable component and installation position alternatives. In addition, it is systematic and transparent due to the use of dimensional chains. The author illustrates the method using the example of the vehicle front of passenger cars.

Applying the method, concept engineers can develop modular systems under holistic consideration of the solution space and with fast iterations. This allows the identification of the best solution as well as the reduction of development times.

This thesis also contributes to the systematization of the vehicle concept development and the modular systems development. Notably, the development of geometric substitute models and the structuring of dimensional chains enable a holistic and yet systematic as well as transparent concept development. Therefore, this lays the foundation for further research into vehicle concept development and modular systems development.

1.3 Thesis Structure

This thesis is divided into six chapters (Figure 1.4). The first chapter outlines the need for a method for the automated development of modular systems. Afterward, the author describes the state of the art regarding vehicle concept development and modular systems development in the second chapter. Moreover, the presentation of existing methods in this chapter leads to the derivation of a research gap. Based on the research gap, the third chapter presents the method for the automated development of modular systems within the vehicle front of passenger cars. The fourth chapter evaluates the functionality of the method using existing series vehicles and modular systems. Afterward, in chapter 5, the author discusses the overall method and its application. Finally, chapter 6 provides the conclusion and outlook.

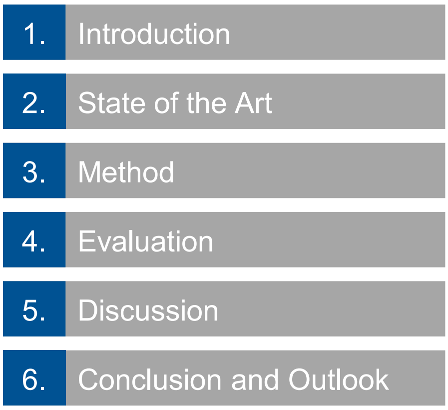


Figure 1.4: Overview of the thesis structure

2 State of the Art

The development of modular systems is part of the vehicle concept development. Therefore, this chapter at first gives an overview of the vehicle concept development and the vehicle concept development process. Afterward, the author provides detailed information about the process of developing modular systems. Subsequently, a description of related methods and tools as well as the identification of a research gap follows.

It is important to note that the following chapter intends to give an overview of the vehicle development processes for passenger cars. The terminologies and description focus on the development of new vehicles and may vary with other development projects such as face-lifts. Furthermore, the exact scope and implementation vary depending on the automotive manufacturer. However, the author's project experience and discussions with experts at the Vehicle Concept Development Department of the AUDI AG [28, 29] lay the foundation for the following descriptions.

2.1 Overview of Vehicle Concept Development

The main objective of the vehicle concept development is the development of geometric vehicle concepts. In the following the author describes the position of the vehicle concept development in the overall vehicle development process and the general process for the development of one vehicle concept. Subsequently, this section outlines the approach for the development of multiple vehicles concepts with modular systems and platforms.

2.1.1 Position in the overall vehicle development process

The vehicle development process describes the phases from the product idea to the start of production (SOP). One partition is into the planning-, the definition-, the realization- and the production-phases (Figure 2.1) [30, 1.1-3]. Beginning with the project start, the planning phase includes the refinement of the product idea and the derivation of requirements [17, p. 1140]. Another task is the development of initial vehicle concepts as a preliminary representation of the product. This phase ends with a technical and financial feasibility check of the product idea and the vehicle concepts [17, p. 1143]. Depending on the feasibility checks the development of the vehicle concepts continues with an increasing degree of detail, during the definition phase. With the design freeze, the development transitions into the realization phase. In this series development, the vehicle concepts are described in detail and tested to finally arrive at manufacturable vehicles. Due to the ramp-up of the production, the production phase starts with a pilot series before the realization phase ends with the official SOP.

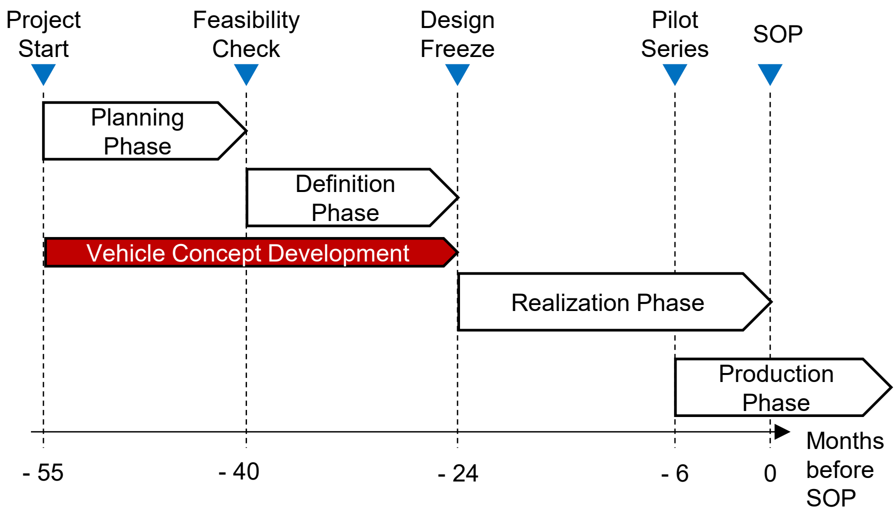


Figure 2.1: Vehicle development process and positioning of the vehicle concept development, based on [19, p. 5, 30, p. 3, 31, p. 9]

According to the overall process, the vehicle concept development takes place during the planning and definition phases. It is one of the first stages of the development as it starts almost in parallel to the development of the product idea [17, p. 1143]. After continuously increasing the level of detail of the vehicle concepts, the vehicle concept development ends with the design freeze.

2.1.2 Main objective of vehicle concept development

The primary objective of the vehicle concept development is the creation of vehicle concepts. A vehicle concept is a preliminary representation of the product which fulfills the requirements demanded. It includes the dimensions and positions of all components of the vehicle as illustrated in Figure 2.2. During this phase, the representation is usually virtual using computer-aided design (CAD) programs [17, p. 1143]. In the automotive industry, the term vehicle package is an alternative designation for the vehicle concept [17, p. 130].

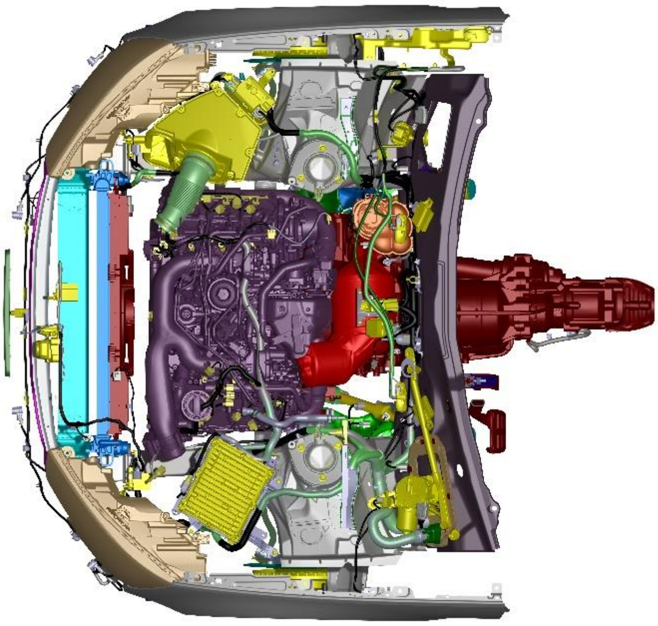


Figure 2.2: Exemplary illustration of a vehicle concept/package within the vehicle front

Manifold requirements and component, as well as installation position alternatives, exist for a vehicle concept. A more detailed objective of the vehicle concept development is therefore to create a vehicle concept by dimensioning and selection of the component and installation position alternatives which represent the best fulfillment of the requirements [17, p. 1143].

Figure 2.3 shows examples of requirements on the vehicle concept, which originate from the product idea and further development within the planning phase.

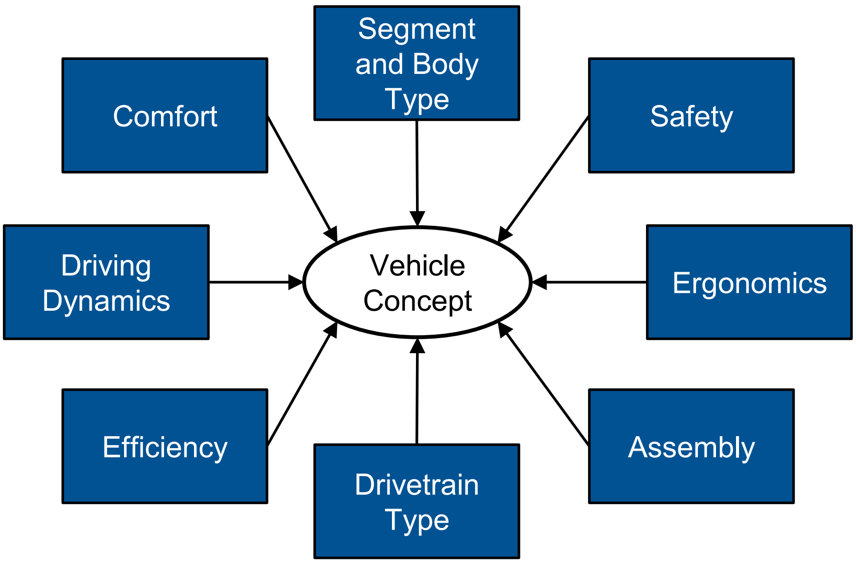


Figure 2.3: Examples of requirements for the vehicle concept, based on [17, p. 131]

Examples of component alternatives are in-line and V-type combustion engines. However, component alternatives may vary not only in their component type but also in component performance, such as engines of 200 N m and 600 N m torque. Examples of installation positions of combustion engines are the longitudinal and the transversal installation. In general, an alternative is another possibility to a component or installation position.

2.1.3 General process of vehicle concept development

To achieve the objective of the vehicle concept development, concept engineers, i.e. experts of different departments responsible for concept development, carry out the vehicle concept development process (VCDP). As illustrated in Figure 2.4, the process is divided into the vehicle dimensions design, the vehicle architecture design, and the vehicle package design [16, pp. 4-5].

In the following, the process will refer to the development of one vehicle concept. The application of the approach to multiple vehicles with different variants is described in the subsequent sections. The following explanation is based on a previous publication of the author [16].

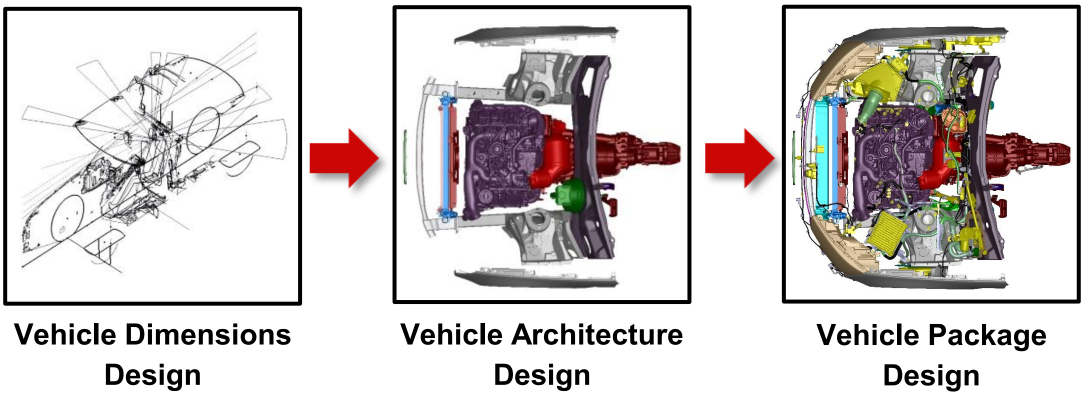


Figure 2.4: Overview of the vehicle concept development process [16, p. 5]

The process begins with the vehicle dimensions design, which aims to define the available installation space. Based on requirements of the vehicle segment and type, as well as on the ergonomics, the task at this stage is the definition of the passengers' positions and the specification of overall vehicle dimensions, like the front and rear overhang, the wheelbase, and the track width [17, p. 132, 32, pp. 14-15, 33, pp. 39-40, 34, pp. 97-129]. The SAE J1100 defines most of these dimensions [35]. If available, predecessor and competitor vehicles are used as orientation for the vehicle dimensions as well as the required installation space of components [36, p. 913]. The defined available installation space serves as an additional requirement for the following stages.

Afterward, the process continues with the definition of the vehicle architecture during the vehicle architecture design. In this context, the vehicle architecture consists of the body structure and the dimensions and positions of the most essential components, such as engine, gearbox, chassis, and cooling. This is an intermediate stage to the vehicle package design because the number of components considered is smaller. At this stage, it is not meaningful to consider all components, as some, like the engine, the chassis, or the energy storage have a strong impact on the vehicle, while the influence of other components like control units or cables is comparably low.

For the generation of the architecture during the vehicle architecture design, concept engineers first define the dimensions of the components based on the input requirements [16, p. 4]. For example, the engine length, width, and height are dimensioned based on the required vehicle performance. Second, they position the dimensioned components within the available installation space defined by the vehicle dimensions design. This is repeated several times with variations in the component and installation positions alternatives, thus generating different architecture alternatives. However, it is not possible to consider all component and position alternatives as this would result in an extremely high number of architecture alternatives. Subsequently, within each of the architecture alternatives, the concept engineers analyze required distances between components, as for example for crash safety or assembly, using dimensional chains. As illustrated in Figure 2.5, dimensional chains consist of the minimum distances between adjacent components and the effective component sizes measured between two ambient distance measurements. Hereby, all dimensions are oriented along a defined coordinate direction. In addition, the concept engineers compare the required installation space of the architecture with the available installation space.

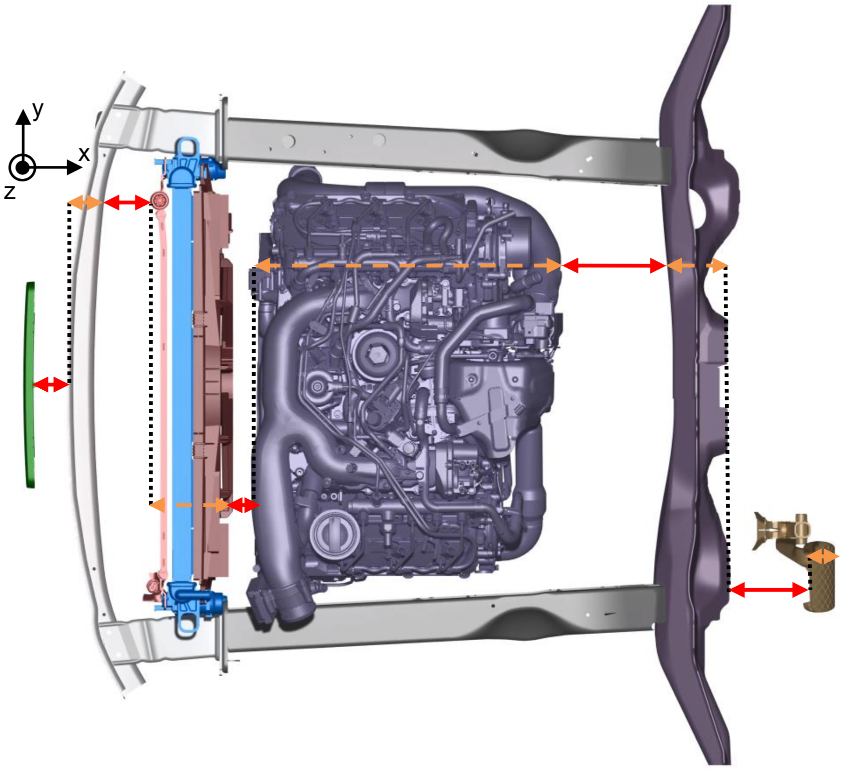


Figure 2.5: Example of a dimensional chain, based on [37, p. 194]

If none of the architecture alternatives is feasible, a first iteration attempts to optimize the component dimensions and the required distances of the components. If this does not make sense, within a second iteration, the concept engineers create further architecture alternatives by varying of so far unconsidered component and position alternatives. Finally, it may be necessary to adjust the input requirements and the available installation space during a third iteration.

For technical and financial reasons, the concept development team selects one architecture out of the feasible architectures. Technical reasons mainly concern the fulfillment of the requirements, while economic reasons depend on the costs of the alternatives.

The vehicle package design represents the third and last stage of the VCDP. Thereby, concept engineers integrate all remaining components (including cables and hoses) into the selected vehicle architecture [16, p. 4]. Moreover, within this stage, the level of detail of the components increases. There are different alternatives available for the additional components, which result in several package alternatives. The analysis of the package alternatives uses more detailed dimensional chains. Therewith, concept engineers examine the distances and collisions as well as the conformity of the required installation space with the available installation space. The vehicle architecture design might also require iterations with refined dimensions, selection of other component and position alternatives, or the adjustment of requirements.

All three stages of the VCDP require iterations. Besides, iterations between the stages may be necessary. If no package alternative complies with the available installation space or other requirements, the process may need to be restarted from the vehicle architecture design or even the vehicle dimensions design [16, p. 4]. To avoid time-consuming iterations, the concept engineers must anticipate aspects of the following stages as best they can.

After the VCDP, the entire vehicle development process continues with the selection of one package alternative and the series development. During this realization phase, the vehicle concepts are ascertained based on more detailed simulations and tests [16, p. 5]. In addition, the assignment of suppliers and the preparation of production takes place.

2.1.4 Process of the development of multiple vehicle concepts

In the previous section, the author described the VCDP for a single vehicle concept. However, automotive manufacturers are developing and offering multiple vehicle models with further variations. To avoid the individual design of all vehicles and variants, an enhanced development process is necessary.

In this context, the term vehicle model defines a combination of the vehicle segment and body type. For each vehicle model, there are further vehicle variants with different performance classes, drive types, and drivetrain types. Table 2.1 gives an overview of possible combinations. In this, the vehicle segments and body types follow the designations of LIENKAMP [30, 1.0-58] and BRAESS [17, p. 136]. The different combinations of the vehicle models and variants offered by an automotive manufacturer are referred to as external or product variance [18, p. 285, 19, p. 12, 20, pp. 22-23] since the customer can directly influence it.

Table 2.1: Possible combinations for vehicle models and their variants [17, p. 136, 30, 1.0-58]

Vehicle segment	Body Type	Performance	Drive Type	Drivetrain Type
A000	Sedan	Entry	Two-Wheel	Gas
A00	Hatchback	Medium	All-Wheel	Diesel
A0	Coupe	Sport		Natural Gas
A	Convertible			Hybrid
B	MPV			Electric
C	SUV			Hydrogen
D	Pickup			
E				

In the case of individual concept development, all vehicle models and variants could consist of different component and position alternatives, overall resulting in a large number of component and position variants within the automotive manufacturer. The total number of component variants and position variants selected from the alternatives is referred to as internal or technical variance [18, p. 285, 19, p. 12, 20, pp. 22-23]. The high internal variance would lead to high development times and production costs as synergies and quantities decrease [17, p. 156, 18, pp. 293-296, 38, p. 227].

Vehicle concept development, therefore, avoids the individual design of vehicle concepts. In addition to the selection of component and position alternatives based on the best fulfillment of the requirements, the aim is to minimize the internal variance [20, p. 5]. However, it should be noted that there is a conflict of interest between the external variance and the internal variance [19, p. 12]. The higher the external variance, the less chance of reducing the internal variance. As for example, high external variance with different performance classes and drivetrain types requires different engines and thus limits the reduction in internal variance. Consequently, the vehicle concept development develops multiple vehicles and vehicle variants in parallel, while reducing the internal variance at different levels of external variance.

This leads to the multiple vehicle concept development process (MVCDP), as illustrated in Figure 2.6. The first stage is the definition of the available installation spaces. In the following, the author does not further describe this stage because it is the exact application of the VCDP vehicle dimensions design to multiple vehicles and does not affect the variance. Stages two through four are the development of modular systems, platforms, and vehicle models that apply variations in the vehicle architecture design and vehicle package design. These three stages build on each other and reduce the internal variance with different levels of external variance. Together, these facilitate an overall minimal internal variance [17, p. 155]. The foundation of these development stages is standardization, which means the overarching use of the same element [3, pp. 118-119, 39, p. 57]. Similar to the VCDP, iterations can exist within and between the different stages of the MVCDP.

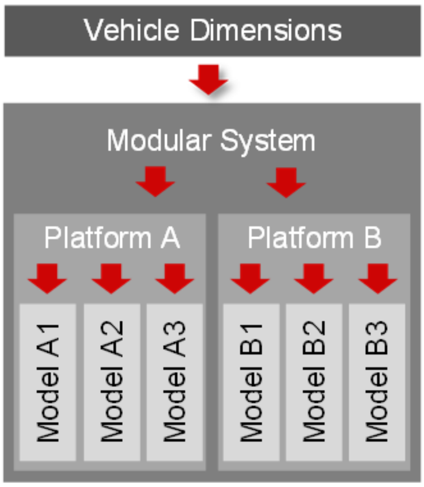


Figure 2.6: Illustration of the multiple vehicle concept development process and the top-down relation between the modular system, platforms, and vehicle models, based on [22, p. 13]

In this context, modular systems and platforms relate exclusively to the vehicle level. Further approaches exist at the component level. A more detailed definition of different terminologies can be found in the literature [3, pp. 134-138, 17, pp. 154-155, 20, pp. 51-53, 40, p. 18, 41, p. 17, 42, pp. 662-667].

Based on the vehicle requirements and the available installation space, the development of the modular system takes place as the second stage of the MVCDP. For multiple variants of various vehicle models of different segments, concept engineers define vehicle architectures with unified architectural standards and cross-vehicle modules [3, p. 119]. Architectural standards are standardized elements of the vehicle architecture, such as longitudinal or transversal engine installation [43, p. 954]. Further examples are the drive type and the chassis type [24]. Cross-vehicle modules are component variants such as a specific engine variant which finds application in multiple vehicles. This stage is based on a variation of the vehicle architecture design.

For modular systems, there is the single- and the multi-drivetrain approach. Within the single-drivetrain approach, the modular system includes either vehicles with combustion drivetrains or vehicles with electric drivetrains. The advantage of this procedure is the individual adaptation to the drivetrain characteristics [44]. In the multi-drivetrain approach, the modular system takes all drivetrain types into account [45]. The advantage here is the flexible response to customer demand within the production [27, p. 2].

Based on the modular system, concept engineers derive multiple platforms [22, p. 13]. While the modular system includes vehicles of different segments, one platform bundles the vehicle models and variants of the same segment [2, p. 6]. With the unified architectural standards as the foundation, platform development aims to increase the standardization of the architecture [46, p. 30]. This leads to fully standardized architectures. Also, a platform standardizes some components and installation positions which belong to the vehicle package. With the standardization of architectures and package components, the development of platforms is based on both vehicle architecture design and the vehicle package design.

Finally, the platforms provide the foundation for the derivation of vehicle models [22, p. 13]. Within each vehicle model, there are different vehicle variants with varying performance classes and drivetrain types. The aim is therefore to standardize the vehicle variants of a vehicle model with not yet considered components and installation positions. The development of the vehicle models and variants is solely a variation of the vehicle package design.

The modular systems, platforms, and vehicle models differ in the external variance covered, the reduced internal variance, and the overall effects on the internal variance.

Regarding variance, the modular system with a multitude of vehicle models and variants from different segments covers the highest external variance. However, this does not necessarily include the overall external variance, as automotive manufacturers can develop multiple modular systems. There may also be individual platforms or vehicle models besides the modular system. With the high external variance, the possibilities for reducing the internal variance are small. Within the platform, the external variance decreases as only vehicles of the same segment are considered. Therefore, within the smaller external variance covered, the internal variance decreases with the standardization of more components and positions. Finally, within the vehicle models, the external variance consists only of multiple vehicle variants with different performance classes and drivetrain types. Within this scope, the vehicle standardization reduces the internal variance the most.

It is important to note that while the internal variance within the modular system is the highest, it allows the minimum overall internal variance of the automotive manufacturers. Without the modular system, the variance across vehicles of different segments would be much higher. In contrast, the impact of the platform and the vehicle models on the overall internal variance is lower because they cover fewer vehicles.

Table 2.2 gives an overview of the differences between modular systems, platforms, and vehicle models in terms of the external variance covered, the reduced internal variance, and the overall effects on the internal variance.

Table 2.2: Differences between modular systems, platforms and vehicle models

	External Variance Covered	Reduction of Internal Variance	Impact on overall Internal Variance
Modular System	High	Low	High
Platform	Medium	Medium	Medium
Vehicle Model	Low	High	Low

2.2 Development of Modular Systems

Within the MVCDP, the development of a modular system is most complex, as the external variance is high, and the solution space is almost unlimited. Therefore, this section describes the process for developing modular systems and the current challenges in detail.

Instead of developing an architecture for one vehicle, the objective of the modular systems development is to develop vehicle architectures with unified architectural standards and cross-vehicle modules for multiple vehicles.

In the description, the focus is solely on the development of modular systems. This thesis does not cover the financial assessment of modular systems based on production and sales figures.

2.2.1 Modular systems development process

The aim of the modular systems development is the development of vehicle architectures with unified architectural standards and cross-vehicle modules for multiple vehicles. The process starts around five years ahead of the SOP of the first vehicle [27, p. 2].

The initial situation is a high external variance with multiple vehicles and vehicle variants. This means that the vehicles differ in their segments and types. Besides, each vehicle has variants with different performance classes and possibly drivetrain types. For each of the vehicle models and variants, the requirements must be known. Also, the vehicle dimensions design defines the available installation space of each vehicle ahead of the modular system development.

Based on these inputs, the modular system development process begins. The process is a variation of the vehicle architecture design described in section 2.1.3. At first and in parallel, several vehicle architectures alternatives are defined and dimensioned separately for the different vehicle models' variants, depending on their requirements [27, p. 2]. This means that the development is done bottom-up with the vehicle variants as the smallest subdivision of the modular system with impact on the architectures. The maximum amount of component and installation position alternatives that concept engineers can consider limits the number of architecture alternatives. The selection of these alternatives is based primarily on assumptions and experiences as, for example, from predecessor vehicles. The concept engineers then compare the required installation space with the available installation space of each vehicle. In a second step, the feasible architectures of all vehicle variants are aligned to determine whether there are architectures with the same architectural standards within all of them [24, 27, p. 2]. In addition, concept engineers analyze whether components with the same types and properties exist within the feasible architectures to form cross-vehicle modules.

If no modular system is possible, up to four iteration loops are necessary, within all or only particular vehicle variants and vehicle models [27, p. 2]. Within the first two iterations, concept engineers try to optimize the architectures to increase the number of architectures complying with the available installation space. In the first iteration, the target is to refine and reduce the component sizes and distances between components and thus the required installation space. During the second iteration, concept engineers create further architecture alternatives with not yet considered component and installation position alternatives. Within the third and fourth iterations, it is necessary to adjust the inputs. The third iteration reduces the requirements or increases the available installation space. Finally, the fourth iteration reduces the external variance by the exclusion of vehicle variants or models that are not suitable for the modular system. A particular case within the fourth iteration would be the reduction of the internal variance, thus building the modular system on fewer architectural standards. However, this is not common as different drive types and chassis types would significantly affect the standardization of platforms and vehicle models.

Figure 2.7 illustrates the modular system development process.

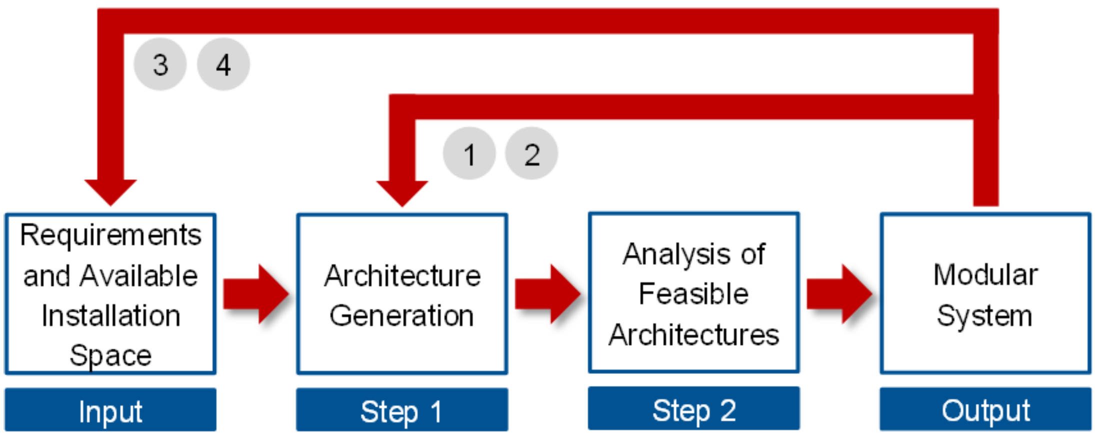


Figure 2.7: Process for the development of modular systems

2.2.2 Challenges of the modular systems development process

In the previous sections, the process for the development of architectures (2.1.3) and modular systems (2.2.1) has been abstractly described. In reality, however, the processes are complex and demanding. Therefore, this section outlines the challenges within today's vehicle architecture and modular system development. The author has already explained parts of the following description in an earlier publication [27].

The development of one vehicle architecture is already complex, time-consuming, and requires the cooperation of concept engineers from different departments. One problem is the definition of a large number of dimensions, while another problem arises from conflicts of interests. For one architecture, hundreds of component dimensions and distances between components have to be defined [27, p. 2]. The dimensions depend on the requirements and vary with the component and position alternatives. For example, the engine length depends on the required torque but also on the engine type. Since there is a multitude of requirements and alternatives, the correlations between the requirements and the dimensions are often unknown at this early stage of the development [47, p. 262]. To avoid high uncertainty, it is possible to assume the dimensions based on predecessor or competitor vehicles. However, this is only possible in case the requirements and the alternatives do not significantly vary. Otherwise, more detailed investigations and simulations are necessary [27, p. 2]. In addition to the dimensioning, the requirements, such as crash safety, are steadily increasing and lead to higher required installation space. However, the overall limitations of the vehicle size also limit the available installation space. This leads to conflicts of interests and iterations to find trade-offs.

Development is even more difficult for a modular system because concept engineers need to generate and compare vehicle architectures for multiple vehicles. The holistic development of a modular system would require the generation and comparison of hundreds of thousands of vehicle architectures [27, p. 2]. This is unpracticable due to the considerable time spent on the generation and dimensioning of the architectures and the high complexity of comparing the feasible architectures to determine unified architectural standards and cross-vehicle modules.

Consequently, automotive manufacturers limit the solution space of the modular system. Based on predecessor vehicles and benchmarks, some of the architectural standards and modules are predefined [27, p. 3]. This reduces the number of available component and position alternatives and thus the number of conceivable architecture alternatives. However, the process still requires time-consuming iterations to resolve conflicts of interests between the requirements, the required and the available installation space, and the external variance.

Besides, it is possible that the best solution is precluded due to the limited solution space and the considered component or position alternatives [27, p. 3]. This means that a modular system was only possible with the adaptation of the requirements or the external variance. The consideration of other architectural standards and modules could have avoided these adaptations. In worst-case, it is impossible to cover the external variance at all with the predefined architectural standards.

2.3 Existing Methods Related to Modular Systems Development

There are multiple approaches and algorithms in the literature for solving packaging problems, that is, the integration of components into an available installation space [48–57]. Although these methods and tools often use vehicles as a field of application, the focus is on the development and evaluation of algorithms and not on the generation of vehicle architectures. MATZ [31, pp. 14-15] gives an extensive overview of these approaches.

In the following, the focus is solely on methods immediately related to modular systems. These are approaches that generate vehicle architectures and identify architectural standards and modules. While this thesis is aimed at passenger cars, the review also includes two methods within the field of commercial vehicles. The author already gave an overview of these methods in previous publications [27, 47].

For the generation of vehicle architectures of passenger cars, several approaches are available. Besides the consideration of only hybrid and electric drivetrains, the four methods of J. FUCHS [19], KUCHENBUCH [58], MATZ [31], and RIED [59] have in common the generation of architectures for one individual vehicle. The order of description is based on the degree of automatization of the methods and tools.

J. FUCHS [19] created a method for generating vehicle architectures for battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). For the generation of the architectures, he uses physical and empirical correlations within geometric substitute models for the electric machine, the hydrogen tank, and the high-voltage electrical system. Furthermore, he assesses the geometry of the battery and the fuel cell stack based on reference geometries and an analytical determination of the required number of modules/stacks. The remaining modeling of the components is done either in low-detail or with existing components as a reference. With his model, J. FUCHS can analyze the solution space of the architectures to identify their degrees of freedom and effects on the overall vehicle. However, the tool does not automatically create all solutions. Instead, it requires a manual configuration of the architecture as input. Figure 2.8 illustrates the vehicle architecture of the method and tool of J. FUCHS.

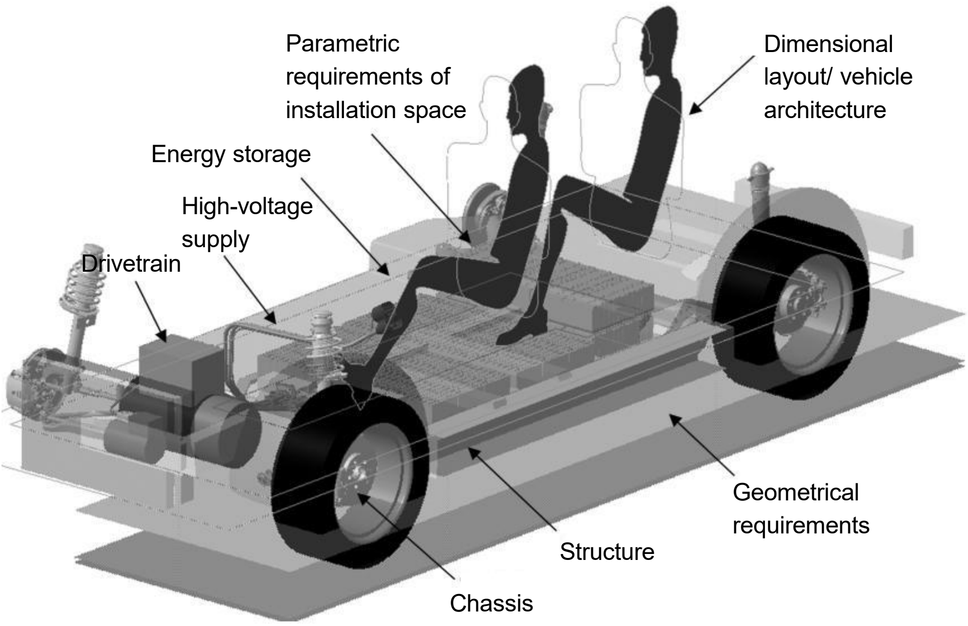


Figure 2.8: Vehicle architecture within the method and tool of J. FUCHS, based on [60, P. 135]

RIED [59] developed a method and tool for the generation of vehicle architectures of plug-in hybrid vehicles (PHEV). The objective hereby is the automated analysis of the overall solution space of PHEV based on the available battery volume and the resulting capacity as well as the cost-benefit ratio of the customer. By varying the underbody battery topology, he can create different architectures. Due to the limitation to underbody batteries, however, only three different architectures are possible. Based on the available battery volume of each architecture, he uses a geometric substitute model of the battery to calculate the battery capacity. Therefore, the model uses a factor for the volumetric energy density and the volume utilization. Different architectures within the vehicle front and rear are not taken into consideration, as he derives the PHEV from existing vehicles with combustion drivetrains. The cost-benefit ratio depends on the costs of additional components of PHEV, e.g. the battery, and savings due to reduced fuel consumption. Finally, he assesses the architectures in terms of the feasible battery capacity and the cost-benefit ratio. In a previous publication, RIED also mentioned the creation of geometric substitute models for components, such as the combustion engine and the electric machine [61, p. 28]. However, he did not explain the models and their use.

KUCHENBUCH [58] explicitly focused on the generation of vehicle architectures for BEV. His goal is to analyze the solution space of architectures with electric drivetrains. Instead of automatically considering the overall solution space, he uses a multi-criteria optimization. With only two optimization criteria, he searches for architectures and battery topologies that represent the best compromise between energy consumption and battery range. He uses a geometric substitute model for the battery, to calculate the battery capacity based on reference battery cells. A database contains the remaining components.

MATZ [31] also worked on the generation of vehicle architectures for BEV (Figure 2.9). With his multi-criteria optimization algorithm, he identifies the best architectures under consideration of the vehicle requirements as well as the modal split of the customers, i.e. the availability and use of public transportation systems. For the battery, he uses a geometric substitute model, based on physical equations and reference cells. His tool selects the remaining components from a database.

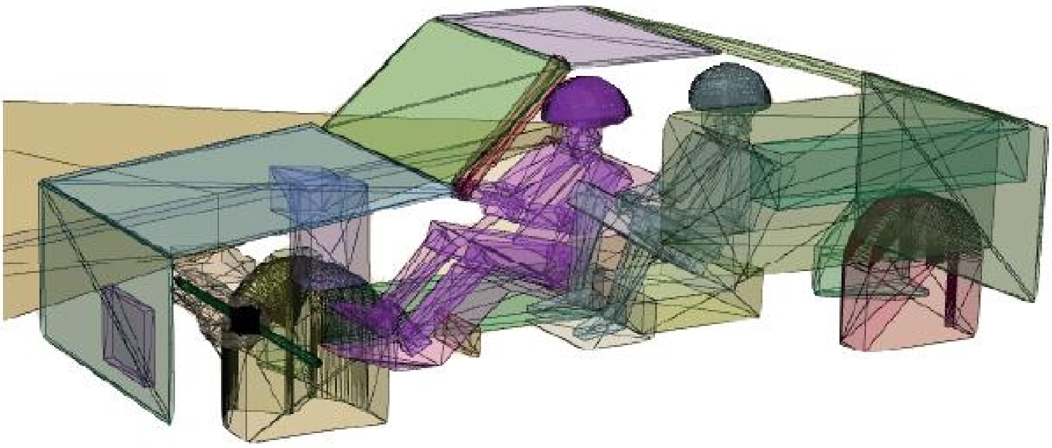


Figure 2.9: Vehicle architecture within the method and tool of MATZ [31, P. 84]

In addition to the consideration of either hybrid or electric drivetrains and the limited use of geometric substitute models, all the methods presented generate architectures for only one vehicle at a time.

For passenger cars, the author is unaware of any approaches to generating of architectures of multiple vehicles and comparisons to identify unified architectural standards and modules. In the field of commercial vehicles, however, FÖRG [62] and STOCKER [63] generate and align architectures of multiple vehicles to identify architectural standards at different levels of automatization. Hereby, both only contemplate combustion drivetrains.

FÖRG [62] created a method and tool to support the generation and standardization of vehicle architectures for multiple commercial vehicles. Within the tool, a concept engineer manually defines the architecture of the first vehicle (Figure 2.10) by selecting components from a database and defining the installation positions. If possible, this architecture sets the architectural standards for subsequent vehicles. During the architecture definition for the other vehicles, the tool proposes component types and installation positions based on the architectural standards of the predefined architecture. If it is not possible to build a new architecture based on the existing architectural standards, the user can define a new architecture. After generation of all vehicles architectures, the tool rates the overall degree of standardization and suggests areas of improvement. The tool supports the manual generation of architectures and identification of architectural standards. However, the degree of standardization depends heavily on the initially defined architecture. Also, the automated identification of the best solution is not possible.

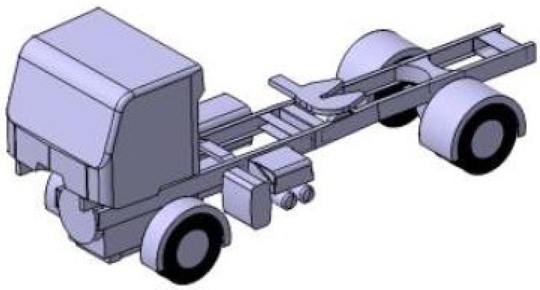


Figure 2.10: Vehicle architecture within the method and tool of FÖRG [62, P. 9]

Based on the method and tool of FÖRG, STOCKER [63] continues the research on vehicle architectures and architectural standards within commercial vehicles. Unlike FÖRG, he focuses on the frame-mounted parts of commercial vehicles and neglects the vehicle front. He fully automates the generation of all conceivable vehicle architectures and the identification of architectural standards and modules. The tool initially generates all architectures for all considered vehicles. The selection of components is based on a database. Within the feasible architectures, the tool identifies architectural standards and modules. The final selection of the architectural standards and modules also considers costs and production volumes. Based on these factors, the tool can define architectural standards and modules for all or groups of vehicles.

Table 2.3 summarizes the description of the existing methods that are related to the development of modular systems.

Table 2.3: Overview of existing methods related to the development of modular systems

Degree of Fulfillment:

● 100 % ◕ 75 % ◑ 50 %

◔ 25 % ○ 0 %

			J. FUCHS [19]	RIED [59]	KUCHENBUCH [58]	MATZ [31]	FÖRG [62]	STOCKER [63]
Vehicle Type and Area	Passenger Cars	Front	●	○	●	●	○	○
		Middle	●	●	●	●	○	○
		Rear	●	○	●	●	○	○
	Commercial Vehicles	Front	○	○	○	○	●	○
		Frame	○	○	○	○	●	●
Drivetrain Types	ICEV		○	○	○	○	●	●
	HEV/PHEV		○	●	○	○	○	○
	BEV		●	○	●	●	○	○
	FCEV		●	○	○	○	○	○
Objective	Architecture Generation		●	●	●	●	●	●
	Architecture Standardization		○	○	○	○	●	●
Level of Automatization	Manual Configuration		●	○	○	○	●	○
	Automated – Permutation		○	●	○	○	○	●
	Automated – Optimization		○	○	●	●	○	○
Level of Modelling	Component Database		◑	◑	◕	◕	●	●
	Geometric Substitute Models		◑	◑	◔	◔	○	○

2.4 Research Gap

Modular systems set the foundation for the development of multiple vehicles with a minimum of internal variance. With the steadily increasing variance, they are of great importance for the economic success of an automotive manufacturer. However, the current process for developing modular systems is time-consuming and complicated. This makes a holistic consideration of the solution in practice impossible.

Despite the high importance of modular systems and their difficult development, none of the existing methods can adequately address this issue. As shown in Table 2.3, the related methods lack either the consideration of multiple vehicles, different drivetrains, or scalable substitute models. All these aspects, however, are essential for the holistic development of modular systems.

Related methods within passenger cars only involve the generation of architectures for one vehicle at a time. Hence, none of the methods can identify architectural standards and modules within multiple vehicles. In addition, none include all combustion, hybrid and electric drivetrains. However, all these drivetrains currently play an important role in the automotive industry and are necessary for the analysis of multi-drivetrain modular systems. Moreover, the methods only use a limited number of substitute models and select many components from a database. This limits the adjustment to alterations of the input requirements and thus the holistic development of modular systems.

Within commercial vehicles, there are already two methods that take into account vehicle architectures of multiple vehicles. Therefore, the architecture standardization is possible by identifying architectural standards and modules. However, these methods mainly focus on the frame-mounted parts and are not applicable to passenger cars. While the methods consider multiple architecture alternatives, they are not fully holistic due to the lack of geometric substitute models for continuous scaling.

Consequently, no method for the holistic development of modular systems for passenger cars, with architecture generation and standardization by consideration of multiple vehicles, different drivetrains, and scalable substitute models exists. However, such a method would allow the identification of the best solution and the reduction of development times. It would also set the foundation for further research into the development of modular systems.

3 Method

Based on the research gap, this thesis describes a method for the automated development of modular systems. A software tool makes the method applicable, using MATLAB and CATIA. This tool is also referred to as “Parametric Automotive Concept Engineering” (PACE). The following uses the terms method, tool, and PACE synonymously.

The primary objective of PACE is the automated, rapid and holistic development of modular systems. With the requirements as inputs, the method generates hundreds of thousands of vehicle architectures for multiple vehicle variants of different vehicle models. The generation includes the permutation of all conceivable component and installation position alternatives and the requirement-based dimensioning with continuously scaling geometric substitute models. Furthermore, it involves the analysis of the feasibility with dimensional chains. Subsequently, the method identifies unified architectural standards and cross-vehicle modules forming the modular system for all vehicle variants and vehicle models.

Applying this method, concept engineers can develop modular systems under holistic consideration of the solution space. Moreover, it is possible to resolve conflicts of interest during fast iterations. This allows the identification of the best solution as well as the reduction of development times.

At the beginning of the chapter, the author describes the requirements and boundaries of the method. The subsequent sections provide an overview of the method as well as a detailed description of the individual stages and steps. The chapter closes with an explanation of the application of the method. Previous publications by the author have already dealt with some aspects of the following [27, 47].

3.1 Requirements and Boundaries of the Method

The requirements of the method can be clustered into three categories:

- Applicability: At the beginning of the modular systems development, there is a high degree of uncertainty, with only limited requirements being known and defined. Therefore, the tool must operate with a limited amount of input parameters. In contrast, this early stage also requires a lower level of detail, so that full detailing of the components is not necessary.
- Holism: To identify the best solution, it is essential to consider the solution space holistically. Therefore, it is necessary to generate all conceivable architectures with combustion, hybrid, and electric drivetrains. The tool must also be adjustable to different requirements.

- Transparency: The solution space of modular systems is extensive. To ensure the reliability of the tool, the process and the results must be transparent and replicable. Therefore, PACE is based on dimensional chains and excludes the identification of entirely new solutions.

In addition to the requirements, there are several boundaries within the method and its application:

The focus of the method within the development of modular systems is on the generation of the architectures and the identification of architectural standards. Though included, the tool covers the modularization only briefly. Furthermore, a financial assessment of the resulting architectures and modular systems is out of the scope.

The tool covers combustion, hybrid, and electric drivetrains and thus currently the most important ones. However, it does not include natural gas and hydrogen as possible energy sources and drivetrain types, because, at this time, the demand is limited [64, p. 183]. In addition, the focus within the hybrids is on the parallel topology, as their application is already more common today and will increase in future as the efficiency is higher than with serial or power split hybrids [65, 66, 67, pp. 347-494]. Also, in combustion and electric drivetrains, the focus is on topologies with widespread and not niche applications such as combustion engines in between the axles or electric wheel hubs.

The field of application for the method is passenger cars. The author also demonstrates the method only within the vehicle front. This reduces the complexity that is already high for the vehicle front with its numerous components and dimensional chains as well as hundreds of thousands of conceivable vehicle architectures. However, with the current mix of drivetrains, the vehicle front is the most important area of the vehicle. Nevertheless, the method partly considers the interior and the occupant cell of the vehicle. It only excludes the rear of the vehicle. However, the extension of the method to the overall vehicle would be possible.

In the following, the architecture of the vehicle front will still be referred to as vehicle architecture.

3.2 Overview of the Method

The method for developing modular systems is divided into three consecutive stages: definition of requirements (3.3), generation of architectures (3.4), and derivation of modular systems (3.5). These are mainly implemented in MATLAB.

In the first step of the first stage, the user defines the requirements for the modular system and multiple platforms/vehicle models and vehicle variants as inputs (3.3.1). Within the tool, platforms and vehicle models are equivalent because, at this early stage, the only distinction of the body type is by low- and high-ground. Therefore, the vehicle models do not yet need a detailed definition of the body type. Moreover, a modular system does not necessarily need to consist of platforms. Therefore, the author refers to vehicle models in the following. For each vehicle model, several vehicle variants with different performances are possible. By limiting the inputs to an early stage, the user only specifies the performance requirements such as the acceleration, but not the engine power or the number of gear speeds. Therefore, the second step (3.3.2) of the first stage is a longitudinal dynamics simulation. It converts the inputs of each vehicle variant into the engine power/torque. For each set of inputs, there are multiple solutions for the engine power/torque due to different drivetrain types as well as a varying number of gear speeds. Therefore, the result of this step is multiple instances of fully specified requirements, including the engine power/torque, the transmission ratios, and the number of gear speeds. These instances are also referred to as engine-gearbox combinations.

The second stage focuses on the generation of feasible vehicle architectures for the different vehicle variants of each vehicle model. The foundation hereby is empirical and semi-physical geometric substitute models (3.4.1). These convert the requirements into component sizes and distances between components. Using the models, the tool synthesizes and dimensions all conceivable vehicle architecture alternatives by permuting the engine-gearbox combinations with all component and position alternatives (3.4.2). The subsequent step (3.4.3) derives the available installation space based on the exterior dimensions of each vehicle model. In the last step of this stage, the comparison of the installation space required by each architecture alternative with the available installation space leads to the identification of feasible architecture alternatives (3.4.4).

Until this stage, the tool developed the architectures separately for all vehicle variants of the different models. However, to derive the modular system, this stage considers all feasible architectures together. Hereby, the first step is the identification of cross-vehicle modules (3.5.1). Afterward, the resulting architectures of all vehicle variants are outputted to the user in the modular systems matrix (MSM) to derive architectural standards (3.5.2). In addition, a parametric CATIA model is available to visualize the resulting architectures in CAD.

If no modular system is feasible, the user can iterate with adjusted inputs. Figure 3.1 gives an overview of the developed method.

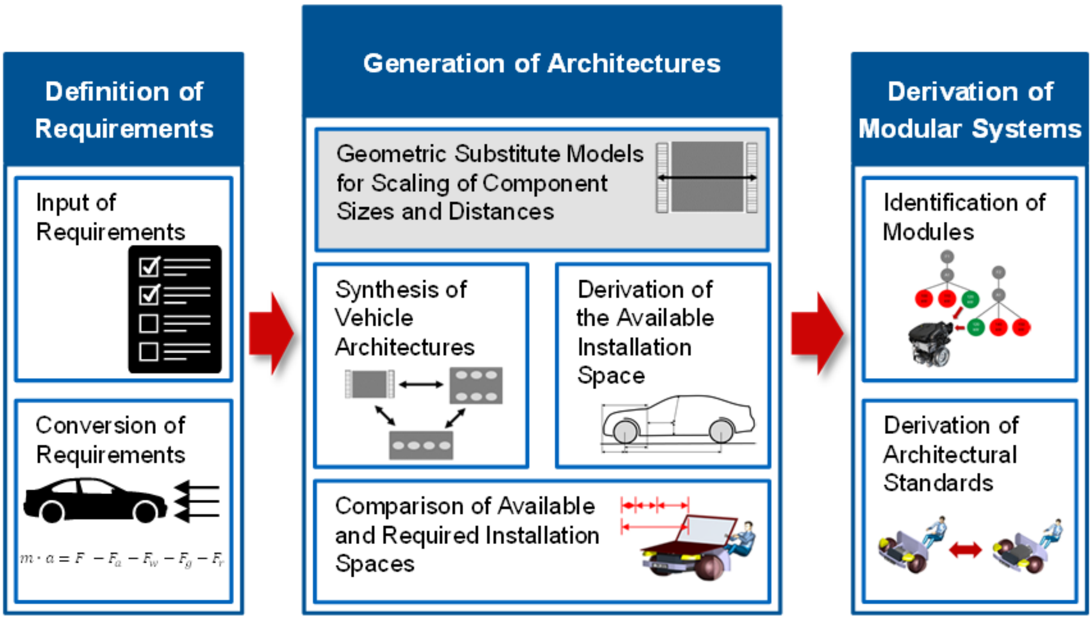


Figure 3.1: Overview of the method for the development of modular systems

Within the following description, the author refers to the vehicle coordinate system defined within the SAE standard J1100 (Figure 3.2) [35, p. 31].

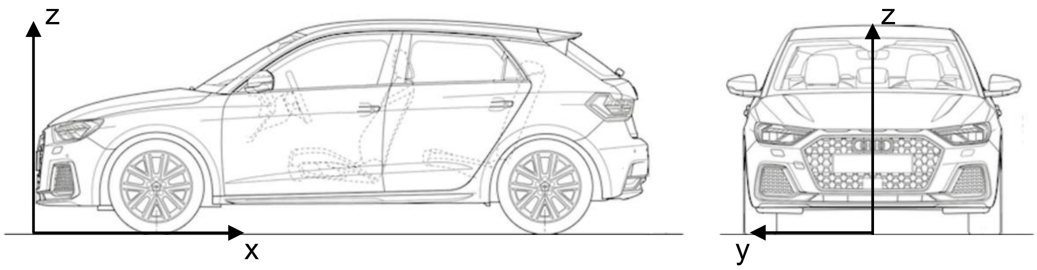


Figure 3.2: Vehicle coordinate system defined within the SAE standard J1100 [35, p. 31] (Image Source: [68])

3.3 Requirement Definition

In the beginning, concept engineers need to define requirements for the modular system, the vehicle models, and the vehicle variants (3.3.1). The early stage of the development of a modular system limits the availability of inputs. Therefore, the method includes a longitudinal dynamics simulation (LDS) to fully determine all performance requirements (3.3.2).

3.3.1 Input of requirements

First of all, the concept engineer defines the input requirements. The selection of the following requirements as inputs is based on the information available from product planning and the necessity for the modular system development. It is possible to divide the requirements into three groups: the modular systems requirements, the vehicle model requirements, and the vehicle variant requirements.

The modular system requirements consist of the number of vehicle models included as well as the type of modular system. The latter input distinguishes between single- and multi-drivetrain modular systems.

For up to five vehicle models, the user specifies more detailed vehicle requirements. These are the number of included vehicle variants, the body type, the exterior, and additional dimensions as well as the drivetrain types. The body type can be either low-ground or high-ground. Low-ground represents most of the body types, such as sedans and hatchbacks, while high-ground is for SUVs. The exterior dimensions are the overall vehicle length, the wheelbase, the front overhang, the prestige measure (distance between the front axle and the drivers' ball-of-foot (BOF)), and the vehicle width (Figure 3.3). Another exterior dimension is the curvature of the front bumper.

Additional dimensions are the H30-measure, which defines the seat height, as well as the minimum rim size. As drivetrains, combustion (ICEV), parallel full- or plug-in hybrid (HEV/PHEV), and electric (BEV) ones are available. In this context, HEV will refer to both full- and plugin-hybrids. Within the drivetrains, further selection or exclusion is possible for the engine types, such as gas or diesel engines, and the gearbox types. Additional requirements on vehicle level are the headlight and battery type.

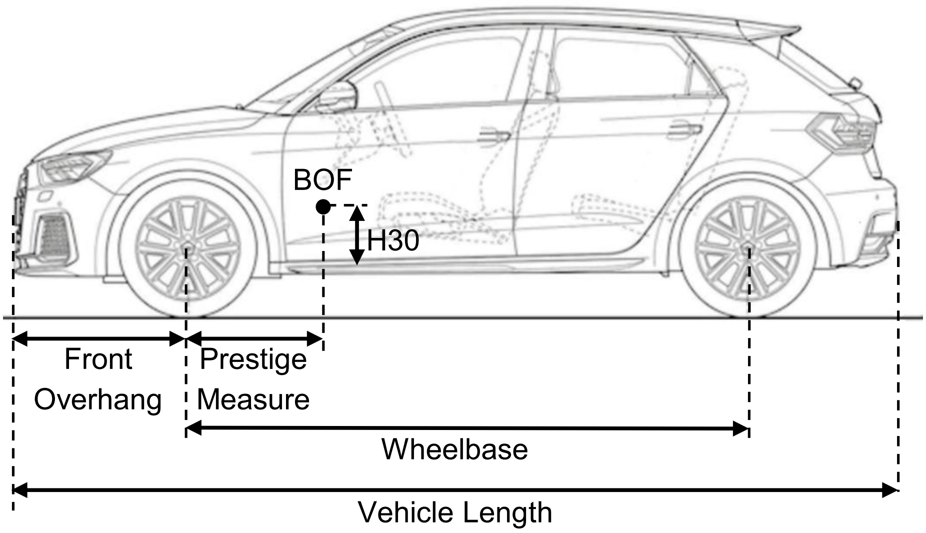


Figure 3.3: Exterior dimensions required as inputs (Image Source: [68])

For each of the vehicle models, it is necessary to define the requirements of up to three vehicle variants separately. This includes the allocation of performance classes (entry, medium, and sports level). The entry level applies for vehicle variants with low performance (maximum velocity lower than 200 km/h), the medium level to the ones with average performance (maximum velocity between 200 and 230 km/h), and the sports level to high-performance variants (maximum velocity faster than 230 km/h). This serves to distinguish the vehicle variants and influences the engine and gearbox design in the following. In addition, the drive type (two-wheel or four-wheel drive) must be defined. Also, the user distinguishes between regulatory or insurance classification as design types. The second design type usually applies only to one vehicle variant of a vehicle model. Within this variant, the distance between the bumper beam and the cooling system needs to be higher to avoid damages during the low-speed RCAR Structure Test [69]. High damages consequently would lead to a higher insurance class. Further inputs are the reduced curb weight, the weight of extra equipment, the load capacity, the maximum trailer load (at 12 % inclination), the acceleration time, the maximum velocity as well as the tank volume and the battery capacity. The reduced curb weight represents the vehicle weight without the weight of the driver and his luggage, defined in the EU directive EWG 92/21 [70], and without the weight of fuel and high-voltage batteries. This simplifies the input for the concept engineer because he does not need to know the different energy densities and weights. Furthermore, it is important to note that within the last inputs the method allows for the separate definition for ICEV/ HEV and BEV.

Within the requirements, there is a high dependency between the exterior dimensions, the drivetrain type, and the reduced curb weight of the vehicle. Therefore, in addition to the manual input of the weight, the method provides the option to use an empirical model for weight estimation. Using regression functions, the model estimates the vehicle weight based on the substitute volume of the vehicle, the drivetrain type, and performance requirements such as the acceleration time. This is particularly useful for vehicles without predecessors or benchmarks. The author described the model and its development in [71].

Table 3.1 gives an overview of the different requirements, which are all adapted to the early stage of the modular systems development.

Table 3.1: Overview of the requirements for the modular system, the vehicle models, and the vehicle variants

Modular Systems Requirements	Vehicle Model Requirements	Vehicle Variant Requirements
Number of Vehicles	Number of Vehicle Variants	Performance Class
Modular System Type	Body Type	Drive Type
	Exterior Dimensions	Design Type
	Additional Dimensions	Reduced Curb Weight
	Drivetrain Type	Equipment Weight
	Engine Type	Load Capacity
	Gearbox Type	Trailer Load
	Headlight Type	Acceleration Time
	Battery Type	Maximum Velocity
		Tank Volume
		Battery Capacity

In addition to the requirements, the concept engineer can define optimization parameters within the Graphic User Interface (GUI). These allow concept engineers to use advanced technologies and to adjust the dimensions. With discrete parameters for the technologies, for example, it is possible to switch from tires of normal load to extra load, or from a passive hood to an active hood. Regarding the dimensions, it is possible to switch from the default robust design option to the progressive design option. The progressive design option decreases the required distances between components, such as the distance between the cooling system and the engine. Besides, the user can reduce the size of components and distances by defining continuous optimization parameters. The progressive design option and the continuous optimization parameters are primarily intended for use during iterations of the tool and only when necessary, as the advanced technologies and decreased dimensions usually come with higher costs.

Appendix A displays the GUI of the tool for the input of the requirements and the optimization parameters.

3.3.2 Conversion of requirements

Especially for new vehicles without any predecessors, the engine power and the number of gear speeds are unknown at this early stage of the development. Therefore, the user input does not include engine and gearbox requirements. Consequently, it is necessary to calculate the engine power/torque as well as the gear speeds and transmission ratios based on input parameters such as the curb weight and the acceleration time to complete the stage of the requirements definition. However, this problem is underdetermined as neither the engine nor the gearbox is known.

The tool performs a longitudinal dynamics simulation for all vehicle variants and drivetrain types, including further subdivisions, separately. The process of the LDS is divided into three steps, the scaling of engine load curves, the gearbox design, and the acceleration time simulation (Figure 3.4). Due to the underdetermined problem, the scaling of the engine load curves and the gearbox design are required to create and design all engine-gearbox combinations. The acceleration time simulation filters the engine-gearbox combination by the achieved and required acceleration time of 0 to 100 km/h.

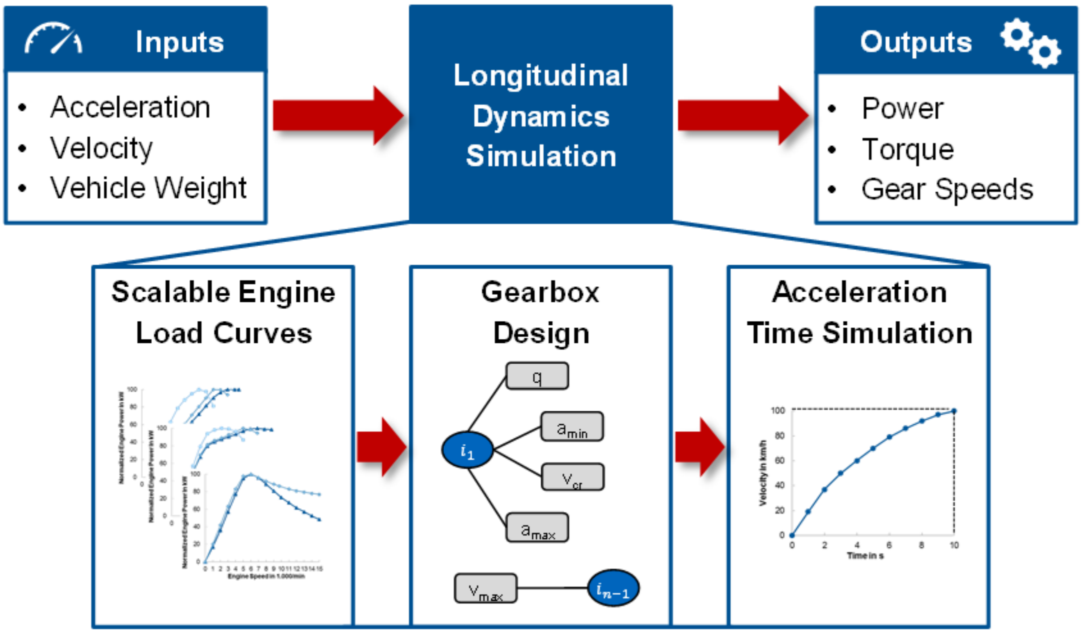


Figure 3.4: Overview of the LDS

Prior to the first step of the LDS, the method includes calculating the curb weight by adding the weight of the driver and his luggage as well as the weight of the fuel tank and/or the high-voltage battery to the reduced curb weight. The calculation of the latter weights is based on the tank volume and energy densities for gas and diesel as well as the battery capacities and different energy densities for the different battery technologies.

Within the scaling of engine load curves, the LDS scales to 100 kW normalized load curves of existing engines with factors from 0.4 to 4 in steps of 0.05, to arrive at multiple load curves from 40 to 400 kW. For the three combustion, parallel hybrid, and electric drivetrain types, the LDS includes a total of twelve different load curves (Figure 3.5). The three combustion engines are the gas naturally aspirated, the gas supercharged, and the diesel supercharged engines. The three hybrids are a combination of each combustion engine with a permanent synchronous electric machine (PSM). In practice, asynchronous machines (ASM) do not find application within parallel hybrids. A complex operating strategy for the hybrid drivetrains is not necessary, as the LDS targets the acceleration from 0 to 100 km/h and therefore fully exploits the power of both engines. For the electric vehicles, the electric machines are either PSM or ASM. For each of them, there are three load curves with low, medium, and high rotational speeds. References for the load curves are engines of prototype or series vehicles of the AUDI AG. However, the tool offers the possibility to exchange the load curves, as needed.

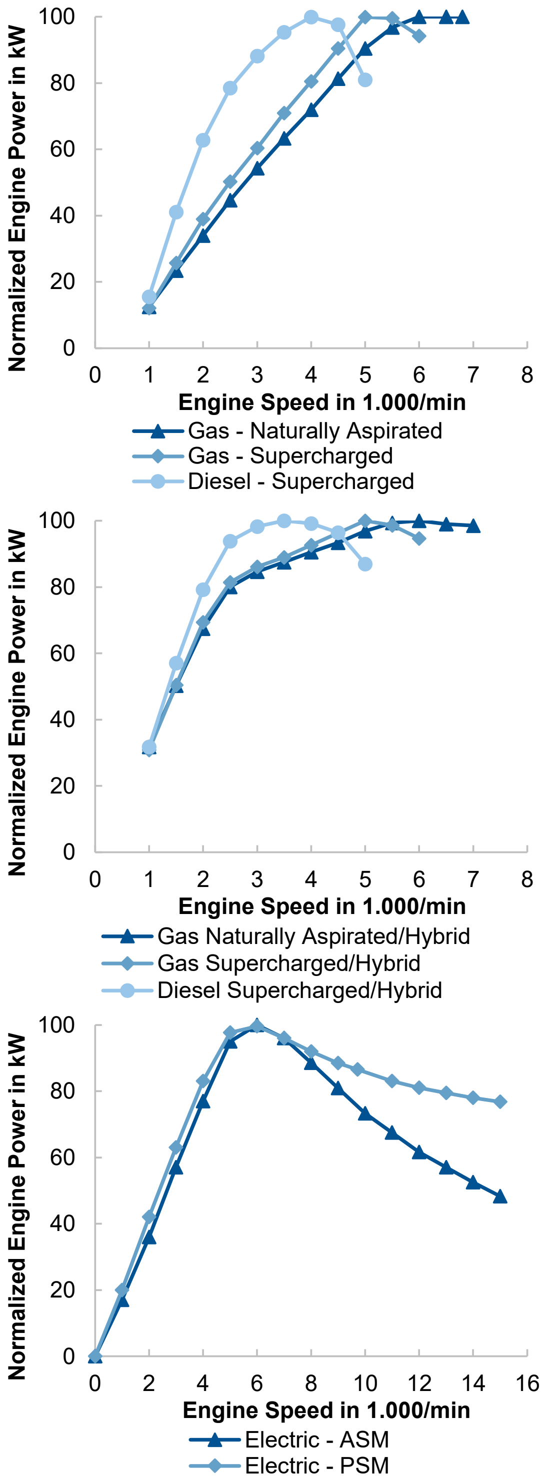


Figure 3.5: Normalized load curves of the different drivetrains and engines used for the scaling of the engine load curves

To reduce the number of engine characteristics created by the scaling, the LDS calculates the power required to drive at maximum velocity, overcoming the rolling and the air resistance (Equation 3.1, Table 3.2). Normally, the definition of the maximum speed does not include any slope. Considering a lower and upper tolerance, the LDS eliminates all instances below and much higher than the required power [72, p. 48]. Here, the upper tolerance varies with the performance class to ensure that enough power reserve remains at the sports level. However, these coherences do not apply to the electric drivetrains because, in most load curves, the maximum power is not available at the rotational speed required for the maximum velocity. For further information regarding vehicle's longitudinal dynamics, and driving resistances, the author refers to the literature [73, 74].

$$P_{v_{\max}} = m_{V,0}\, g\, c_{\mathrm{RR}}\, \left(v_{\max} \pm v_{\mathrm{tol,L/U}}\right) + \frac{1}{2}\, c_{\mathrm{W}}\, A_A\, \rho_A\, \left(v_{\max} \pm v_{\mathrm{tol}}\right)^3 \qquad 3.1$$

Table 3.2: Explanation of the parameters required for calculating the required engine power

Symbol	Unit	Description
$\mathrm{A_A}$	m^2	Vehicle front surface
c_{RR}	-	Rolling resistance
c_{W}	-	c_W-value
g	m/s^2	Force of gravity
$m_{V,0}$	kg	Vehicle curb weight
ρ_A	kg/m^3	Air density
$P_{v_{\max}}$	kW	Required engine power for maximum velocity
$v_{\max}$	m/s	Maximum velocity
$v_{\mathrm{tol,L/U}}$	m/s	Lower/upper tolerance velocity

Afterward, the remaining engine characteristics permute with the alternatives of the number of gear speeds. For the gearboxes of combustion or hybrid drivetrains, the number of gear speeds ranges from five to nine. The gearboxes of electric drivetrains contain only one gear speed. This creates a multitude of engine-gearbox combinations.

For each of the engine-gearbox combinations, the LDS designs the gearboxes, i.e. the transmission ratios. This varies between combustion/hybrid and electric drivetrains. In the combustions/hybrids, the design of the transmission ratio of the first gear speed is the most complex. It has to be high enough to fulfill the climbing ability, the starting acceleration, and the creep velocity [72, p. 48, 75, pp. 46-47].

The climbing ability ensures that the vehicle can drive uphill (Equation 3.2, Table 3.3). Hereby, different scenarios with different slope and different vehicle and trailer setups exist.

$$i_{G_{cl}} = \frac{m_{V,L}\, g\, r_{\mathrm{dyn}}(c_{\mathrm{RR}} \cos q + \sin q)}{T_{\mathrm{E,Max}}\ \eta_{\mathrm{dr}}} \qquad 3.2$$

The starting acceleration defines the lowest acceleration of the vehicle (Equation 3.3, Table 3.3), based on the performance class. For the entry and medium classes, the targeted starting acceleration is moderate. For the sports class, it is as high as possible, thus limited only by the traction limit.

$$i_{G_a} = \frac{\mathrm{m}_{V,0}\ r_{\mathrm{dyn}}\ (\lambda\ a_{\mathrm{min}} + g\ c_{\mathrm{RR}})}{T_{\mathrm{E,Max}}\ \eta_{\mathrm{dr}}} \quad 3.3$$

The creep velocity (≈ 7 - 9 km/h) is the lowest speed at which the vehicle can drive [75, p. 42], due to the idling speed of the combustion engines and the transmission ratio. It must be small enough to avoid uncoupling in low-speed roads and during traffic congestion (Equation 3.4, Table 3.3).

$$i_{G_{cr}} = \frac{n_{\mathrm{E,min}}\ 2\ \pi\ r_{\mathrm{dyn}}}{v_{\mathrm{Cr}}} \quad 3.4$$

While these design criteria define the minimum required transmission ratio of the first speed, the traction limits the transmission ratios to prevent the tires from slipping (Equation 3.5, Table 3.3). The acoustics and manufacturability define another maximum for the transmission ratio [75, p. 50].

$$i_{G_t} = \frac{m_{\mathrm{V,0}}\ \lambda\ a_{\mathrm{max,T}}\ r_{\mathrm{dyn}}}{T_{E,Max}\ \eta_{\mathrm{dr}}} \quad 3.5$$

The LDS only considers engine-gearbox combinations where the transmission ratios of the first gear lie between these boundaries (Equation 3.6, Table 3.3).

$$\max\left(i_{G_{cl}}, i_{G_a}, i_{G_{cr}}\right) < i_{G_1} < \min\left(i_{G_t}, i_{G_p}\right) \quad 3.6$$

After the first gear, the LDS designs the transmission ratio of the second to last gear taking into account the maximum velocity [72, p. 50]. The last gear is not considered as this is usually a fuel-efficient overdrive. The transmission ratios of the intermediate gear speeds are then determined based on a progressive grading between the first and the second last gear speed [72, p. 50], leading to an even distribution of the velocity intervals of the gear speeds.

Table 3.3: Explanation of the parameters required for the gearbox design

Symbol	Unit	Description
q	°	Slope angle (varies according to scenario)
a_{min}	m/s²	Minimum acceleration
$a_{\mathrm{max,T}}$	m/s²	Maximum acceleration due to traction limit
i_{G_1}	-	Transmission ratio of the first gear speed
i_{G_a}	-	Minimum transmission ratio for minimum acceleration
$i_{G_{cl}}$	-	Minimum transmission ratio for climbing
$i_{G_{cr}}$	-	Minimum transmission ratio for creep velocity
i_{G_p}	-	Maximum transmission ratio for producibility
i_{G_t}	-	Maximum transmission ratio for traction limit
λ	-	Rotational inertia factor
$m_{V,L}$	kg	Loaded vehicle weight (varies according to scenario)
η_{dr}	-	Efficiency of the drivetrain
$n_{\mathrm{E,Min}}$	1/min	Idle speed of the engine
r_{dyn}	m	Dynamic rolling radius
$T_{\mathrm{E,Max}}$	N m	Maximum torque of the engine
v_{Cr}	m/s	Creep velocity

In the electric drivetrains, the gearbox design varies because the tool only considers gearboxes with one gear speed. Additional gear speeds are not required because the electric machine provides high power and torque in most areas of the engine speed range. Therefore, almost all existing electric vehicles have gearboxes with only one gear speed. With only one gear speed, the tool calculates the transmission ratio solely based on the maximum engine speed and the desired maximum velocity. Afterward, with the calculated transmission ratio, the LDS eliminates the engine-gearbox combinations whose machine power is too low for the required climbing ability and the starting acceleration, and too high for the traction limit. The creep velocity is not relevant to electric machines because the idle speed of the machine is zero. Further information about the design of gearboxes is given by [76, pp. 95-136].

Finally, for the remaining engine-gearbox combinations, the LDS simulates the time to accelerate from 0 to 100 km/h. This is the central part of the LDS. At each time step of the simulation, the LDS uses the current velocity and the transmission ratio of the engaged gear to calculate the engine speed. With the engine speed, it is possible to look up the torque and power of the engine available at that time in the corresponding engine load curve. By comparing the engine torque with the driving resistances, the LDS calculates the possible acceleration at that time step (Equation 3.7) [72, p. 11]. The driving resistances do not include the climbing resistance because, for maximum acceleration, the slope is zero. Integrating the acceleration leads to the velocity at the next time step.

$$a_{\mathrm{V,t}} = \frac{T_E\, \eta_{\mathrm{dr}}\, \frac{i_{\mathrm{G_n}}}{r_{\mathrm{dyn}}} - \mathrm{m_{V,0}}\, \mathrm{g} - \frac{1}{2} c_{\mathrm{W}}\, \mathrm{A_A}\, \rho_A\, v_{\mathrm{V,t}}^2}{\lambda\, m_{V,0}} \quad 3.7$$

Table 3.4: Explanation of the parameters required for simulating the acceleration time

Symbol	Unit	Description
$a_{\mathrm{V,t}}$	m/s^2	Acceleration at the current time step
i_{G_n}	-	Transmission ratio of the engaged gear speed (with differential)
$T_{E,t}$	N m	Engine torque at the current time step
$\mathrm{v_{v,t}}$	m/s	Velocity at the current time step

Since the goal is to accelerate as fast as possible, the LDS can also shift at each time step to always engage the gear speed with the highest power. This analysis of the gear speeds is based on the current velocity of the vehicle and, with the different transmission ratios, the various engine speeds and load points in the load curves.

The time steps increase incrementally until the vehicle reaches 100 km/h. Finally, the LDS compares the time of each engine-gearbox combination with the acceleration time required by the concept engineer and eliminates the ones out of tolerance.

The required parameters for the LDS are calculated either using a geometric substitute model (3.4.1), like tire diameter based on the vehicle weight, or derived from empirical valuations such as the c_W-values or the load distribution for different drive types. The use of dimensional chains of the vehicle dimensions design also determines the vehicle height (3.4.3) which is required to calculate the vehicle front surface.

The LDS runs on all possible vehicle variants as well as the different drivetrain types, including the variation of the fuel type, the charging type, and in the case of the electric machines, the engine type (ASM or PSM). If the selected drive type is not all-wheel drive within a vehicle variant, the LDS also iterates for the front- and rear-drive types. The result of the LDS is a variety of possible engine-gearbox combinations for each of the vehicle variants of the different vehicle models. The different engine-gearbox combinations fulfill the same input requirements and only vary in the power/torque and the number of gear speeds. In the following, each engine-gearbox combination represents one alternative set of requirements for the different vehicle variants (Figure 3.6).

	Engine-Gearbox Combination 1	Engine-Gearbox Combination 2	…	Engine-Gearbox Combination 15	Engine-Gearbox Combination 16	…	Engine-Gearbox Combination 25	Engine-Gearbox Combination 26
Vehicle	1	1	…	1	1	…	1	1
Vehicle Variant	1	1	…	1	1	…	1	1
Performance Class	Entry	Entry	…	Entry	Entry	…	Entry	Entry
Drive Type	Front	Front	…	Front	Front	…	Front	Front
Drivetrain Type	ICEV	ICEV	…	HEV	HEV	…	BEV	BEV
Fuel Type	Gas	Gas	…	Gas	Gas	…	Electric	Electric
Charging	Nat. Aspir.	Nat. Aspir.	…	Nat. Aspir.	Nat. Aspir.	…	High Speed	High Speed
Engine Type	-	-	…	-	-	…	ASM	PSM
Engine Power Combustion in kW	140	130	…	120	130	…	-	-
Engine Power Electric in kW	-	-	…	30	20	…	70	60
Engine Torque Combustion in N m	230	210	…	190	210	…	-	-
Engine Torque Electric in N m	-	-	…	110	70	…	120	100
Number of Gear Speeds	6	7	…	9	9	…	1	1

MALKIC [72], gives a more detailed description and evaluation of LDS. Besides, S. FUCHS [77] uses a similar acceleration time simulation for his weight estimation tool. However, he does not design the gearboxes and only simulates one engine-gearbox combination at a time.

3.4 Architecture Generation

The main stage of the modular systems development (2.2.1) and thus the method is the generation of architectures. The foundation is geometric substitute models for the requirement-based, continuous scaling of components and distances between components (3.4.1). With the requirements as input, the method uses the geometric substitute models to synthesize and dimension all conceivable vehicle architecture alternatives (3.4.2) for all variants of the different vehicle models. Afterward, the method derives the available installation space (3.4.3). Finally, it is possible to identify feasible architecture alternatives by comparing the required and the available installation space with dimensional chains (3.4.4).

3.4.1 Geometric substitute models

A primary element of the architecture generation is the dimensioning of component sizes and distances between components. One option for dimensioning is the use of discrete datasets for a component. This allows the use of existing components. However, the discrete scaling restricts the adaptation to alterations of the input requirements and thus the holistic consideration of modular systems.

To enable the requirement-based, adjustable scaling of component sizes and the distances between them, this method uses geometric substitute models. The following describes the geometric substitute models that the method mainly applies during the synthesis of architectures (3.4.2). However, some of the models also find application during other stages and steps of the method. The following description is based in part on a publication of the author [47].

A geometric substitute model converts one or more requirements as model inputs into component sizes and distances as outputs (Figure 3.7).

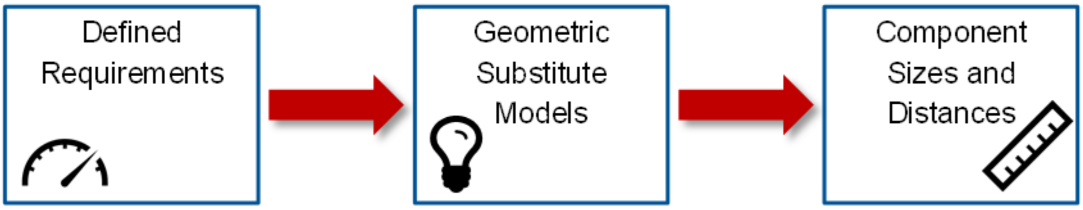


Figure 3.7: General idea of geometric substitute models

Within the outputs, the focus is on the main dimension. Therefore, the geometric substitute models abstract the complex geometries into simpler shapes such as cuboids or cylinders (Figure 3.8).

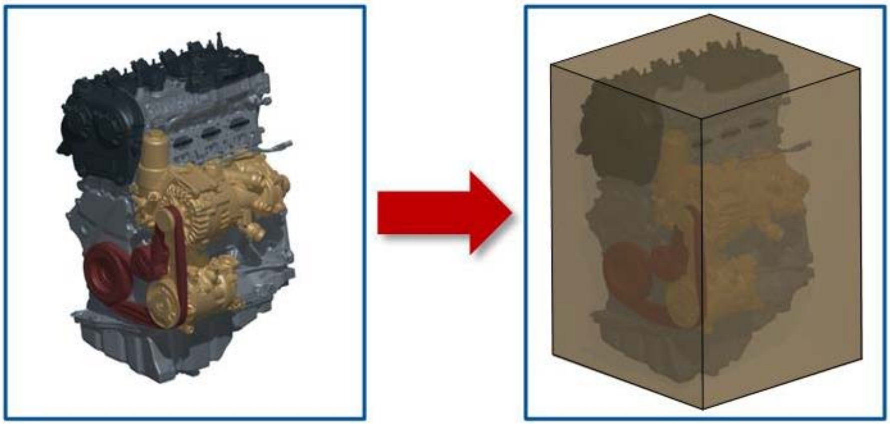


Figure 3.8: Abstraction of complex geometries using the example of combustion engines

The geometric substitute models differ by the modeling granularity and the modeling types.

Depending on the modeling granularity, the geometric substitute model consists either of the overall dimension or of multiple subdivisions that add up to the overall dimensions. Figure 3.9 illustrates the breakdown of the overall engine length into different subdimensions.

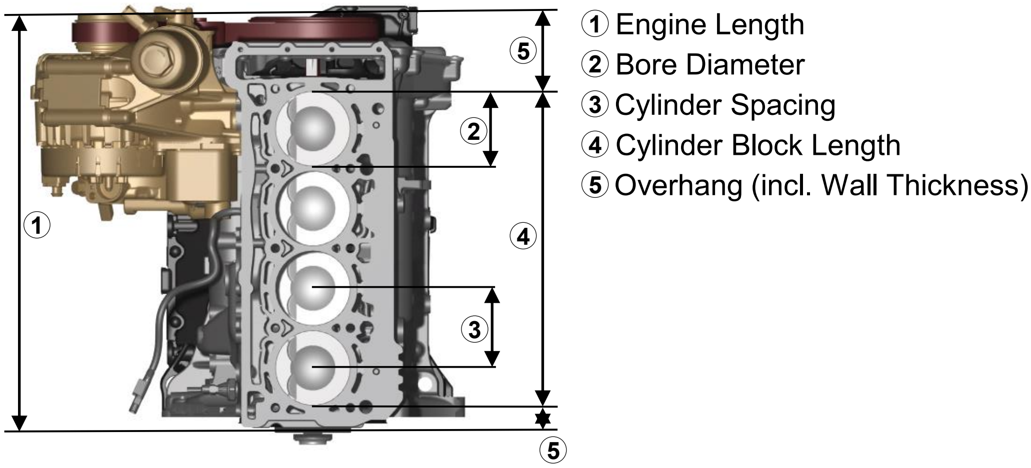


Figure 3.9: Breakdown of the engine length into subdimensions, based on [47, p. 265]

SCHORN [78, pp. 27-29] defines the white-box models, the light-gray-box, the dark-gray-box, and the black-box modeling as modeling types. The white-box models are entirely based on physical laws and correlations. The gray-box models use both physical laws and empirical correlations to varying degrees [79, p. 145]. Black-box models empirically define the correlation between an input and an output using statistical methods. In the following, the author refers to them as physical-, semi-physical for both light gray and dark gray models as well as empirical models.

The use of the modeling types depends on factors such as the complexity of the physical principles and the availability of empirical data [47, p. 267]. This thesis only considers geometric substitute models with empirical and semi-physical modeling types. For physical models, the correlations such as the chemical reaction within combustion engines are complex and therefore require input parameters that are not available at this early stage.

For the different modeling types, the author describes the development of the models in detail in the following. The remainder of the section then presents the created substitute models. To create individually adapted models the author usually applies the approaches separately to different component and installation position alternatives.

An empirical substitute model either models the overall dimensions, or it consists of multiple empirical models for subdimensions. In the latter case, the entire model is an interconnection of the different submodels. For one dimension, the empirical modeling can be either a regression function or a constant value derived from a normal distribution. When using regression functions, the dimensions vary with different requirements. For example, the cylinder block length as an active subcomponent varies with the engine torque. In contrast, constant values do not deviate with the requirements. This is plausible for components or subcomponents with limited variations in the automotive industry, such as the bumper beam. Moreover, this can be the case for passive (sub)components, like the engine overhang. Another reason is that, in particular, constant values usually do not model all but only certain alternatives of a component such as xenon headlights, or of a distance.

For every empirical model, data on the dimensions as well as the corresponding properties are necessary.

As the main data source for the dimensions, the author uses the automotive benchmarking database of A2Mac1 EURL [80]. The company disassembles vehicles and provides detailed benchmarking information in terms of dimensions and properties. For the dimensions, they provide a 2D database with images and dimensions of components (Figure 3.10) as well as a 3D database with 3D scans of the vehicle front (Figure 3.11). Considering only the vehicles from 2010 to 2018 to avoid the influences of technology leaps, the 2D database contains over 350 vehicle disassembles of over 40 automotive manufacturers. The 3D database includes 56 vehicle scans from 21 manufacturers. Additional sources for the dimensions were 3D data from vehicles of the AUDI AG as well as CAD sectional drawings from the Global Car Manufacturers Information Exchange (GCIE) [81]. Despite the multitude of data sources, it is important to know that the available data is divided into different technologies such as combustion, hybrid, and electric engines, thus reducing the available data points per model. Usually, each model builds only upon 2D or 3D databases.

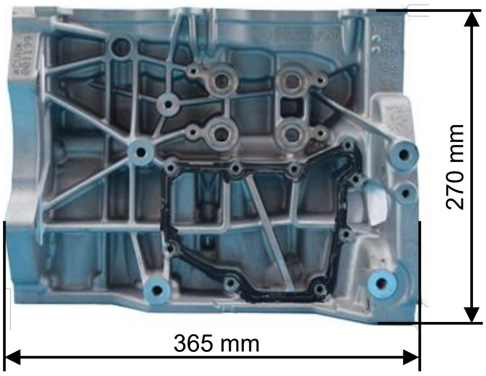


Figure 3.10: A2Mac1 2D documentation of an AUDI A4 engine, based on [80]

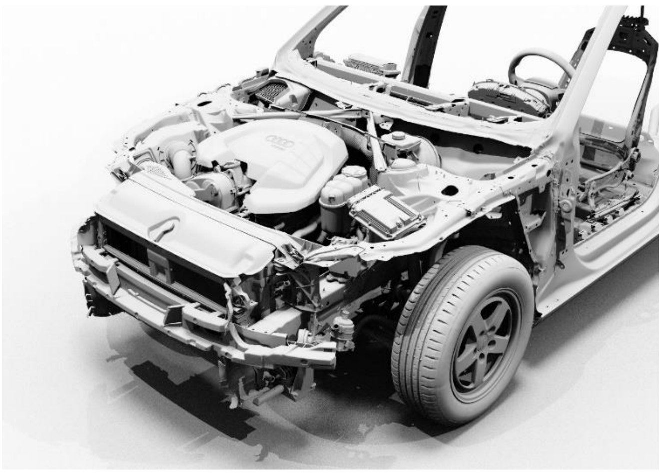


Figure 3.11: A2Mac1 3D Scan of an AUDI A4 [80]

In addition to the dimensions, appropriate information on the component and vehicle properties is required. This information is also based on A2Mac1 and experts in the development departments of AUDI AG. Other sources are the database of the Allgemeine Deutsche Automobil-Club (ADAC) e.V. [82], as Europe's largest automobile club, as well as the database of the auto magazine Auto Motor und Sport (AMS) [83]. In this context, the difference between properties and requirements is that the properties describe the characteristics of existing vehicles and the requirements describe the desired characteristics for future vehicles. Consequently, the properties of current vehicles apply for the creation of the models and the requirements of future vehicles for the use of the models.

Using the empirical data, the empirical modeling of the dimensions is based on a standardized approach. Initially, the goal is to create a multiple linear regression function that associates the properties with the dimension using the least squares method. Here, the dependent variable is a dimension and can be a function of multiple metric (e.g., engine power) or binary (e.g., fuel type) explanatory variables (Equation 3.8).

$$D = \alpha + \beta_i\, V_{M,i} + \gamma_i\, V_{B,j} + \ \delta_i\, V_{M,i}\, V_{B,j} \tag{3.8}$$

Table 3.5: Explanation of the parameters of a generic linear regression function

Symbol	Description
D	Dependent variable (Dimension)
$V_{M,i}$	1 to i metric explanatory variables
$V_{B,j}$	1 to j binary explanatory variables
α	Constant term
$\beta_i, \gamma_i, \delta_i$	Gradient term
$V_{B,j}$	1 to j binary explanatory variables
$V_{M,i}$	1 to i metric explanatory variables

Derived from the generic linear regression function, Figure 3.12 illustrates a linear regression function with one metric explanatory variable.

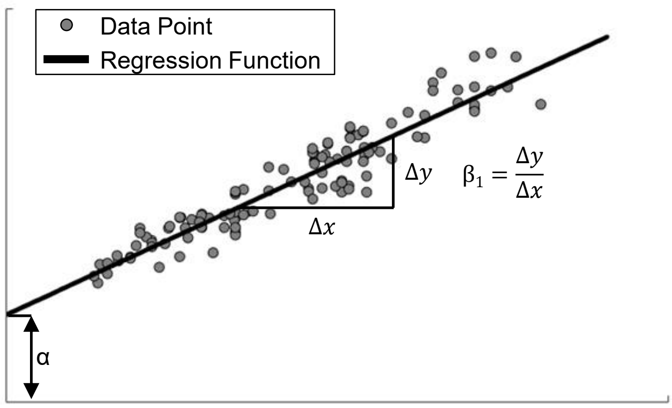


Figure 3.12: Illustration of a linear regression function with one metric explanatory variable, based on [84]

Various statistical tests, such as the Variance Inflation Factor (VIF) [85, p. 98], the homoscedasticity [86, pp. 78-79], as well as the F- and T-test [87, pp. 43-47], ensure the validity of the results. In addition, different statistical values output the accuracy of the regression. These are mainly the coefficient of determination (adj-R^2), which indicates the coverage of the real data by the regression, and the normalized mean absolute error (nMAE). With the statistical values, it is also possible to compare different variations of a regression function. Finally, an out-of-sample test (OOST) analyzes the general validity of the regression function [88]. Depending on the overall number of data sets, the test recreates the regression function with only 75 to 90 % of the data. It then applies the regression function to the remaining data and evaluates the deviations between the calculated and the real dimensions. The OOST iterates multiple times to avoid influences of random sampling.

If there is no correlation between dimensions and properties, the creation of empirical geometric substitute models is continued with the derivation of a constant value α for the dimension D (Equation 3.9) using a histogram of the data (Figure 3.13). Consequently, the approach analyzes whether a normal distribution exists within the empirical data. In this case, the mean is defined as the constant value. To evaluate the normal distribution, the Kolmogorov–Smirnov Test exists [89]. Further statistical values for evaluation are the variance, the nMAE as well as the OOST.

$$D = \alpha = const. \tag{3.9}$$

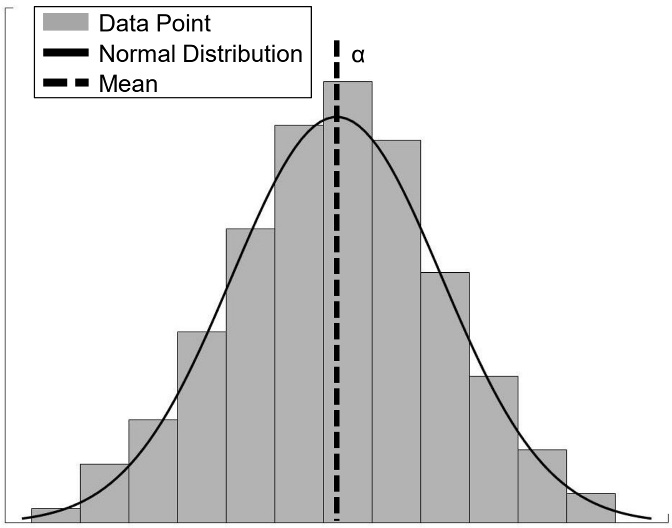


Figure 3.13: Derivation of a constant value using a histogram and normal distribution, based on [84]

To develop the models, using the presented statistical approach, and to ensure a maximum of reproducibility, a statistics tool was created in MATLAB. The author gives a more detailed description of the statistical approach as well as the statistical tool in [47]. BORTZ [90] and STOETZER [87] provide further information on statistical analysis.

Within the semi-physical approach, the dismantling of the component or distance into subdimensions is inevitable. The procedure then uses the described empirical modeling for some of the dimensions. However, the model also consists of physically modeled dimensions. These link the input and the output by physical laws. While this approach does not require any empirical data, it needs more detailed parameters for the modeling. Typically, the physical modeling applies to active components, such as the cylinder block length, and the empirical modeling to passive subcomponents like the engine overhang.

The author applied the empirical and the semi-physical modeling approaches to the components and distances relevant to the architecture in the vehicle front. This resulted in geometric substitute models for over 20 components and distances of the drivetrain, the cooling, the chassis, the body, and the interior (Figure 3.14). For each of the different alternatives of components and distances, different geometric substitute models exist.

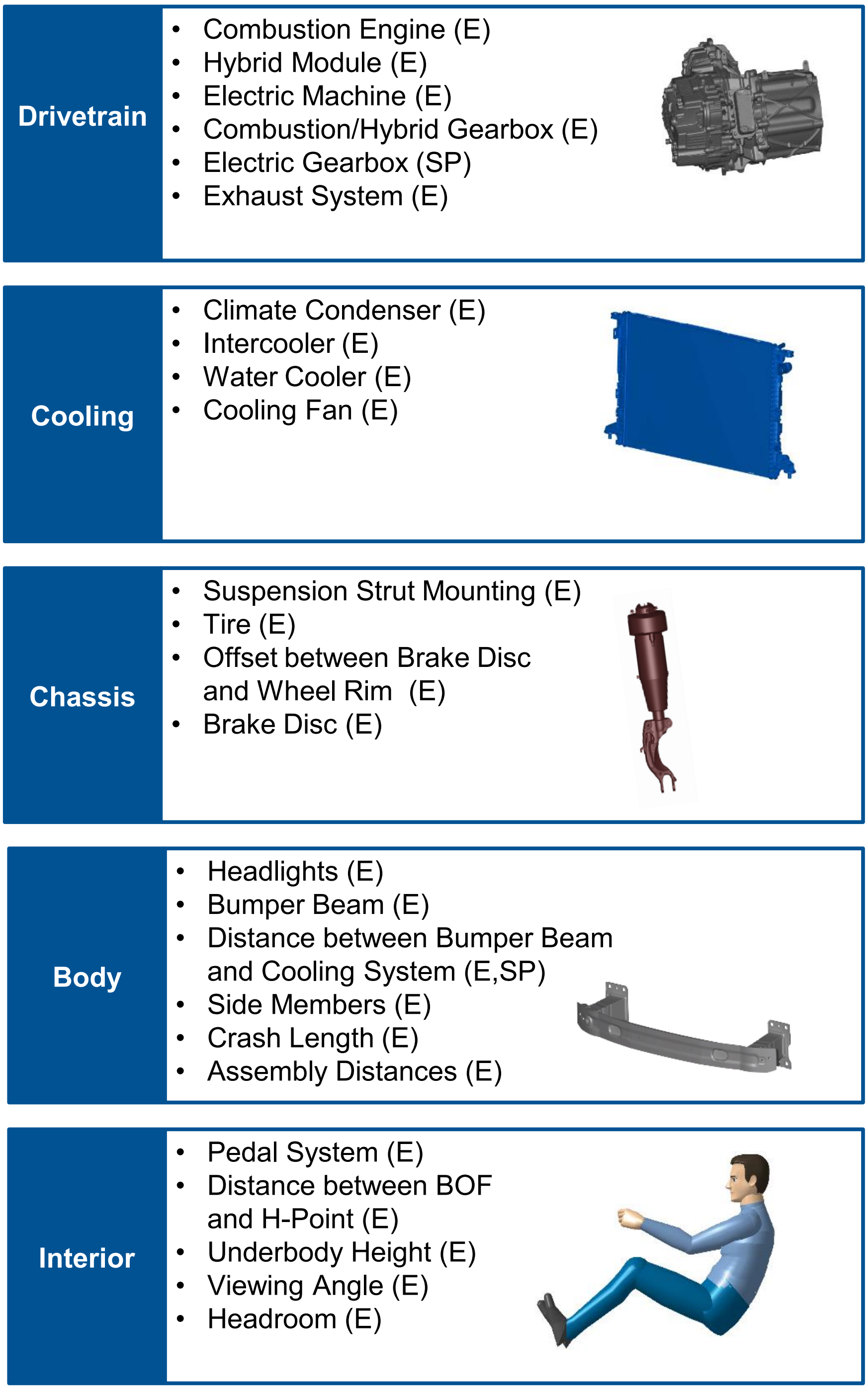


Figure 3.14: Overview of the created geometric substitute models (E: Empirical, SP: Semi-Physical)

The combustion engine is one of the most complex components in motor vehicles. Therefore, the following exemplifies geometric substitute models by reference to combustion engines. To increase the model accuracy, the model consists of several submodels for the subdimensions (Figure 3.9).

Due to the complex physical correlations, this is an empirical model. Inputs are the subdimensions of over 220 combustion engines from A2Mac1. Also, the peak torque and power of the engines are available. If several variants exist for one engine, the peak values come from the variant with the highest performance.

In the following, the author explains in detail the geometric substitute for the length of in-line engines with different fuel types (gas/diesel) and charging (naturally aspirated/supercharged). This model consists of the combination of two regression functions and three constant values.

At first, regression functions convert the engine torque $T_{E,max}$ into the required engine displacement volume V_{ED}. There are different regression functions for the gas naturally aspirated (Equation 3.10), the gas supercharged (Equation 3.11) and the diesel supercharged (Equation 3.12) engines. Since the engine type does not influence the engine displacement volume extremely, this equation is based on and valid for in-line and V-type engines. Within the regressions, the engine power is not an explanatory variable, as a mutual influence on the torque exist. The visualization of the equations (Figure 3.15) show that the supercharged diesel engines require the lowest engine displacement for the same torque. For the supercharged engines, the regression function does not differentiate the number of turbochargers.

$$V_{ED_{NAG}} = 71.2\,cm^3 + 9.8\frac{cm^3}{N\,m}\,T_{E,max} \tag{3.10}$$

$$V_{ED_{SCG}} = 40.7\,cm^3 + 5.9\frac{cm^3}{N\,m}\,T_{E,max} \tag{3.11}$$

$$V_{ED_{SCD}} = 497.6\,cm^3 + 4.0\frac{cm^3}{N\,m}\,T_{E,max} \tag{3.12}$$

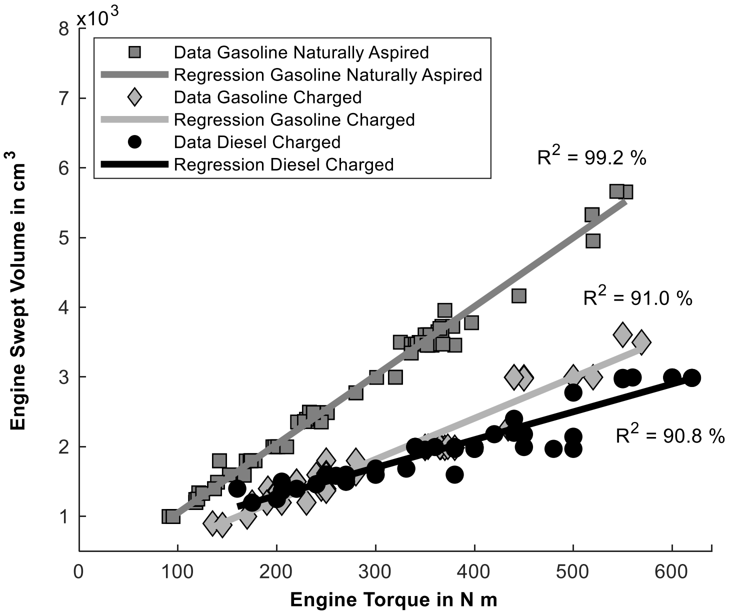


Figure 3.15: Regression function between the engine displacement volume and the engine torque, based on [47]

To determine the number of cylinders n_C, the model must divide the resulting engine displacement volume by an optimal cylinder swept volume V_{OC}. For all in-line engines, the statistical evaluation of the cylinder swept volume with values from 300 to 650 cm³ shows a high variance. The main reason for the dispersion is the high bandwidth of the engine displacement volumes in the database, which range from around 900 to 3000 cm³. Due to this bandwidth, the model considers two values for the optimal cylinder swept volume, for engines with an engine displacement volume lower and higher than 1800 cm³. This limit is chosen as it is in-between the popular 1.6-liter and 2.0-liter engines. For the engines with a smaller engine displacement volume, the optimal cylinder swept volume is 400 cm³. While the statistical mean is 374 cm³ (Figure 3.16), the model considers this even number in orientation to the commonly used 1.2-liter (3 cylinders) and 1.6-liter (4 cylinder) engines. For engines with a higher engine displacement volume, the optimum cylinder swept volume is 500 cm³. In contrast to the slightly different statistical mean of 530 cm³ (Figure 3.17), this value makes it possible to derive engines with integer numbers of liters, like 2-liter (4 cylinders) or 3-liter (6 cylinders) engines [91, p. 22]. Overall, the distinction of the optimal cylinder swept volumes prevents the output of engines with too few or too many cylinders. However, the cylinder swept volume remains dependent on the automotive manufacturers' design philosophies. Consequently, it is possible for concept engineers to adjust the optimal cylinder swept volume used by the model.

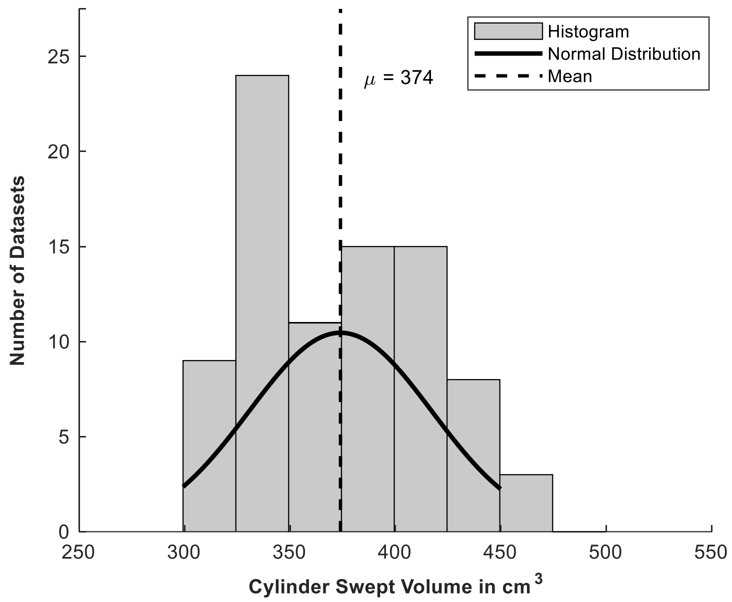


Figure 3.16: Optimal cylinder swept volume for engines with engine displacement volume lower than 1800 cm³

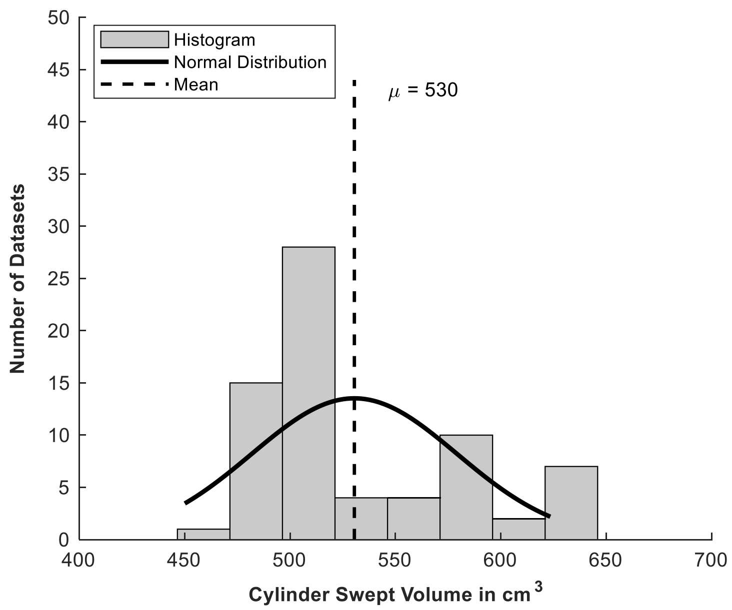


Figure 3.17: Optimal cylinder swept volume for engines with engine displacement volume higher than 1800 cm³

With the two optimal cylinder swept volumes, it is possible to calculate the number of cylinders. Therefore, the model divides the engine displacement volume by either of the optimum cylinder swept volumes. Since the division does not necessarily result in an integer number of cylinders, the model needs to round the resulting number of cylinders to an integer number (Equation 3.13).

$$n_C = \left\lfloor \frac{V_{ED}}{V_{OC}} \right\rfloor \bigvee \left\lceil \frac{V_{ED}}{V_{OC}} \right\rceil \qquad 3.13$$

Due to the rounding, the final cylinder swept volume V_C differs slightly from the optimal cylinder swept values, which makes a further calculation necessary (Equation 3.14).

$$V_C = \frac{V_{ED}}{n_C} \qquad 3.14$$

Using a constant value for the stroke-bore ratio r_{SB} (Figure 3.18), the calculated cylinder swept volume can be divided into the bore diameter b (Equation 3.15) and the stroke s (Equation 3.15). In the case of the in-line engine, the result is a long stroke-bore ratio that is similar to findings in previous studies [91, p. 22, 92, p. 13].

$$b = \sqrt[3]{\frac{V_C}{r_{SB}\ \frac{\pi}{4}}} \qquad 3.15$$

$$s = b \cdot r_{SB} \qquad 3.16$$

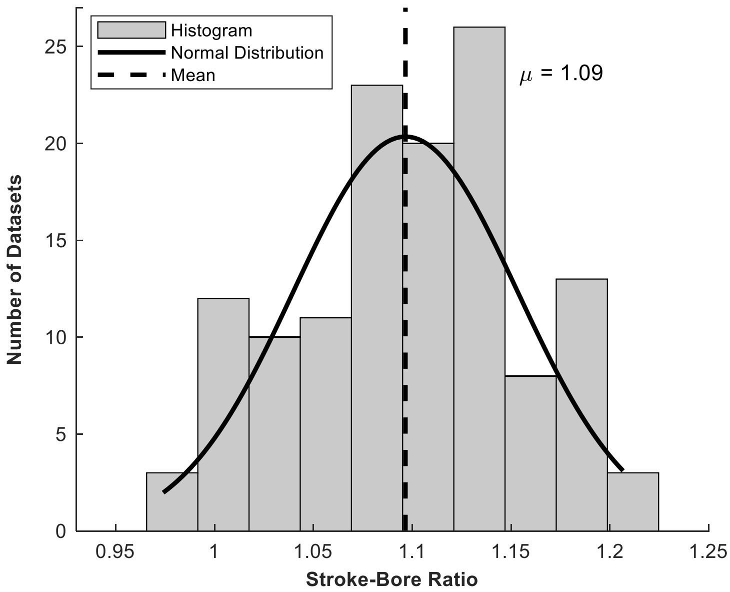


Figure 3.18: Normal distribution for the stroke-bore ratio, based on [47]

Subsequently, a regression function calculates the cylinder spacing as a function of the bore diameter (Equation 3.17, Figure 3.19). KÖHLER [92, pp. 29-30] identified a similar correlation.

$$cs = 17.4\,mm + 0.9\,b \tag{3.17}$$

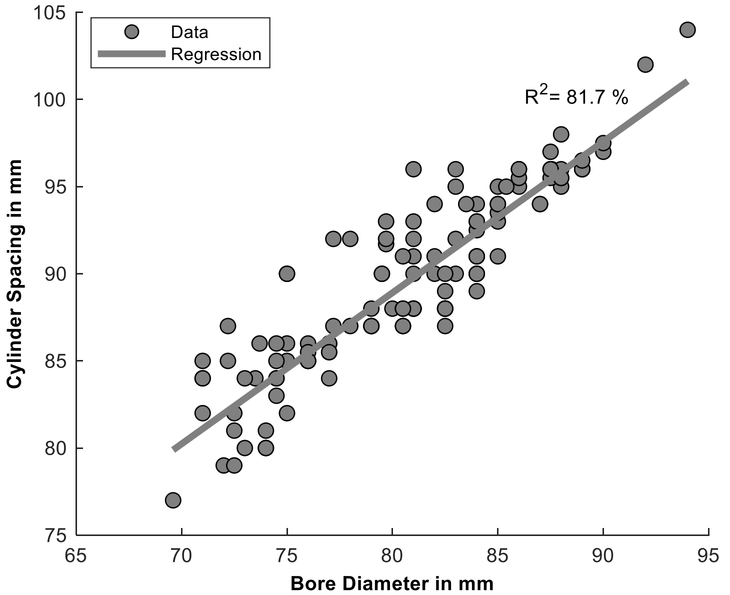


Figure 3.19: Regression function between the cylinder spacing and the bore-diameter, based on [47]

Using the number of cylinders, the bore diameter, and the cylinder spacing, it is possible to already calculate the cylinder block length L_{CB} (#4, Figure 3.9, Equation 3.18).

$$L_{CB} = b + (n_c - 1)\,cs \tag{3.18}$$

In addition to the cylinder block length, a constant value describes the length of the engine overhang L_{OH} (Figure 3.20) for components such as the belt drive. For this subdimension, the data showed no significant dependence on the engine torque or the size of the cylinder block length.

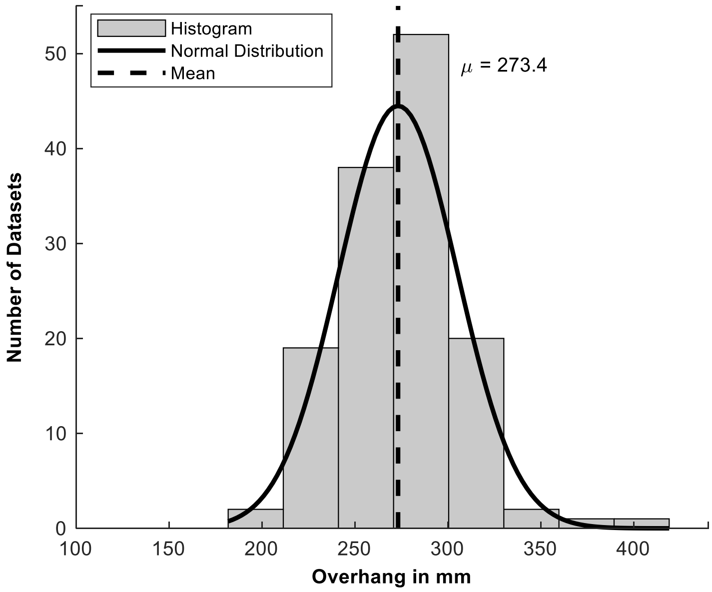


Figure 3.20: Normal distribution for the overhang, based on [47]

The subsequent use and combination of the various regression functions and constant values lead to a geometric substitute model for the length of in-line engines (Equation 3.19, Figure 3.21). The accuracy of the model described, based on the nMAE, is 93.8 %.

$$L_E = L_{CB} + L_{OH} \quad 3.19$$

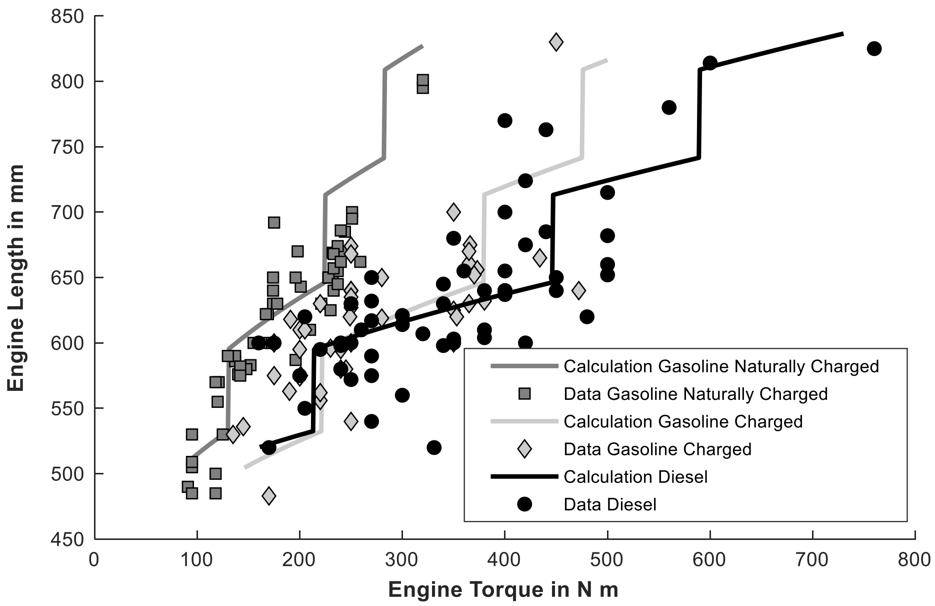


Figure 3.21: Geometric substitute model for the length of in-line engines, based on [47]

Similar results exist for the width and height of the in-line engines. In addition, a model for the V-type engines is available.

The description of all geometric substitute models would far exceed the scope of this thesis. However, Appendix B gives an overview of the most crucial regression functions and constant values of the geometric substitute models. Additional descriptions of the geometric substitute models can be found in previous publications [47, 93] as well as in different student theses [84, 94–101] advised by the author.

In general, the accuracy of most geometric substitute models ranges from 85 to 95 % [100, pp. 45-76]. Lower accuracies around 75 % only result within components with plastic mountings, as within the intercooler, or within components strongly influenced by aesthetics, such as the head-lights. Another reason for models with lower accuracies is a limited amount of data, as within the exhaust system. However, even with only 75 %, the accuracy is high enough for use in the early stages of the vehicle architecture design. Moreover, the relative accuracy does not describe the impact on the overall model, due to different sizes of the components and distances.

Furthermore, it is important to know that the empirical and semi-physical models do not output the best or smallest solution available for a component or distance. Instead, they output the statistically most likely dimension, which results in a robust and conservative solution. Within the tool, the concept engineer can deviate from the statistical solution by defining optimization parameters in the GUI (3.3.1).

3.4.2 Synthesis of vehicle architectures

This step generates and dimensions all conceivable vehicle architectures by permuting of the component and installation position alternatives as well as the requirement-based dimensioning with the geometric substitute models.

The inputs of the synthesis are the engine-gearbox combinations, which, as explained in section 3.3.2, represent multiple instances of requirements (Figure 3.6). They describe all requirements for one combination of the vehicle model, the vehicle variant, the drivetrain, and the engine fuel and charging type. Due to the different load curves, the engine-gearbox combinations of the electric drivetrains also include the information about the engine type (ASM or PSM).

With the fuel type, the charging type, and the engine type, the engine-gearbox combinations already include some information about the architectures. The synthesis of the architectures extends the engine-gearbox combinations of all vehicle variants stepwise with all other combinable type and position alternatives of all considered components. After each extension, the method includes the dimensioning of the related component sizes and distances. The dimensioning is based on the requirements by applying the geometric substitute models.

As the first step within the synthesis, the engine-gearbox combinations are permuted with the different type and position alternatives of the engines/machines. This means that the engine-gearbox combinations of combustion engines are permuted with the in-line and the V-type type alternatives as well as the longitudinal and transversal installation position alternatives. This extends the engine-gearbox combinations to a multitude of preliminary architecture alternatives. Within each of these, the tool dimensions the engine length, width, and height. Therefore, the tool selects the corresponding geometric substitute model of the engine (3.4.1) based on the component and position alternatives defined in the respective preliminary architecture alternative. With the requirements of the individual architecture alternative as inputs conveyed by the engine-gearbox combinations, the selected geometric substitute model outputs the dimensions of the engine. Hereby, the method eliminates architecture alternatives which exceed technical boundaries, like in the case of in-line engines more than six cylinders. The only difference for the engine-gearbox combinations of the hybrid engines is that the tool also dimensions the hybrid machine within this step. In contrast to the combustion/hybrid drivetrains, electric drivetrains do not have a multiplication effect on the engine-gearbox combinations. One reason is that the engine-gearbox combinations already include the machine type alternatives (PSM, ASM). Besides, for electric engines, no other than the transversal installation position is available on the market and within the method. Therefore, it is possible to use the geometric substitute model of the electric machines without a preceding extension.

In subsequent steps, the preliminary architectures are permuted with the combinable type and position alternatives of the gearbox, the exhaust system, the cooling system (climate condenser, intercooler, water cooler, and cooling fan), the chassis, the headlights, and the high-voltage battery. Figure 3.22 gives an overview of the possible component type and installation position alternatives considered within this thesis. It turns out that different type or position alternatives are not available for all components. Moreover, as within the engines, the preliminary architectures are not permuted with every component and position alternative. Instead, depending on the already defined specifications of an architecture alternative, the method only considers matching component and installation position alternatives. For example, the exhaust system is only available for combustion and hybrid drivetrains and varies with the engine type and the engine installation position. In contrast, the electric machines do not require an exhaust system, but an indirect water cooling is indispensable. Even though different types exist for the headlights and the high-voltage battery, the user can only select one per vehicle.

As within the first step of the synthesis, the method applies the geometric substitute models for the scaling of the component sizes and distances between components after each extension. Furthermore, the tool eliminates the architecture alternatives that do not comply with different technical boundaries, such as the maximum number of seven gear speeds for manual gearboxes.

After the permutation steps, the architectures are still preliminary. To fully specify them, the tool needs to add remaining components, which are the bumper beam, the side members, the bulk wall as well as the tires. For these components, the different component types vary only slightly in their geometries. Given the level of detail in the vehicle architecture design, the effects on the contemplated dimensions are negligible. In addition, only one installation position exists in reality. Consequently, the method considers only one component type and installation position alternative within the tool. Therefore, it is possible to merely include and dimension these components without permutation.

At the end of this step, the method also involves bundling some components, such as the climate condenser, the intercooler, the water cooler, and the cooling fan, to form a uniform cooling system. Therefore, the different dimensions are compared, and all components are assigned the maximum width and height. Another example for the bundling is with the clutch, hybrid module, and gearbox.

The synthesis results in over 250,000 generated vehicle architectures for all vehicle variants of the different vehicle models. The architectures are fully specified with one combination of component and installation position alternatives as well as all relevant component sizes and distances between components. However, it is not yet known whether the architectures comply with the available installation space and are thus feasible.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7
Engine Type	In-Line	V-Type	ASM	PSM			
Engine Installation Position	Longitudinal	Transversal					
Hybrid Module	PSM	None					
Gearbox Type	Manual	Double Clutch	Automatic	Axially Parallel			
Exhaust System Type	Gas Exhaust	Diesel Exhaust	None				
Exhaust System Position	Lateral Horizontal	Lateral Vertical	Rear Horizontal	Rear Vertical	Rear Central	Front & Rear Central	None
Climate Condenser Type	Gas/ Liquid						
Intercooler Type	Direct (Air/Air)	Indirect (Air/Water)	None				
Water Cooler Type	Indirect (Air/Water)	None					
Cooling Fan Type	Single/ Double						
Cooling System Position	Fullface	IC Below & Ahead	IC Below & Behind	Lateral IC			
Chassis Type	McPherson	Multi-Link					
Headlight Type	Halogen	Xenon	LED				
HV-Battery Type	Prismatic	Pouch	Cylindrical	None			

Figure 3.22: Illustration of the considered component and installation position alternatives

3.4.3 Derivation of the available installation space

The synthesis of the vehicle architectures generates a multitude of vehicle architectures. To identify the feasible architectures in the following, the method includes the derivation of the available installation space.

The available installation space defines the areas each vehicle model provides, unified among all vehicle variants, for integrating the components of the architecture. Within the vehicle front, only three areas with available installation spaces exist. One area is within the engine compartment and the other two are within the side aprons in front of the wheel house. The size of these areas depends on the exterior dimensions as well as some components and distances of the architectures, such as the bumper beam, the side members, and the wheel house.

The derivation of the available installation spaces is done using dimensional chains of the vehicle dimensions design in the x-, y-, and z-directions. The SAE standard J1100 [35] and the ISO standard 4131 [102] define the overall vehicle dimensions and set the foundation of the derivation.

In the x-direction, the available installation space of the engine compartment $AIS_{EC/X}$ is determined based on the length of the vehicle front overhang OH and the prestige measure PM minus the license plate thickness $s_{LCP/x}$, the distance for pedestrian protection $d_{PP/x}$ and sizes of the bumper beam $s_{BB/x}$, the bulk wall $s_{BW/x}$,and the pedal system $s_{PE/x}$ (Equation 3.20). It is possible that the slope angle limits the space, leading to different lengths of the engine compartment at different z-levels.

$$AIS_{EC/X} = OH + PM - s_{LCP/x} - d_{PP/x} - s_{BB/x} - s_{BW/x} - s_{PE/x} \tag{3.20}$$

The length of the side apron equals the overhang minus the pedestrian protection distance, the size of the bumper beam, and half of the wheel house. Hereby, the method contemplates the slope angle as well as the contour of the tire and its rotation, which leads to different lengths of the apron at different z-levels. In addition, the front of the side apron depends on the curvature of the bumper beam, which results from the curvature of the bumper. However, the curved side part of the bumper beam exists only for active pedestrian protection, which is a discrete optimization parameter within the tool.

Starting from the vehicle width in the y-direction, the tire width and the turning angle, as well as the strut mounting, define the position of the side members. The position of the side members determines the width of the side aprons as well as of the engine compartment. Figure 3.23 shows the derivation of the available installation spaces in the x- and y-directions.

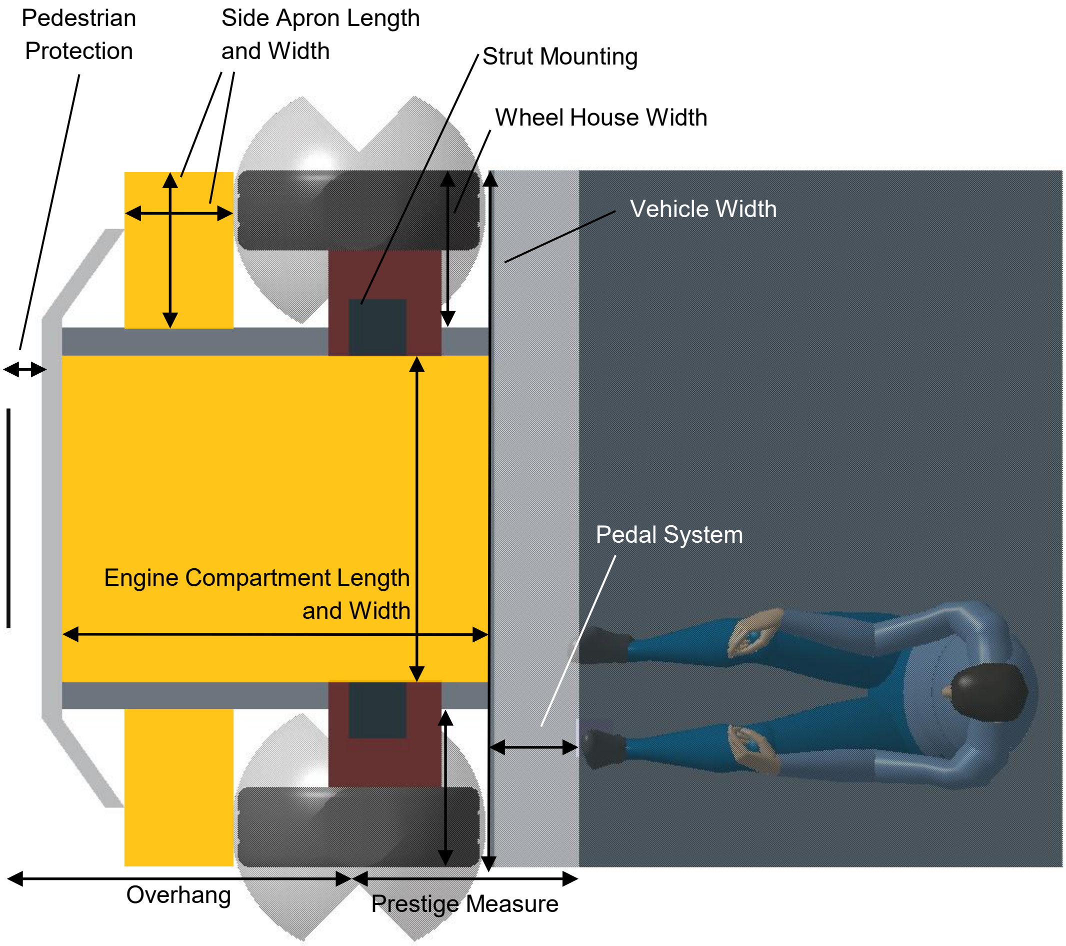


Figure 3.23: Derivation of the available installation spaces in the x- and y-directions

The derivation of the available installation space in the z-direction is the most complicated since it depends on the angle and height of the hood and thus on the viewing angle and eye points of the driver (Figure 3.24). To determine the eye points, it is first necessary to decide on the x- and z-coordinates of the seating reference point (SgRP), with the 95th percentile male as reference [103, p. 397]. The method defines the x-coordinate from the gas pedal (BOF) as a function of the driver's legs and the H30-measure due to the knee-angle. The z-coordinate depends on the ground clearance, the underbody height, and the H30-measure. From the SgRP, the SAE standard J941 [104], with the body height of the 95th percentile male, defines the position of an eye ellipse. Despite the positioning with the 95th percentile male, the eye ellipse represents 95 % of all percentiles and gender eye points. In addition, the EU directive 77/649/EWG [105] defines two different eye points of the driver from the SgRP. Within the directive, the definition of the points is not directly linked to percentiles and genders. From the eye ellipse and the eye points, viewing angles limit the available installation space. In both, the viewing angles are different. As only guidelines for the angle exists within the SAE, the method considers a statistically derived angle. In contrast, the EWG defines a regulatory viewing angle [33, pp. 19-20]. Since the eye points and the viewing angles vary within the SAE and the EWG, each of them can be relevant to the derivation of the available installation space at different x-coordinates. Therefore, the tool always compares the viewing straights and derives the height of the engine compartment at the contemplated x-coordinate based on the in z-direction lower viewing straight and the pedestrian protection distance. In the z-direction, the distance for pedestrian protection depends on the material of the hood (aluminum/steel) and the type of pedestrian protection (active/passive). For the height of the available installation space on the side, it is not necessary to consider the pedestrian protection. BUBB [103, pp. 350-405] provides further information on the positioning of the driver in the vehicle. The required component sizes and distances for the available installation space in the z-direction, such as the underbody height or the viewing angle of the SAE, are also based on empirical geometric substitute models (3.4.1).

The method performs the derivation of the available installation space for each vehicle model separately. However, within one vehicle model, some dimensions initially vary within the different vehicle variants and drivetrain types. Since the tire size depends on the weight, the dimension is usually the highest for the vehicle variant with the maximum performance. Furthermore, the underbody battery of the electric vehicles influences the weight, and thus the tire size but also the underbody height and, consequently, the eye points and vehicle height. Thus, the method derives and unifies the minimal available installation space among all vehicle variants. However, the modular system type also influences the unification of the available installation spaces. Within a single-drivetrain approach, the tool derives and unifies the minimal installation space among all vehicle variants but separately for combustion/hybrid and electric drivetrains. The multi-drivetrain approach unifies the minimum installation space between all vehicle variants and drivetrain types. This leads to unified positioning and dimensions of the body components, such as the side members and strut mount.

In addition to the definition of the eye points, the tool similarly defines the height of the vehicle for the LDS (3.3.2).

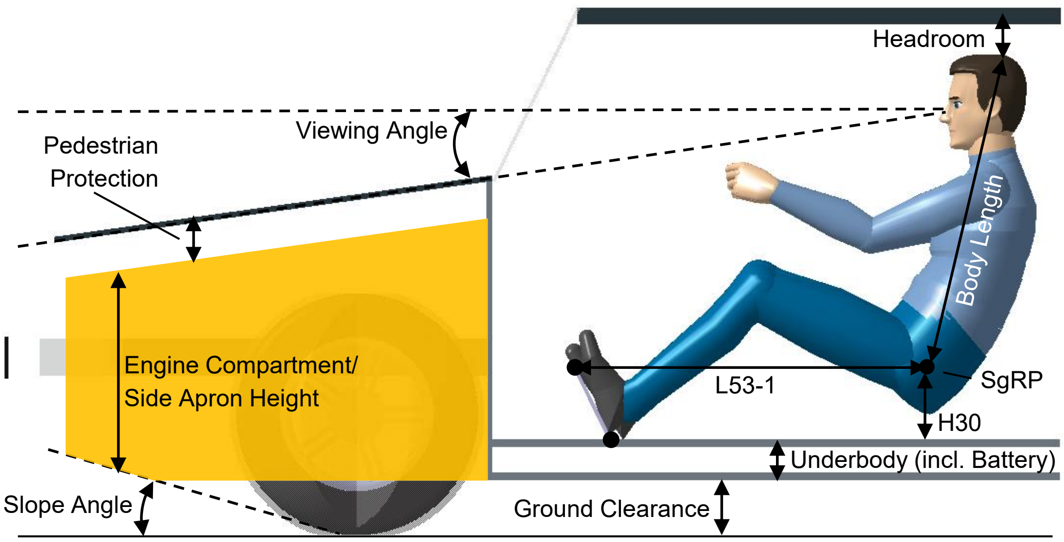


Figure 3.24: Derivation of the available installation spaces in the z-direction

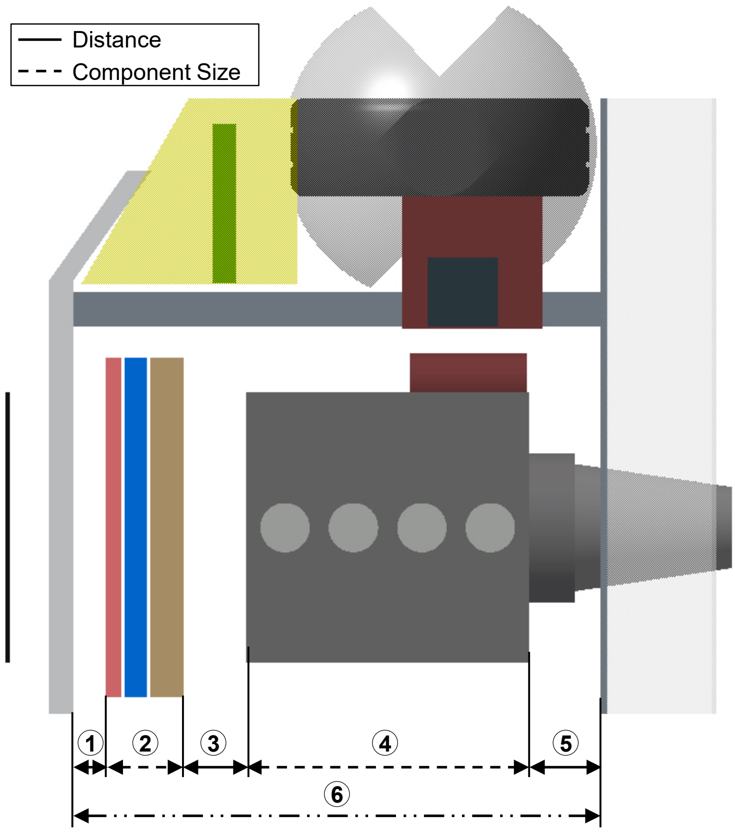
3.4.4 Comparison of the required and the available installation space

Based on the available installation spaces, it is now possible to analyze the feasibility of the vehicle architectures, defined in the synthesis of architectures (3.4.2). The method, therefore, compares the required installation space of each architecture alternative of every vehicle variant with the available installation space of the corresponding vehicle model. In this method, the comparison is based on the dimensional chains of the vehicle architecture design, which assess whether the distances between components comply with minimum specifications.

As explained by the author in [37, pp. 192-193], dimensional chains of the vehicle architecture design consist of component sizes and distances between ambient components within a start and end point along a defined coordinate direction (Figure 2.5).

Within this method, there are nine main dimensional chains in the x-, y-, and z-directions with over 20 variants and more than 200 parametric component and distance chain elements. This high number results from the fact that the various component types, such as engine types and installation positions such as the lateral positioning of the intercooler, require different variants of the main dimensional chains with varying chain elements. One example is the lateral intercooler, which requires a dimensional chain on the side of the vehicle. Another example is the longitudinal and transversal installed gearboxes. Furthermore, there are dimensional chains without variations, such as the one from the bumper beam over the headlight to the wheel house.

For the comparison with the available installation space, the start and end points are located within the available installation space, for example, within the bumper beam and the bulk wall. Figure 3.25 shows a dimensional chain in the x-direction in the engine compartment. Further illustrations of the most important dimensional chains and their variants can be found in Appendix C.



① Distance between bumper beam and cooling system
② Thickness of the cooling system
③ Distance between cooling system and engine
④ Length of the engine
⑤ Distance between the engine and the bulk wall
⑥ Length of the engine compartment

Figure 3.25: Dimensional chain within the engine compartment in the x-direction

Using the dimensional chains, the comparison is divided into three steps, which the method conducts for all dimensional chains of an architecture alternative and for each of the 250,000 architecture alternatives.

As the first step, the tool selects the appropriate dimensional chain variants and chain elements based on the component types and installation positions of the architecture alternative.

In the second step, the tool inserts the component sizes into the corresponding component chain elements. For example, it inserts the length of a longitudinal installed engine into the chain element for the engine within a dimensional chain in the x-direction. In addition, the tool inserts the minimum required values into the distance chain elements of the dimensional chain. The distances, such as the distance between the cooling system and the engine, mainly represent crash and assembly requirements but also vibration and thermal requirements. The distances also depend on the different component types and installation positions. The mentioned distance between the cooling system and the engine is small for front-drive type architectures, while it is high for the rear-drive types to achieve an optimal load distribution for each drive type. To determine the distances, empirical geometric substitute models exist (3.4.1). These are mainly constant values, as in the previous example. In some cases, the constant value is not based on the mean but on the 25th or 15th percentile, for instance. Hereby, the concept engineer can choose between the two percentiles by switching from the robust to the progressive design option, which is a discrete optimization parameter. For the distance between the bumper beam and the cooling system, there exists an empirical substitute model for the regulatory design. In the case of the insurance classification design, a semi-physical model calculates the distance required to protect the cooling system from damages during the Research Council for Automobile Repairs' (RCAR) structure test [69].

Afterward, the component and distance chain elements add up to the overall length of the dimensional chain. Equation 3.21 gives an example of the addition of the x-dimensional chain over the engine in the engine compartment.

$$DC_{EC/X} = d_{BB-CS/x} - c_{CS/x} - d_{CS-E/x} - c_{E/x} - d_{E-BW/x} \quad 3.21$$

Table 3.6: Explanation of the parameters required for calculating the dimensional chain over the engine in the engine compartment

Symbol	Unit	Description
$d_{BB-CS/x}$	mm	Distance between the bumper beam and the cooling system in the x-direction
$d_{CS-E/x}$	mm	Distance between the cooling system and the engine in the x-direction
$DC_{EC/X}$	mm	Length of the dimensional chain over the engine in the engine compartment
$d_{E-BW/x}$	mm	Distance between the engine and the bulk wall in the x-direction
$s_{CS/x}$	mm	Cooling system thickness in the x-direction
$s_{E/x}$	mm	Engine length in the x-direction

Then the method entails comparing of the length of the dimensional chain with the corresponding available installation space. One exemplary comparison is between the dimensional chain within the engine compartment $DC_{EC/X}$ and the length of the engine compartment $AIS_{EC/X}$ (Equation 3.22). This comparison can lead to three different results: either the required installation space is similar, lower, or higher than the available installation space.

$$AIS_{EC/X} \leftrightarrow DC_{EC/X} \tag{3.22}$$

No action is required if the required and the available installation spaces are similar. In case the installation space is lower, it is necessary to define which distance chain element of the dimensional chain to increase. This means that each dimensional chain requires one or more distance elements with a higher degree of freedom. In the case of the front-drive type, this is the distance between the engine and the bulk wall. In the rear-drive type, this is the distance between the cooling system and the engine. This leads to the best load distribution for the corresponding drive type. In the y-direction, the tool increases the distances on both sides of the engine for symmetrical positioning. In the z-direction, the distance between the hood and the engine is adjustable to increase pedestrian protection.

If only within one dimensional chain the required installation space is higher than the available installation space, the architecture alternative is not feasible. Another criterion for feasibility exclusively in the x-direction is the crash length. This means that the sum of all distances between the bumper beam and the bulk wall in the x-direction must be higher than a minimum empirical value to provide enough space for the energy reduction during a crash.

In most dimensional chains, this step ultimately determines the feasibility of the architecture alternative. For example, if the space for the headlamps within the bumper beam and the wheel house is too small, the architecture alternative is not feasible. In this case, the tool issues an error report to help the concept engineer define adjustments.

In one case, however, it is possible to influence the corresponding dimensional chain and to iterate the second and third steps. The tool initially positions the cooling system and the engine for front-drive type as far forward as possible. This allows a high load distribution on the front axle favorable for this drive type. However, the positioning is problematic for the distances in the z-direction between the cooling system and the engine to the hood since the available installation space decreases in the z-direction toward the front of the vehicle. Therefore, if the cooling system or the engine does not comply with the available installation space in the z-direction, the tool moves it sufficiently backward within the iteration to conform with the z-dimensional chain. This leads to an adjustment of the distance between the bumper beam and the cooling system as well as between the cooling system and the engine in the x-direction. Within the dimensional chains in the x-direction, it is therefore necessary to reassess whether the distance between the engine and the bulk wall is still higher than the minimum required value. This possibility of iteration only exists because the available installation space in the z-direction decreases toward the front. Moreover, the iteration is only successful if additional installation space is available in the x-direction. For the rear-drive type, this iteration makes no sense since the positioning of the engine is already as close as possible to the bulk wall, to allow a higher load distribution on the rear axle.

Due to the adjustment of the distance elements either due to an excess of available installation space or as a result of the described iteration, this step leads to a repositioning of the components. Consequently, it changes the initially defined architectures and outputs the final architectures.

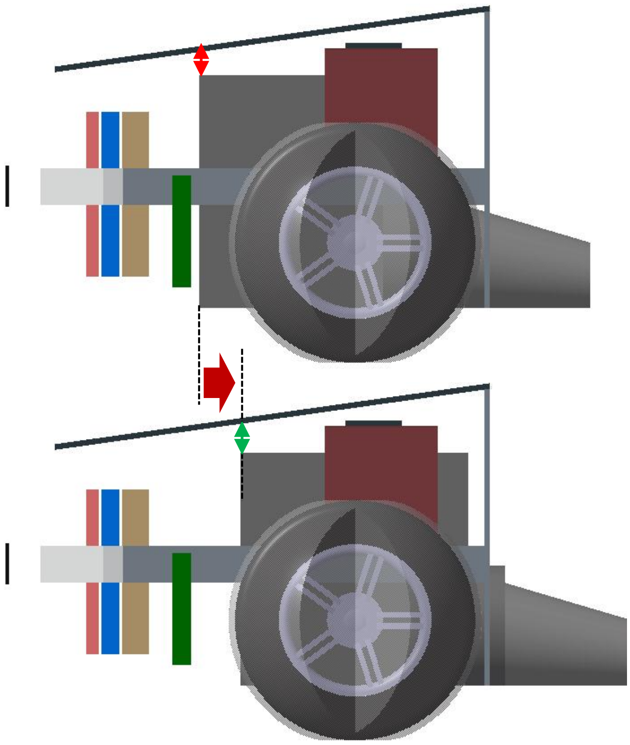


Figure 3.26: Displacement of the engine in the x-direction to increase the pedestrian protection distance in the z-direction

Figure 3.27 gives an overview of the three-step process for comparing the required and available installation space.

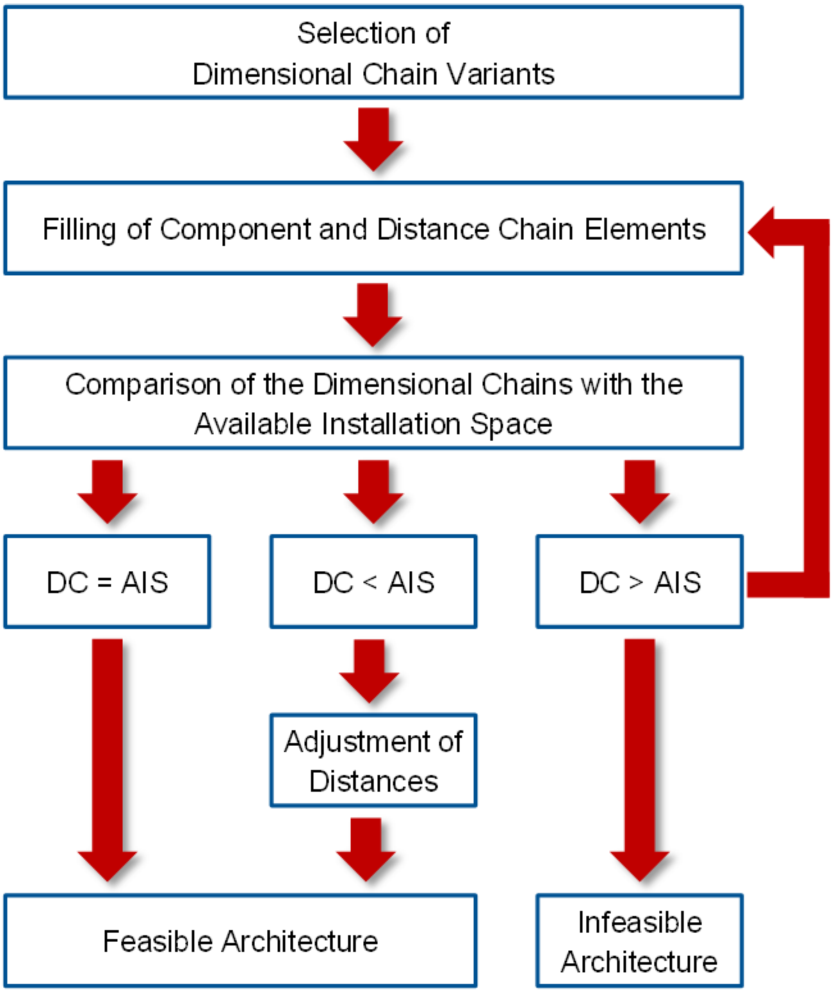


Figure 3.27: Overview of the process for the comparison of the required and available installation space using dimensional chains (DC: length of the dimensional chain; AIS: available installation space)

The systematization of the dimensional chains with different variants, as well as the use of variable distance elements and iterations for repositioning components, enable the implementation of the dimensional chain systematic usually performed manually by concept engineers. This ensures a transparent and systematic approach.

3.5 Derivation of Modular Systems

With the generation of over 250,000 vehicle architectures, through the permutation of the engine-gearbox combinations with the conceivable component type and installation position alternatives, the entire solution space is considered. The comparison of the required and the available installation space already significantly reduced the number of vehicle architectures. However, a variety of architectures is still available for each vehicle model and vehicle variant. These architecture alternatives differ in their external variants as a combination of the vehicle model, the vehicle variant, and different drivetrain types, as well as the internal variance, such as the engine type and the engine installation position. Other internal variants are the engine-gearbox combinations in terms of the engine power or the number of gear speeds or the various cooling system positions. Figure 3.28 shows an example of various architecture alternatives. Hereby, it should be noted that the figure does not illustrate all external and internal variants, as this would lead to thousands of branches/architecture alternatives. In addition, the vehicles and vehicle variants do not necessarily have to have the same number of architecture alternatives. Depending on the requirements, more or fewer architectures are feasible.

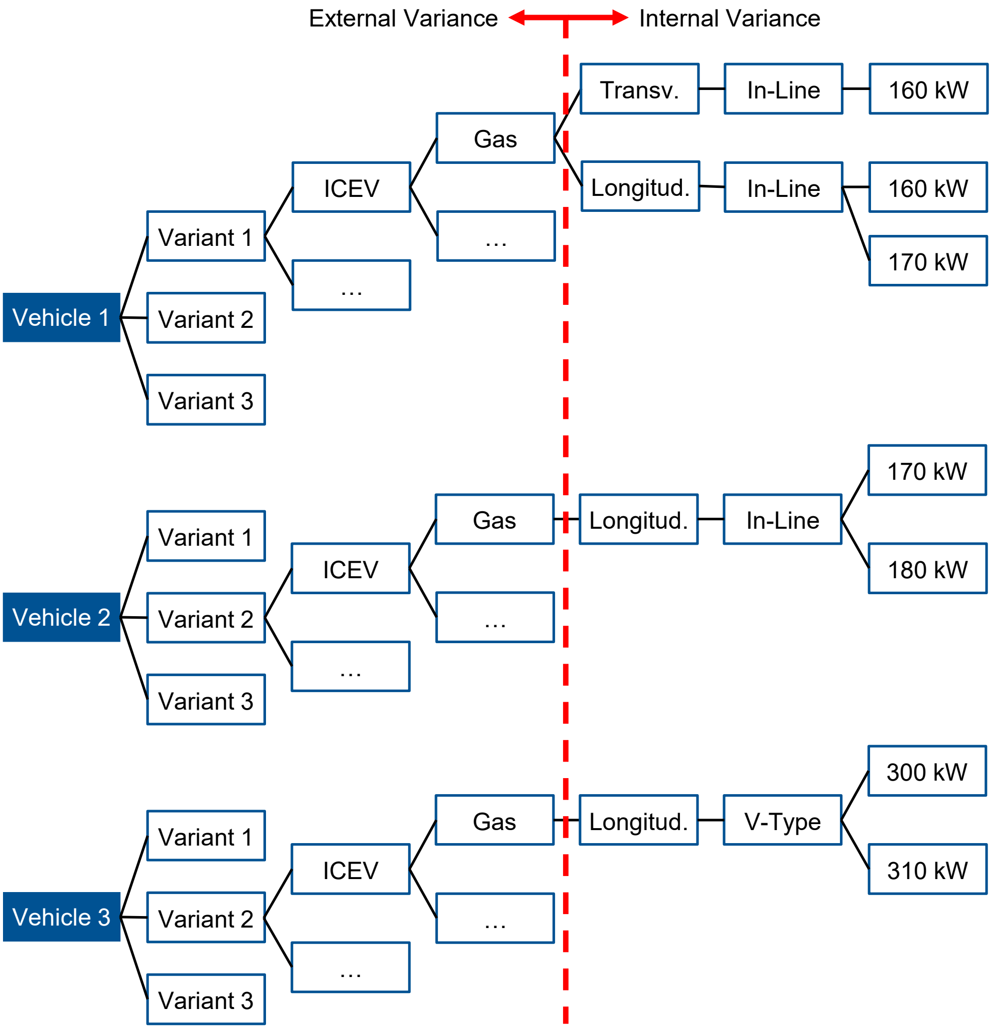


Figure 3.28: Examples of different architecture alternatives (each branch represents an architecture alternative)

In general, the goal is to offer any combination of the external variants to fulfil the requirements of the customers. This means that, for each combination of the external variants, only one architecture must exist. Further architectures are not necessary as the internal variance is not relevant to the customer. Consequently, it is necessary to select one architecture alternative per combination of external variance and to eliminate all the other architecture alternatives.

One possible way is to select the architecture alternatives based on their individual properties, such as the performance or the required installation space. Since the selection would be made separately for each combination of external variants, the selected architectures could vary in their internal variance. This means that the internal variance of the first variant of the first vehicles would differ from the other variants or vehicles. Consequently, this would lead to a high internal variance among the vehicle models and vehicle variants. As the aim of this method is to develop a modular system and thus minimize the internal variance, this procedure is not applicable.

Therefore, the choice of the architecture alternatives within this method is based on minimizing the internal variance. Thus, it is necessary to consider all architecture alternatives of all vehicle models and variants together. Then, the selection process first selects the architecture alternatives that share cross-vehicle modules such as the engine or gearbox. However, modularization does not eliminate all architecture alternatives. Instead, for each combination of the external variance and architectural standards, meaning the drive type, the engine installation position and the chassis type, one architecture alternative remains. Otherwise, the modularization could lead to architecture alternatives with different architectural standards, making the derivation of architectural standards unlikely in the subsequent step. Together, the identification of the cross-vehicle modules and the derivation of architectural standards lead to the derivation of the modular systems and their architectures.

3.5.1 Identification of modules

The first step in reducing the internal variance is the identification of cross-vehicle modules. In this context, a module is a component of a specific type and property that is also present in other vehicle variants and vehicle models. For example, several vehicle variants use the 120 kW gas in-line engine. This method does not cover modules with the same component type, but slightly different properties. For instance, a 150 kW engine could be based on the same engine block as the 120 kW engine when using a separate control unit. Further definitions of modules are available in the literature [3, p. 133, 42, pp. 665-667].

The modularization analyzes if within different vehicle variants, multiple vehicle architectures use the same component. If so, the method defines these components as modules. When defining the modules, the method only considers the corresponding architectures further and eliminates redundant ones. The redundant ones differ only in the internal variance and do not affect the external variance. In case no modules are possible, the selection of the architecture alternatives is based on the minimum required installation space. Overall, the modularization is done separately for all combinations of the external variants and the architectural standards to avoid influences on the derivation of architectural standards.

Continuing with the previous example (Figure 3.28), the modularization would result in a module for the 170 kW gas, longitudinal installed, in-line engine available in variants of vehicle 1 and vehicle 2. The redundant architectures with the 160 kW and 180 kW engines (Figure 3.29) then become unnecessary. No module is possible for the 160 kW, gas, transversal installed, in-line engine because there is no other architecture alternative with same engine installation position and hence architectural standard available. For the 300 kW and the 310 kW engines of the last vehicle, also no modules are possible as no other engines with same engine power exist. Since in this case, the definition of a module is not possible, but several architectures with same architectural standards exist, the selection is based on the minimum required installation space, which is usually the engine with the lower performance.

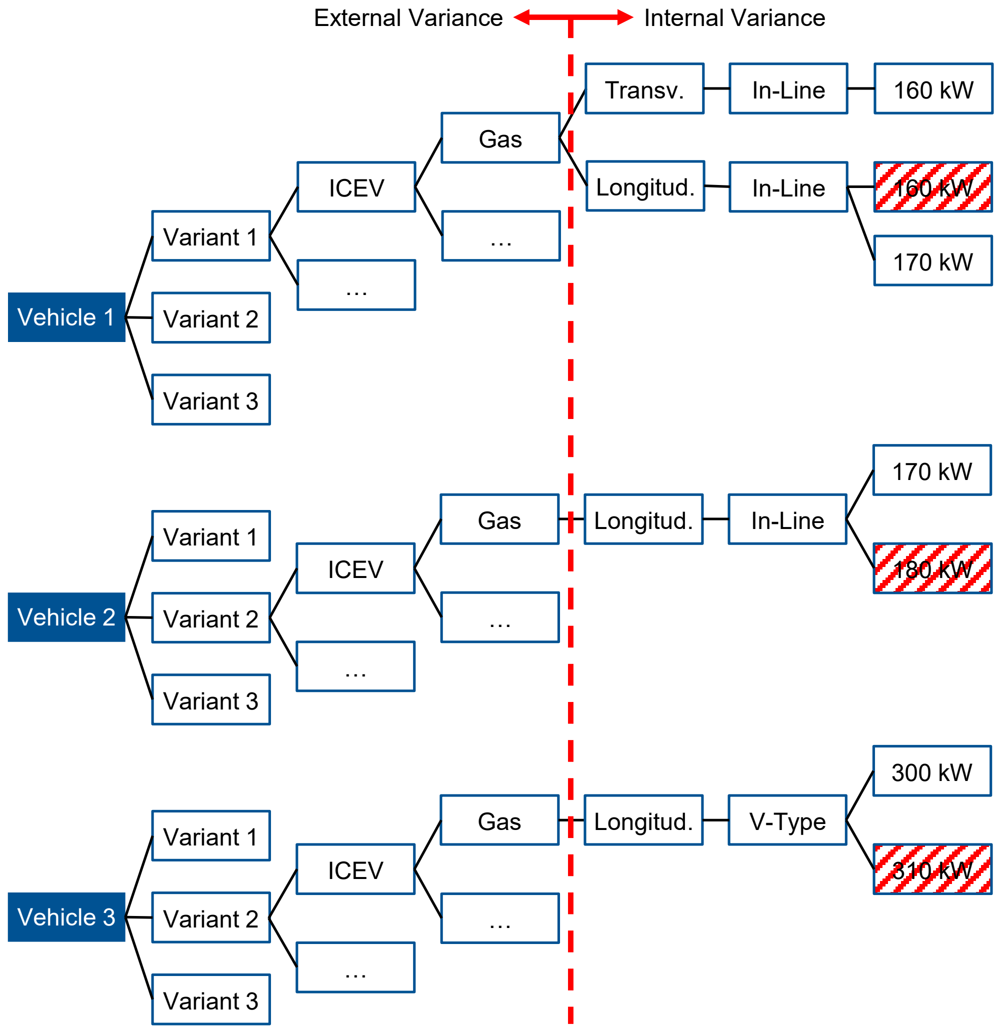


Figure 3.29: Examples of architecture alternatives after the modularization

In the following, the implemented process for the modularization will be described in detail using the example of combustion engines. Within the combustion engines, the tool modularizes gas and diesel engines separately to maintain the external variance. Among the different fuel types, the module can be either in-line or V-type. This means that the different engine types compete with each other. Similarly, the method includes the modularization of the electric machines, the hybrid modules, and gearboxes.

In the first step, the modularization bundles the vehicle architectures of all vehicle variants and in the case of the combustion engines, subdivides them by combinations of the drivetrain type and the fuel type. Of course, it is necessary to merge the architectures of the different vehicles and variants to identify modules, but only within and not across the drivetrain and fuel types. Without the distinction between gas and diesel engines, modularization would lead to the definition of modules but also to the elimination of architectures with different external variants.

In the second step, the tool subdivides the preceding group of vehicle architectures into all combinations of the architectural standards. Within this method, the architectural standards are the drive type, the engine installation position, and the chassis type. The classification is necessary because otherwise, the modularization would lead to modules in architectures with different architectural standards. As a result, the chances of identifying architectural standards across all vehicle variants and modules in the final step would diminish.

As a result of the first and second steps, the tool grouped the vehicle architectures through combinations of the external variance and architectural standards. Within each combination, the architectures differ only in further internal variants such as the engine type (in-line or V-type) and the engine-gearbox combinations (engine power/torque and number of gear speeds). Another distinction between the architectures can be the type and position of the cooling system.

The third step is to identify possible modules by analyzing within each group whether different vehicle variants use the same engine. The engines must be identical in their type and properties to form a module. One example is an in-line gas engine with 120 kW. This step is repeated until the tool compares all architectures and identifies all possible modules. The possible modules either differ in their type, for example, within the combustion engines, the in-line or V-type, or in their properties such as, for example, the engine power of 130 kW. Consequently, the results of the third step are the overall possible modules.

The fourth step is to select within each group the modules that together cover all vehicle models and variants. The general idea is to choose one module after the other until the modules cover all vehicle variants and vehicle models. This means that the tool only contemplates the architecture alternatives with the selected modules further and eliminates all the remaining alternatives.

However, the selection is more complicated because the result of step 3 is a higher number of modules than required. This is primarily due to the high internal variance caused by the various engine-gearbox combinations. The higher number of modules leads to an intersecting coverage of the models. Consequently, various possible modules cover the same vehicle variants.

Due to the intersections, the modules are interdependent. Therefore, selecting one module changes the coverage of the remaining modules and makes the order of the selection important. However, the dependency also makes it possible that the selection of one module makes a further module superfluous since it does not cover any additional vehicle variants and vehicle models.

Therefore, the challenge is to identify the combination of possible modules that, with the intersecting coverage, overall minimizes the number of modules and eliminates as many other modules as possible.

In order to compare different combinations of modules, the author and LEVRAT [106] introduced the level of modularization η_{Mod} (Equation 3.23). With the maximum required number of components $n_{c,Max}$ minus the after the modularization existing number of components n_{Mod}, the numerator defines the reduction in variance. The maximum number of components is equal to the number of vehicle variants, i.e. no modules exist. The denominator describes the maximum reduction in the variance, as the minimum number of components $n_{Mod,Min}$ is always 1. In this case, only one module covers all vehicle variants of all vehicle models, which is the best possible result. The level of modularization increases as fewer modules are required to cover the vehicle variants and vehicle models. The values for the level of modularization always range between 0 and 100 %.

$$\eta_{\mathrm{Mod}} = \frac{Reduction\ of\ Internal\ Variance}{Maximal\ Reduction\ of\ Internal\ Variance} = \frac{n_{c,Max} - n_{C,Mod}}{n_{c,Max} - n_{C,Min}} \quad 3.23$$

Using a simplified example for the modularization procedure, the author aims to illustrate the interdependencies within this step. This example is based on diesel engines, with front-drive type, longitudinal engine installation, and multi-link chassis. As shown in Figure 3.30, there are three vehicles with each three vehicle variants. For these, 15 different architecture alternatives with different engine power exist. This leads to three possible modules as described in step 3.

Many of the modules intersect in their covered vehicle variants and consequently vehicle models. For example modules 1 and 2 both cover the vehicle variant 2 of the second vehicle. The modules 2 and 3 both include the vehicle variants of the second and third vehicle.

One possible combination for modularization would be to select module 1 first, then module 2, and then module 3. The selection of module 1 eliminates redundant architectures. Therefore, module 2 no longer covers the second variant of vehicle 2. However, module 2 still covers two vehicle variants and reduces the coverage of module 3 from five to three. Overall, this combination covers all external variants with the exception of one, with three modules thus leading to a level of modularization of 78.6 %. In contrast, modularizing module 1 and module 3 achieves the highest level of modularization with 85.7 %. In this case, two modules and one single component for the first variant of the second vehicle cover all vehicle models and variants.

This example shows the dependencies between the possible modules and the effects of the selection sequence on the overall level of modularization.

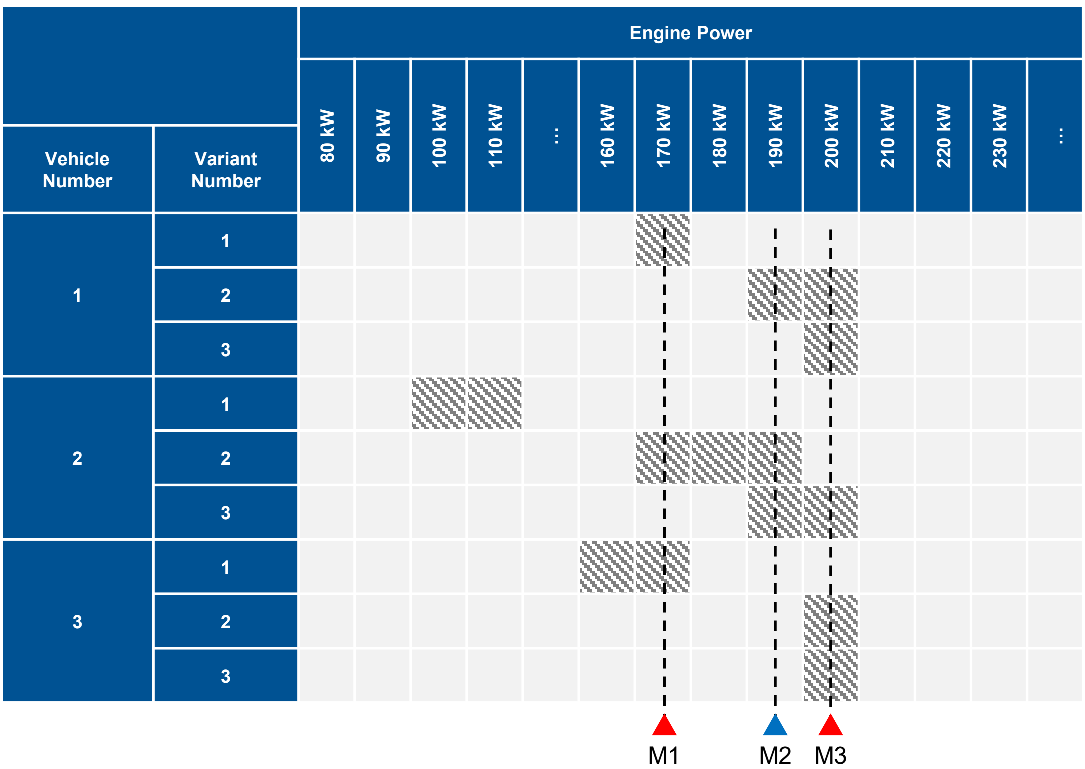


Figure 3.30: Simplified example of the modularization procedure

Apart from the simplified example of the modularization procedure, the higher number of vehicles, vehicle variants, and engine-gearbox combinations quickly lead to over 50 possible modules. Therefore, the solution space exceeds 10^{12} combinations. The consideration of all combinations and permutations would be too time-consuming and is in no relation to the time required for the generation of the architectures (factor > 25). Thus, the method implements an approach that first identifies the local optimum. Based on the local optimal solution, the tool can limit the permutations within the combinations to calculate the global optimal solution.

To identify the local optimal solution, the method first selects the module with the highest coverage of vehicle variants. In the example above, this would be module 3. The selection automatically eliminates all redundant architectures within the covered vehicle variants. The tool then recalculates the coverage of the remaining modules. Based on the recalculation, the tool selects the next module with the highest coverage within the remaining modules. In this example, this would be module 1. This procedure is repeated until either all vehicle variants and vehicle models are modularized or until no further modules are possible. Hereby, already after the second selection, two modules cover all vehicle models and vehicle variants. Only for the first variant of the second vehicle, no module can be defined. Consequently, the level of modularization in this example can only be less than 100 %. The result with the selected modules is the local optimum, which indicates the maximum number of required modules. Any modularization with a higher number of modules would never lead to a better level of modularization.

Then the tool identifies the global optimal solution. Hereby, the tool creates all possible combinations of modules but limits the number of permutations within each combination to the maximum number of required modules (local optimum). In the example, the local optimum solution is based on two modules. Therefore, the global optimum solution calculates any combination of up to two modules (Figure 3.31). This approach significantly reduces the number of possible solutions but can still exceed 10^6 solutions.

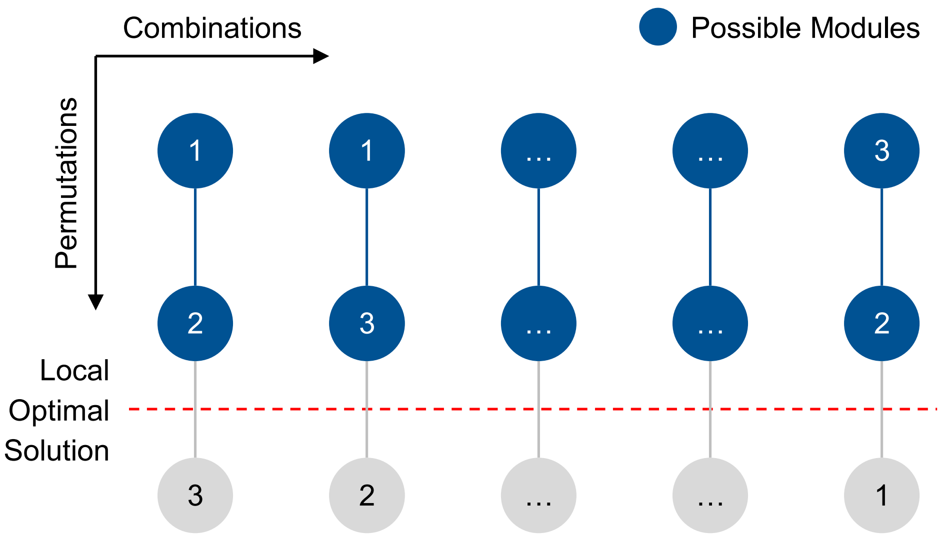


Figure 3.31: Identification of the global optimum with the local optimum as boundary

Within each combination, the tool does not select and modularize the module with the highest coverage but follows the defined sequence of the permutations. The stepwise selection, modularization, and elimination lead to the number of modules required for each combination. Based on the number of modules, the tool calculates the level of modularization and outputs the global optimum solution with the overall highest value. As in the example, it is possible that the local optimum solution is also the global optimum solution.

If multiple combinations exist with the same level of modularization, the selection of the global optimal solution within the method is based on the minimum required installation spaces of the underlying architectures. A smaller required installation space increases the crash performance and simplifies assembly operations. If no module is possible at all within one vehicle model and vehicle variant, the tool also distinguishes the architectures on the basis of the minimum required installation space.

These steps are repeated separately for all combinations of external variance and architectural standards. Besides the combustion engines, the method applies the process to the electric machines, the hybrid modules, and the gearboxes. The thesis does not cover further modularization as the main focus is on the generation of architectures and the derivation of architectural standards. However, it would be possible to apply the approach to additional components such as the cooling system.

As a result of the modularization, the tool only considers the architecture alternatives with the selected modules or, if no modules are possible, the minimum required installation space further eliminates all remaining alternatives. Consequently, there remains only one architecture for each combination of the external variance and the architectural standards. Using the modularization, the reduction is mainly based on the minimization of the internal variance.

3.5.2 Derivation of architectural standards

The previous step reduces the internal variance within one combination of the external variance and architectural standards. Consequently, a few architecture alternatives still exist within every external variant. The aim of this step is therefore to determine whether, architectures with the same architectural standards are feasible in all external variants. In this case, it is possible to eliminate all other architectures, resulting in only one architecture per external variance. The resulting architectures with their modules and architectural standards then form the modular system at a minimum of internal variance.

Again referring to the previous example (Figure 3.28, Figure 3.29), it is apparent that in all external variants, an architecture alternative with longitudinal engine installation is available. Thus, these architectures with their modules and with the longitudinal engine installation as a unified architectural standard form the modular system as a final result. Since there are no other unified architectural standards available among all external variants, the remaining architecture alternatives can be eliminated (Figure 3.32). This leads to exactly one architecture per external variant. It is important to note that in this example, for purposes of illustration, only the engine installation position has been considered an architectural standard.

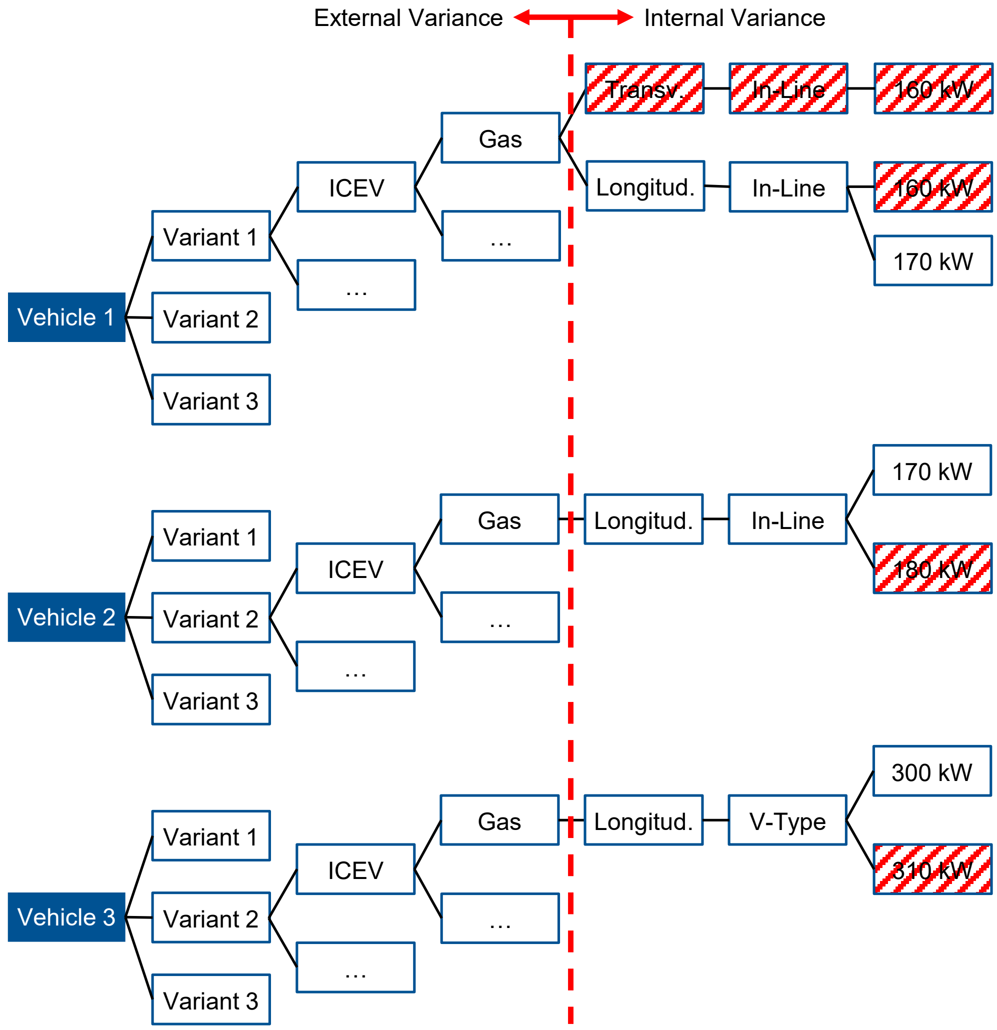


Figure 3.32: Examples of architecture alternatives, after the derivation of architectural standards

According to this simplified example, the general idea of the derivation is to identify whether feasible architectures with the same architectural standards exist for all external variants (different vehicle models, vehicle variants, drivetrain types, fuel types, and gearbox types). In this thesis, the architectural standards are different combinations of the drive type, the chassis type, and the engine installation position. The front- and rear-drive types describe the primary orientation of the drive type but may be in either two- or all-wheel configuration. These are the most essential architectural standards within the vehicle front. Nevertheless, it is possible to extend the method to further architectural standards. If feasible architectures with the same architectural standards exist for all external variants, unified architectural standards can be derived. The architectural standards then define the modular system together with the cross-vehicle modules.

This method covers up to 50 external variants due to the different vehicle models, vehicle variants as well as various drivetrain types. With 50 external variants and eight combinations of architectural standards up to 400 feasible or infeasible architecture alternatives exist. Consequently, for the derivation, it is necessary to identify 50 feasible architectures with the same architectural standards, out of the 400 possibilities. This makes the derivation of the architectural standards complex.

An algorithm could quickly identify whether architectures with the same combination of architectural standards are feasible for all external variants. However, if feasible architectures with the same architectural standards are not available for all external variants, the derivation is not possible. In this case, it is difficult for the concept engineer to define required adjustments within an iteration. Besides, it is not possible to identify separate modular systems, with less external variance.

Therefore, the author has developed the modular systems matrix (MSM) which, if feasible architectures exist, outputs for the different combinations of external variants and architectural standards. In this way, the method visualizes the results in a structured manner and give the concept engineer the possibility to analyze the solution space. This allows either the derivation of architectural standards or dedicated iterations.

The columns of the matrix describe the external variance, while the rows represent the architectural standards. Each matrix element represents a feasible or an infeasible architecture. However, BEV architectures with a longitudinal engine installation are not practical. In addition, due to the application of the method to the vehicle front, an architecture for BEV and rear-drive type only exists if the user has selected an all-wheel configuration. In contrast, the tool does not output an architecture for BEV with a two-wheel and rear-drive type configuration.

Using the MSM, the concept engineer can determine whether there are feasible architectures for all external variants and one combination of architectural standards. If this is the case, it is possible to derive architectural standards.

Within the MSM, however, the derivation of architectural standards depends on the defined modular system type. For single-drivetrain modular systems, the derivation is separate for ICEV/HEV and BEV. Within the multi-drivetrain approach, the available installation space of one vehicle model is independent of the drivetrain type. Therefore, it allows the identification of unified architectural standards among all drivetrain types.

Figure 3.33 shows an example of an MSM. By way of illustration, this MSM limits the external variants to two vehicles. This MSM also indicates no further subdivision by fuel type and gearbox type within the ICEV and HEV. Appendix D visualizes a fully specified MSM as the final result of the method.

MSM				External Variance																	
				Vehicle 1									Vehicle 2								
				Variant 1			Variant 2			Variant 3			Variant 1			Variant 2			Variant 3		
				ICEV	HEV	BEV	ICEV	HEV	BEV	ICEV	HEV	BEV	ICEV	HEV	BEV	ICEV	HEV	BEV	ICEV	HEV	BEV
				…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
Internal Variance	Front	McPherson	Longitudinal	✓	✓	▬	✓	✓	▬	✓	✓	▬	✓	✓	▬	✓	✓	▬	✓	✓	▬
			Transversal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Multi-Link	Longitudinal	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬
			Transversal	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Rear	McPherson	Longitudinal	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬
			Transversal	✓	✓	▭	✓	✓	▭	✓	✓	▭	✗	✗	▭	✗	✗	▭	✗	✗	▭
		Multi-Link	Longitudinal	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬	✗	✗	▬
			Transversal	✗	✗	▭	✗	✗	▭	✗	✗	▭	✗	✗	▭	✗	✗	▭	✗	✗	▭

✓ Architecture Feasible ✗ Architecture not Feasible

▭ Architecture only for All-Wheel-Drive ▬ Architecture not Practical

Figure 3.33: Example of the modular systems matrix

In this example, the single-drivetrain approach leads to the front-drive type, the McPherson suspension, and the longitudinal engine installation as one combination of architectural standards for the vehicles with combustion/hybrid drivetrains. Another combination would be the front-drive type, the McPherson suspension, and the transversal engine installation. The architectural standards of the electric drivetrains correspond to the second combination of the combustion/hybrid drivetrains. Either way, the single-drivetrain approach results in the definition of two separate modular systems.

In the case of the multi-drivetrain approach, one modular system for ICEV/HEV and BEV can be defined. In this example, a modular system would be feasible with the front-drive type, the McPherson suspension, and the transversal engine installation as architectural standards. This is only possible as the available installation spaces of one vehicle are similar for all drivetrain types. A particular case for a multi-drivetrain modular system would be with front-drive type, McPherson suspension, and longitudinal installation for ICEV/HEV as well as transversal installation for BEV. This exception is only possible because the engine installation position does not affect the available installation space. This could also be seen as a modular system with only the drive type and the chassis type as architectural standards, as the engine installation position varies. However, this is not possible for the other architectural standards because a modular system would usually not combine different drive types and chassis types.

After selecting a modular system or different variations, all other architectures in the MSM become unnecessary.

However, it is also possible, that no modular system is available because for the different external variants, not all architectures with certain architectural standards are feasible. In this case, the tool provides an error report for each matrix element, indicating the failing dimensional chain and the gap between the required and the available installation space. This helps the concept engineer to define optimization parameters or to adjust the requirements for an iteration.

If using optimization parameters and adjusting the requirements are not successful or not desired, it is possible to derive various modular systems or independent platforms. In the exemplified MSM, the rear-drive type, the McPherson suspension and the transversal engine installation as architectural standards cover variants of vehicle 1. In contrast, the front-drive type, the multi-link, and the transversal engine installation cover all variants of vehicle 2. If there are additional vehicles with the same architectural standards as vehicle 2, these could form a modular system. This would lead to a modular system and an individual platform/vehicle.

Moreover, the tool also outputs the level of modularization in the MSM for each combination of the architectural standards. Even though one combination of architectural standards fulfills all external variants, the level of modularization may be low.

Finally, the method entails the visualization of any vehicle architecture (matrix element) within a parametric model of the vehicle front in CATIA (Figure 3.34).

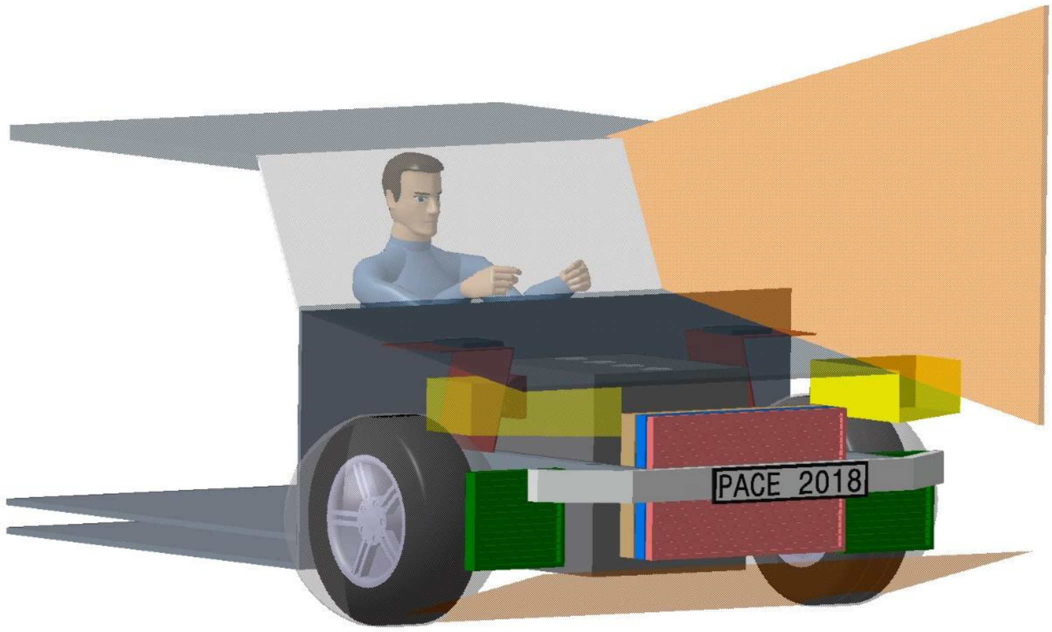


Figure 3.34: Parametric model of the vehicle front for the visualization of the resulting architectures

3.6 Application of the Method

The previous sections describe the method for the automated development of modular systems within the vehicle front. This section outlines its application.

Using the tool, a concept engineer inputs the requirements as a result of the product planning and benchmarks. Depending on the number of vehicle models, vehicle variants, and drivetrains, the application of the method requires less than an hour to generate the architectures and to identify modules and architectural standards.

In the best case, the tool indicates that with the defined inputs, it is possible to derive a modular system with unified architectural standards and a high level of modularization within the cross-vehicle modules.

If there are no unified architectural standards or the level of modularization is too low, the method allows for targeted iteration. Alike to the process for the development of modular systems (2.2.1), three iterations are meaningful. If necessary, concept engineers apply the iterations for single or multiple vehicle variants and vehicle models.

In the first iteration, the concept engineer can use the optimization parameters to deviate from the statistical output component sizes and distances. For example, the concept engineer can reduce the dimensions of the engine by a defined percentage. In addition, it is possible to apply the discrete optimization parameters and switch to extra load tires, for example. To define the optimization parameters, the concept engineer can analyze the error report and the gap between the required and the available installation space that the tool outputs in the GUI. Moreover, the concept engineer can assess the current dimensions to decide if and by how much a reduction of the component sizes and distances is possible.

If the use of optimization parameters is not successful, the concept engineer can use the second iteration to adjust the input requirements. For example, the concept engineer can change the exterior dimensions or the acceleration time and maximum velocity. The assessment of the changes is also based on the error report and the gap of the installation spaces.

The last iteration requires the concept engineer to reduce the external variance because the conflict of interest between the external and internal variance is not solvable even when using optimization parameters and adjusted requirements. This means that he must exclude different vehicle variants or models. The MSM provides a transparent overview of the variants and vehicles to exclude.

Figure 3.35 gives an overview of the application of the method.

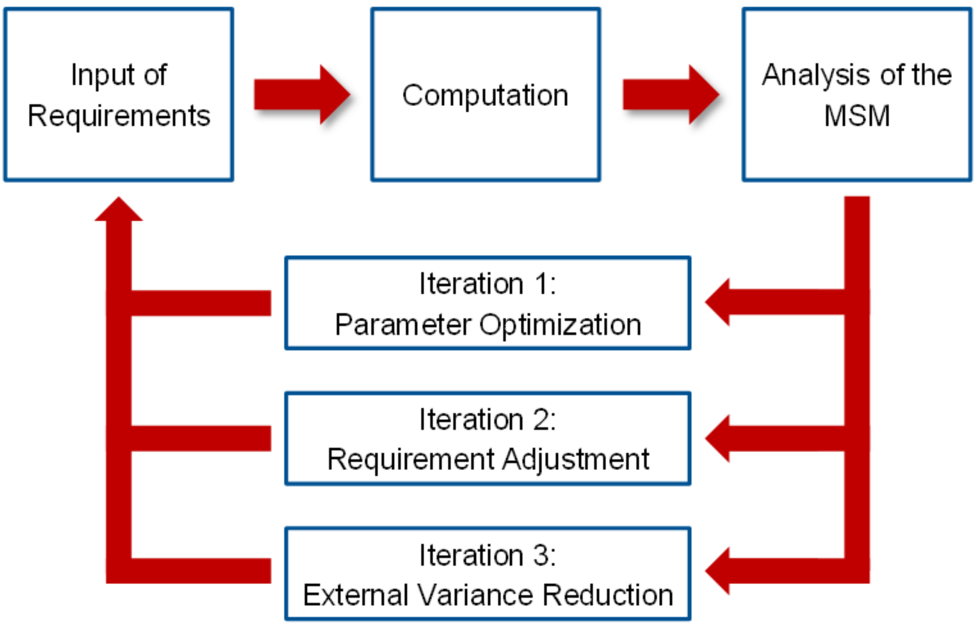


Figure 3.35: Application of the method

Similar to the manual process, the method enables iterations in the case a modular system is not possible. However, compared to the manual process, the time for iterations is much less. In addition, the method covers the entire solution space. An iteration with further architectures is therefore not necessary. Also, with the higher number of solutions, iterations are less likely.

Variations of the described process variations are possible with the tool. However, these represent individual cases, which this thesis does not cover.

4 Evaluation

This chapter describes the evaluation of the presented method. The objective is the assessment of the capabilities and the derivation of improvement measures. The evaluation therefore applies the implemented tool and compares the results obtained with existing series vehicles and modular systems.

The evaluation is divided into two parts. The first part (4.1) focuses on the evaluation of the generation of vehicle architectures. Therefore, this part evaluates the first and second stages of the tool. The evaluation of the resulting architectures is of utmost importance as they set the foundation for the derivation of the modular system. The second part (4.2) evaluates the derivation of modular systems, focusing on the third stage of the tool. Consequently, the second part evaluates the applicability of the entire method for the development of modular systems.

Both stages focus on the functionality of the tool and do not consider the validation of the GUI usability.

LEVRAT [106] and TRÜMPER [99] also cover aspects of this evaluation.

4.1 Evaluation of Vehicle Architectures

The idea of the first evaluation part is to assess, with the properties of existing series vehicles as inputs, whether a feasible output of the tool is the actual architecture of the corresponding series vehicle. This part of the evaluation, consequently, assesses the first two stages of the method, the requirement definition, and the generation of architectures. In the following, the author describes the database, the procedure, and the results of the first part of the evaluation.

4.1.1 Database for the evaluation

To assess the functionality of the architecture generation extensively, the objective is to create a diversified evaluation database, with one vehicle for each combination of the vehicle segment, the body type, the drivetrain type, and the drive type.

However, the evaluation not only requires the properties of the vehicles as input requirements. Besides broadly available information about the engine type and the architectural standards, more detailed information about the architectures, such as the cooling system position, must be present. In the databases accessible to the author, the detailed architecture information is only available in the 3D databases of A2Mac1 [80] and AUDI AG. Moreover, only 3D models allow measurements of the component sizes and the distances between components.

Due to the limited number of vehicles in these databases, a vehicle is not available for every combination of vehicle segment, body type, drivetrain type, and drive type. Nevertheless, the evaluation database consists of 14 series vehicles of six automotive manufacturers from four segments and with low- and high-ground body types. While ten vehicles have a combustion drivetrain, the evaluation database only includes two vehicles for each of the parallel hybrid and electric drivetrains. Figure 4.1 gives an overview of the evaluation database.

		ICEV				HEV				BEV	
		Longitudinal		Transversal		Longitudinal		Transversal		Transversal	
		Front Drive	Rear Drive	Front Drive	Rear Drive	Front Drive	Rear Drive	Front Drive	Rear Drive	Front Drive	Rear Drive
A	Low Ground	-	-	VW Golf	-	-	-	-	-	Renault Zoe VW e-Golf	-
	High Ground	-	-	VW Tiguan	-	-	-	-	-	-	-
B	Low Ground	AUDI A4	MB C-Class	VW Passat	-	-	-	Hyundai Ioniq	-	-	-
	High Ground	-	-	BMW X3	-	-	-	-	-	-	-
C	Low Ground	AUDI A6	MB E-Class	-	-	-	BMW 5 Series	-	-	-	-
	High Ground	-	-	-	-	-	-	-	-	-	-
D	Low Ground	AUDI A8	BMW 7 Series	-	-	-	-	-	-	-	-
	High Ground	-	-	-	-	-	-	-	-	-	-

Figure 4.1: Existing series vehicles for the first stage of the evaluation

Most of the vehicles originate from the A2Mac1 database, which only includes one vehicle variant of each vehicle model. Within the evaluation, a vehicle variant represents one performance class of the vehicle with only one specific engine type, fuel type, and gearbox type. The available variant allows a comparison of the vehicle architectures in terms of the architectural standards but also more detailed specifications such as the cooling system type and position. Also, only for these variants, the dimensions of the architecture are accessible. In most cases, this reference variant does not represent the highest performance class with the maximum required installation space and the greatest impact on the available installation space. Nevertheless, it is possible to include further vehicle variants in the evaluation database as the required input parameters are usually available. However, as the A2Mac1 database does not contain these variants, no detailed information regarding the architectures is accessible. This limits the comparison within these architectures to architectural standards.

In order to consider the vehicle variants with maximum required installation space and the variants with accessible dimensions, the evaluation database considers for each vehicle up to four regular variants with low or medium performance and up to four maximum variants. The total number of variants depends on the available fuel (gas/diesel) and gearbox types (manual/automatic). The reference variant is in most cases one of the regular variants. For newer vehicles like the AUDI A8, it is possible that the overall maximum variant is not yet on the market. To avoid missing input information, the evaluation considers only the available maximum variants. In addition, the maximum variant does not relate to special performance variants of a vehicle model. Furthermore, it is possible that only one variant is present within one vehicle, as in the case of the Renault Zoe.

For comparison, it is necessary to gather the properties as inputs as well as the actual architectural standards for all variants. The database also includes details about the architectures, i.e. the component and installation position alternatives as well as the dimensions for the reference variants.

Even though the 3D data of multiple vehicle variants are available for the AUDI vehicles, the database contains only one reference vehicle variant to ensure a consistent database and approach. Thus, the overall database consists of 14 vehicles with 58 vehicle variants.

4.1.2 Procedure for the evaluation

Due to the limitations of the database, the primary objective of the evaluation is to analyze for all variants of the evaluation vehicles whether the tool can output feasible architectures with the same architectural standards as in reality. Only for the reference variants of the vehicles, the analysis is more detailed. Hereby, the actual architecture with the architectural standards and further component and installation positions must also be a feasible output of the tool. The evaluation succeeds if the results of the tool match the actual data. Otherwise, it is possible to identify reasons for the deviations within the dimensions of the reference variants.

The general procedure of the evaluation is divided into three steps. The first two steps define the requirements and filter the engine-gearbox combinations. The third step generates all vehicle architectures and outputs the feasible ones for comparison. The general procedure applies in two subsequent evaluation stages without and with continuous optimization parameters. The two-stages process originates from the iterative application of the tool, as depicted in section 3.6. Figure 4.2 gives an overview of the evaluation procedure within the evaluation of architectures.

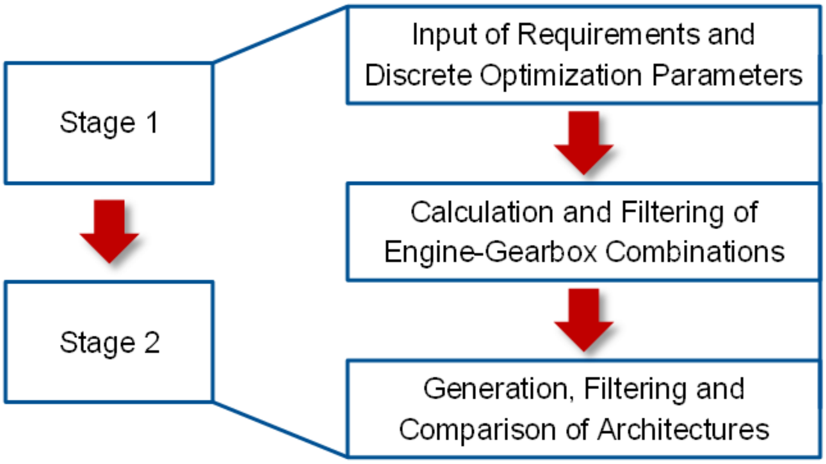


Figure 4.2: Evaluation procedure within the evaluation of vehicle architectures

As the first step, the properties of one vehicle model and all vehicle variants define the input requirements. Section 3.3.1 describes the inputs required, which include, for example, the exterior dimensions, the drivetrain types, and the drive type as well as the reduced curb weight, the acceleration time, and the maximum velocity. In the evaluation, the reduced curb weight includes the weights of the fuel tank and the high-voltage battery to reduce the influence of different energy densities. Even though it is possible that multiple headlight types are available in one vehicle, the evaluation considers only the headlight type of the reference vehicle. In addition to the requirements, the evaluation configures discrete optimization parameters when used in the respective vehicle. This is important because of the influences of, for example, extra-load tires or active hood mechanisms on the installation spaces. Appendix E provides an overview of the requirements and discrete optimization parameters for every vehicle model and its vehicle variants. Sources for the inputs are mainly A2Mac1 [80], ADAC [82], AMS [83] as well as the manufacturers' websites.

As further settings of the evaluation, the definition of the bumper curvature is similar for all vehicles by selecting the low curvature option. In addition, the design type is set to regulatory, and the design option which influences the distances between components is set to progressive. The selected settings either increase the available installation space or decrease the required installation space. This limits the influence of these parameters to a minimum, which is necessary because of their problematic determination.

An additional input for the evaluation that is not included in the GUI is the actual engine torque and power as well as the number of gear speeds for each of the vehicle variants. Further inputs for all variants are the engine type and the architectural standards. For the reference variant, the cooling system type and position are also inputs. These inputs enable the filtering of engine-gearbox combinations and architecture alternatives within the subsequent steps.

In the second step of the evaluation, the tool calculates the engine-gearbox combinations based on the defined inputs using the LDS (3.3.2). Due to the large number of engine-gearbox combinations generated and the large impact on the generation and dimensioning of the architectures, all combinations must be filtered except for the one with the least deviation from the actual engine torque and with the same number of gear speeds. However, the scalable load curves that are integrated within the LDS differ from the engines of the evaluation vehicles. Therefore, it is possible that even after the filtering, large deviations in the engine torque and power exist. If the deviation of the computation is more than ±10 %, the evaluation continues with the actual engine torque and/or power. This limits the influence of the interchangeable load curves on the architecture generation.

Based on the filtered or adjusted engine-gearbox combination, the tool generates all conceivable vehicle architectures with various architectural standards, within the third step of the evaluation. Subsequently, it analyzes the feasibility of the architecture alternatives. The result is a multitude of feasible architecture alternatives. Thereafter, the tool filters the feasible architectures with the actual architectural standards by the actual engine type, such as in-line or V-type. For the reference variant, the tool also filters according to the corresponding cooling system type and position. Filtering ensures that the tool outputs the same architecture as in reality. Within the architectures with other than the actual architectural standards that do not exist in reality, the filtering is based on the minimum required installation space. As a result, the tool outputs only one architecture for each combination of architectural standards per vehicle variant.

The first stage applies the described general procedure to all vehicle variants of the different vehicle models without using the continuous optimization parameters. A comparison after the computation identifies in all vehicle variants whether the tool outputs feasible architectures with the same architectural standards as in reality. Another more detailed comparison is within the reference variant to analyze whether the tool can represent the overall architecture, including the cooling system type and position. The evaluation is successful if the tool outputs a feasible architecture with the actual architectural standards for all vehicle variants as well as the actual architecture for the reference vehicle variant.

In addition to comparing the architectures and architectural standards, the first stage involves identifying deviations between the computed and the actual architectures. For all vehicle variants, the availability of only a few overall parameters, such as the engine torque and the engine displacement volume, limit the comparison. Within the reference vehicle, the comparison of the component sizes and distances between components is possible. By aligning the deviations, it is possible to identify statistical and systematic deviations. In the case of a statistical deviation, no tendency is apparent within the deviations of a component size or distance. These deviations arise because the vehicles considered represent only one data point and can therefore vary from the output of the empirical and geometric substitute models. In contrast, there is a systematic deviation when the dimensions of the tool are in most cases higher or lower than in reality. However, with the limited evaluation database, it remains possible that the systematic deviations are only statistic deviations in a more extensive database.

The second stage of the evaluation repeats the procedure with all vehicle variants of the different vehicle models within which the tool was not able to output feasible architectures matching the actual architecture or architectural standards. However, the second stage runs with continuous optimization parameters. The optimization parameters reduce the respective component sizes and distances by a certain percentage or value. The definition of the percentages and values is based on the analysis of the statistical and systematic deviations. The use of continuous optimization parameters to overcome the statistical deviations is similar to the intended application and iteration of the tool. Besides, the optimization parameters also limit the influence of systematic deviations by geometric substitute models with less accuracy on the general functionality of the tool. However, the systematic deviations indicate areas of improvement.

4.1.3 First stage of the evaluation

The first stage of the architecture evaluation applies the presented procedure to all vehicle models and variants of the evaluation database with the corresponding exterior dimensions and properties but without any continuous optimization parameters as input. Figure 4.3 shows for each vehicle and vehicle variant, whether the architecture with the actual architectural standards (for the reference variant with further component and installation positions) output by the tool is feasible or not. In the case of the ICEV and HEV, the first fuel type is always gas and the second one diesel.

The results show that without the use of optimization parameters, the architectures with the actual architectural standards are only in 25.9 % a feasible output of the tool. Most of the architectures are feasible within the BMW X3 and the VW Tiguan as a high-ground vehicle. The tool also outputs some feasible architectures within the low-ground vehicles with transversal but none for the ones with longitudinal engine installation. While no feasible architectures exist for the hybrids, the architectures of the electric vehicles are feasible results.

Vehicle	Year	Drive Type	Chassis Type	Engine Installation	Regular-Variants Fuel 1 Manual	Regular-Variants Fuel 1 Automatic	Regular-Variants Fuel 2 Manual	Regular-Variants Fuel 2 Automatic	Maximum-Variants Fuel 1 Manual	Maximum-Variants Fuel 1 Automatic	Maximum-Variants Fuel 2 Manual	Maximum-Variants Fuel 2 Automatic
ICEV												
AUDI A4	2015	Front	Multi-Link	Longitudinal	✗ (Ref.)	✗	✗	✗	n/a	✗	n/a	✗
AUDI A6	2018	Front	Multi-Link	Longitudinal	n/a	✗	n/a	✗	n/a	✗ (Ref.)	n/a	✗
AUDI A8	2018	Front	Multi-Link	Longitudinal	n/a	✗ (Ref.)	n/a	✗	n/a	✗	n/a	✗
BMW 7 Series	2015	Rear	Multi-Link	Longitudinal	n/a	✗	n/a	✗ (Ref.)	n/a	✗	n/a	✗
BMW X3	2017	Rear	McPherson	Longitudinal	n/a	✓	n/a	✓ (Ref.)	n/a	✓	n/a	✓
MB C-Class	2014	Rear	Multi-Link	Longitudinal	✗ (Ref.)	✗	✗	✗	n/a	✗	n/a	✗
MB E-Class	2016	Rear	Multi-Link	Longitudinal	n/a	✗	n/a	✗ (Ref.)	n/a	✗	n/a	✗
VW Golf	2013	Front	McPherson	Transversal	✓ (Ref.)	✗	✗	✗	✓	✗	✗	✗
VW Passat	2014	Front	McPherson	Transversal	✓	✗	✓	✗	n/a	✗	n/a	✗ (Ref.)
VW Tiguan	2016	Front	McPherson	Transversal	✓	✓	✓	✓ (Ref.)	n/a	✓	n/a	✗
HEV												
BMW 5 Series	2017	Rear	Multi-Link	Longitudinal	n/a	✗ (Ref.)	n/a	n/a	n/a	✗	n/a	✗
Hyundai Ioniq	2016	Front	McPherson	Transversal	n/a	✗ (Ref.)	n/a	n/a	n/a	n/a	n/a	n/a
BEV												
Renault Zoe	2012	Front	McPherson	Transversal	n/a	✓ (Ref.)	n/a	n/a	n/a	n/a	n/a	n/a
VW e-Golf	2013	Front	McPherson	Transversal	n/a	✓ (Ref.)	n/a	n/a	n/a	n/a	n/a	n/a

(Ref.) Reference Variant; n/a Variant not Available in Reality; ✓ Architecture Feasible; ✗ Architecture not Feasible

Figure 4.3: Feasible and infeasible architectures within the first stage of the evaluation (fuel type 1: gas, gas hybrid or electric; fuel type 2: diesel, diesel hybrid or electric)

To determine the reasons for the low percentage of feasible architectures, especially within the vehicles with longitudinal combustion engines, it is necessary to analyze the deviations in the different properties and dimensions of the vehicles. The deviations can either be statistical, meaning that deviations follow no trend or otherwise systematically. As the architectures of the BEV were feasible, the following analysis mainly focuses on ICEV and HEV.

The missing 3D data limits the analysis of deviations in all vehicle variants to only a few parameters, such as the engine power, the engine torque, and the engine displacement volume.

Within all vehicles, vehicle variants, and drivetrain types, the unfiltered engine-gearbox combinations indicate that only in few cases, the engine torque varies by more than ±10 % from the actual value. On average, the absolute deviations of the engine torque are 6.0 % and of the engine power 10.4 %. The deviations result from the fact that the existing vehicles vary in their engine load curves from the scalable load curves implemented in the tool. Appendix F gives an overview of the deviations between the computed and the actual engine power and torque. As the architecture generation continues with the actual engine power and torque when the deviation is higher than ±10 %, the influence of the engine-gearbox combinations on the feasibility of the architectures is small. Consequently, component sizes and distances, depending on the engine power and torque, such as the engine length, are not extremely under- or oversized.

Nevertheless, this shows the overall functionality of the LDS and thus the calculation of the engine-gearbox combinations. Interchanging the load curves of the tool with the actual ones would lead to even better results.

In addition to the engine power and torque, it is possible to compare the engine displacement volume in all vehicle variants of the ICEV and HEV. The calculation with the engine torque is part of the geometric substitute model of the combustion engine. The absolute average deviation of the engine displacement volume is 8.9 %. The data (Figure 4.4) shows that positive and negative deviations from the actual displacement volume exist, indicating a statistical error. The variability of the engine displacement volume results mainly from different combustion processes and supercharging types. However, especially within medium- to high-torque diesel engines (>400 Nm), the calculated displacement volume is often more than 20 % higher than in reality. This applies to the BMW 7 series, the Mercedes C-Class, the VW Passat, and the VW Tiguan. The main reason for the higher calculated engine displacement volume is that the higher torques are enabled by higher turbocharging. While the corresponding engine of the C-Class uses only one turbocharger, the other three engines use two turbochargers. However, due to the limited availability of data, the implemented regression function does not distinguish between the number of turbochargers. Another factor is that the empirical data is based on combustion engines from the years 2010 to 2017. Consequently, parts of the database are too old to show the growing trend of downsizing. In addition, the number of available data decreases toward higher engine torques, thus leading to an extrapolation of the data (Figure 3.15). Due to the higher engine displacement volumes, the number of cylinders of the in-line engines is higher by one than in reality within the C-Class, the VW Passat, and the VW Tiguan. This has a major impact on the engine length and, especially within transversal engine installation, a high influence on the feasibility of an architecture. Overall, this indicates a systematic error within the high-torque diesel engines. For both gas engines of the BMW 7 series, the calculated engine displacement volume is also more than 20 % higher than in reality. As this occurs only within one vehicle of one manufacturer, this shows a statistical deviation.

		Regular-Variants				Maximum-Variants			
		Fuel 1		Fuel 2		Fuel 1		Fuel 2	
		Manual	Automatic	Manual	Automatic	Manual	Automatic	Manual	Automatic
ICEV									
AUDI A4	∆ Engine Displacement Volume in %	9	9	-11	-11	-	0	-	-3
	∆ Number of Cylinders	0	0	0	0	-	0	-	0
AUDI A6	∆ Engine Displacement Volume in %	-	14	-	7	-	0	-	-7
	∆ Number of Cylinders	-	0	-	0	-	0	-	0
AUDI A8	∆ Engine Displacement Volume in %	-	0	-	-3	-	-11	-	3
	∆ Number of Cylinders	-	0	-	0	-	-2	-	0
BMW 7 Series	∆ Engine Displacement Volume in %	-	21	-	-3	-	28	-	19
	∆ Number of Cylinders	-	1	-	0	-	0	-	0
BMW X3	∆ Engine Displacement Volume in %	-	-13	-	5	-	7	-	-1
	∆ Number of Cylinders	-	0	-	0	-	0	-	0
MB C-Class	∆ Engine Displacement Volume in %	-5	-5	-5	-5	-	-4	-	27
	∆ Number of Cylinders	0	0	0	0	-	0	-	1
MB E-Class	∆ Engine Displacement Volume in %	-	-10	-	7	-	-18	-	11
	∆ Number of Cylinders	-	0	-	0	-	0	-	0
VW Golf	∆ Engine Displacement Volume in %	9	9	17	17	5	5	1	1
	∆ Number of Cylinders	0	0	0	0	0	0	0	0
VW Passat	∆ Engine Displacement Volume in %	-16	-16	-8	-8	-	11	-	26
	∆ Number of Cylinders	0	0	0	0	-	0	-	1
VW Tiguan	∆ Engine Displacement Volume in %	5	5%	-5	-5	-	5	-	23
	∆ Number of Cylinders	0	0	0	0	-	0	-	1
HEV									
BMW 5 Series	∆ Engine Displacement Volume in %	-	-18	-	-	-	-10	-	7
	∆ Number of Cylinders	-	0	-	-	-	-1	-	0
Hyundai Ioniq	∆ Engine Displacement Volume in %	-	-4	-	-	-	-	-	-
	∆ Number of Cylinders	-	0	-	-	-	-	-	-

Figure 4.4: Deviation between the calculated and the actual engine displacement volumes (fuel type 1: gas or gas hybrid; fuel type 2: diesel or diesel hybrid)

Besides the analysis of deviations within all vehicle variants of all vehicles, the reference variants allow a more detailed analysis. Consequently, it is possible to compare the dimensions of the architectures that the tool outputs with the measures from the 3D data.

Many of the component sizes and distances between them are subject to statistical deviations due to the empirical and semi-physical geometric substitute models. As for example, the length and the width of the engines deviate in positive and negative directions (Figure 4.5). Similar correlations exist within the dimensions of the gearboxes (Figure 4.6) and the cooling systems (Figure 4.7). Therefore, no trend is recognizable within these dimensions. The figures also indicate that the deviations are small for many dimensions. Appendix G shows further deviations of the wheel house, the body parts, and distances between components. However, even in the appendix, it is impossible to represent all dimensions due to their extremely high number.

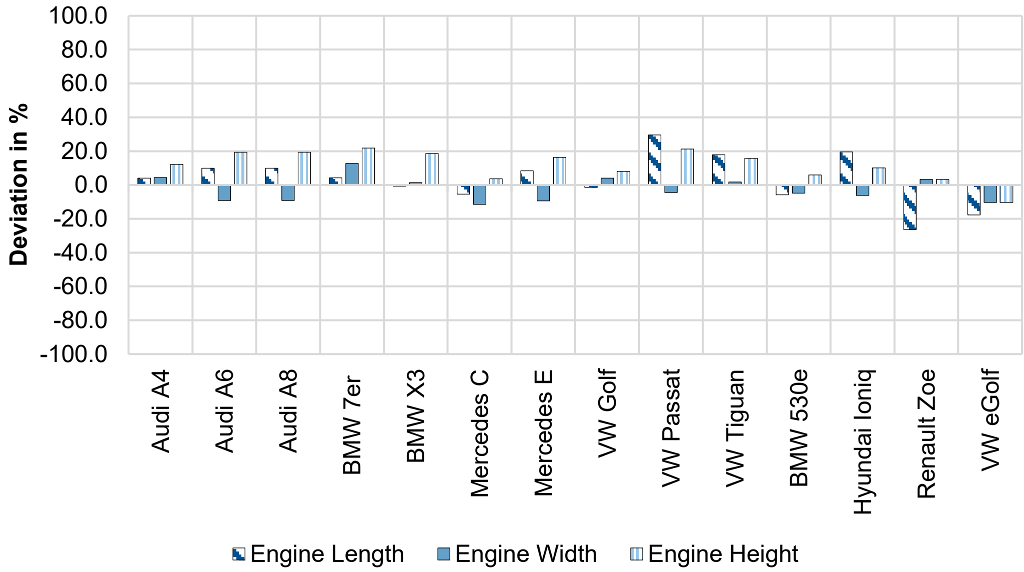


Figure 4.5: Deviations between the calculated and the actual engine dimensions

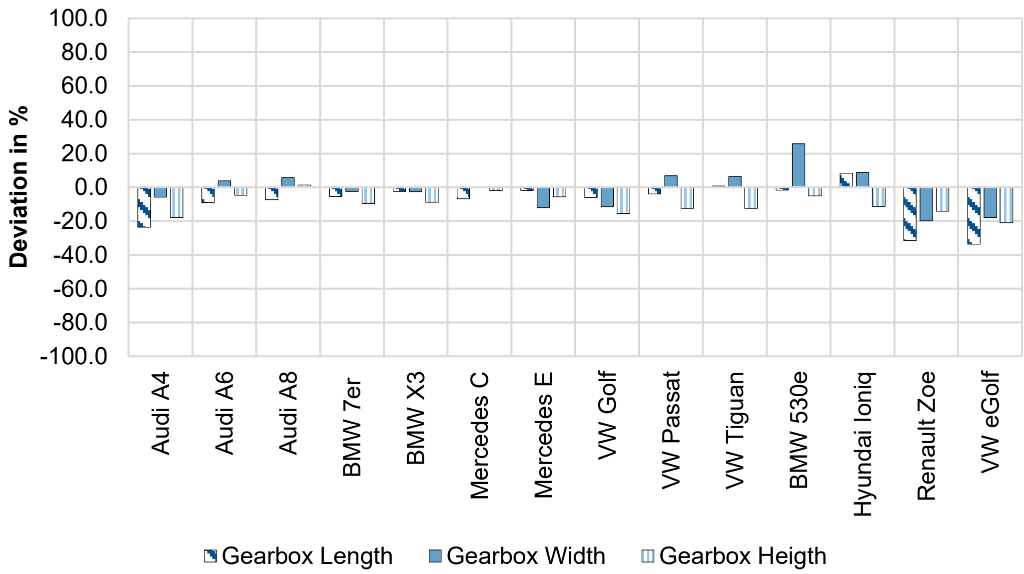


Figure 4.6: Deviations between the calculated and the actual gearbox dimensions

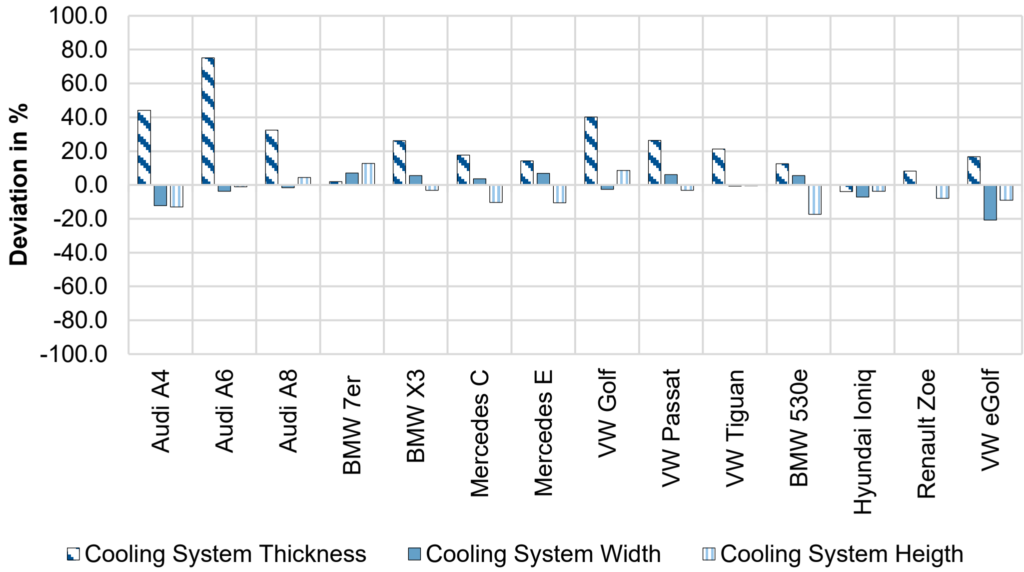


Figure 4.7: Deviations between the calculated and the actual cooling system dimensions

In addition to the statistic deviations, the figures also indicate five systematic deviations. These are the height of combustion engines, the thickness of the cooling system, the length and width of the wheel house, the distance between the bumper beam and the cooling system, and the width of the electric gearbox.

The comparison of the engine heights shows that the results of the tool are on average 13.3 % higher for both in-line and V-type engines. The analysis of the various elements of the geometric substitute model for the engine height indicates that the element with the highest variation in the dimensions is the oil pan. Based on the A2Mac1 database, the height of the oil pan ranges from around 40 to over 200 mm in over 200 engines. The reason for the high deviations is the large variety of shapes to provide a plane surface for tilted engines and avoid collision with chassis and steering parts (Figure 4.8).

Figure 4.8: Different oil pan shapes, based on [84, p. 86] (Image Source: [80])

Due to the high variation in dimensions and shapes, it is difficult to model the oil pan. The geometric substitute model represents the lower part of the cylinder block from the crankshaft downward to the end of the oil pan as a simple cuboid. For the so-called lower overhang, there is a regression function with the torque, the charging type, the engine installation position, and the number of cylinders as explanatory variables [84, pp. 99-102]. The first three parameters mainly influence the crankshaft as part of the lower overhang, but also define the amount of oil required and thus the volume of the oil pan. The consideration of the engine installation position is based on VAN BASSHUYSEN [107, p. 130], who describes the engine installation position as one possible distinction between oil pan types. Despite the high number of explanatory variables, the adjusted R^2, at only 40.8 %, is one of the lowest in the entire tool [84, pp. 99-102]. A further distinction between oil pan types is necessary to improve the model accuracy. However, even with the 200 engines in the A2Mac1 database, no pattern is recognizable. The strong variation of the data also makes a constant value inapplicable. Moreover, distorted reference measures in the 2D database of A2Mac1 limit the quality of the empirical date for the oil pan (Figure 4.9).

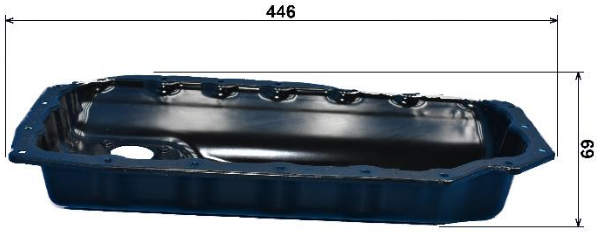


Figure 4.9: Original oil pan measurement from A2Mac1, based on [80]

Comparing the calculated value of the lower overhang with the actual overhang of the VW Passat reference variant thus shows an excess of more than 90 mm. The engine cover also contributes to the over-dimensioning due to the design dependence and variation.

Due to the pedestrian protection distance required between the engine and the hood, the height of the engine is of crucial importance for the feasibility of architectures. Hereby, it should be noted that the hood inclines towards the front, following the viewing angle. Therefore, automotive manufacturers decrease the height of the engine toward the front by appropriate component positioning and tilting of the engine (Figure 4.10). Since the geometric substitute model outputs the engine only as a cuboid with constant height, the over-dimensioning makes the compliance with the pedestrian protection even more difficult. In high-ground vehicles, more space is available in the z-direction, which explains why the tool generates feasible architectures for these vehicles in most cases.

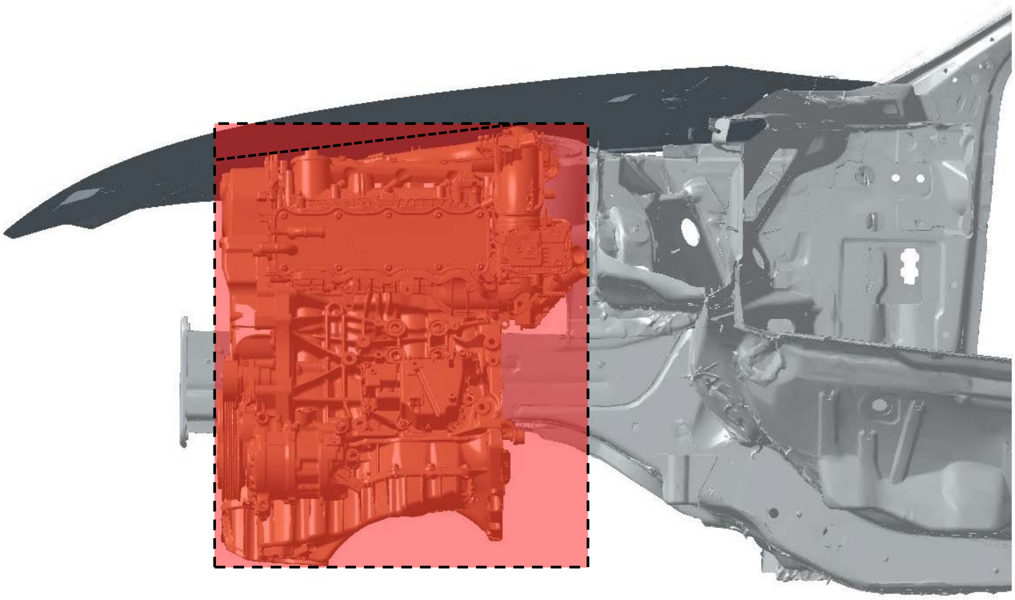


Figure 4.10: Positioning of real engines compared to the representation of the engine in the tool (Image Source: [80])

However, improving the model with the available data is difficult. Even with hundreds of 3D datasets, the improvement of the geometric substitute model for the engine height remains challenging due to high variance and missing pattern for the oil pan shapes.

Besides the high impact of the engine height, the analysis of the dimensions indicates a systematic deviation in the thickness of the cooling system. Depending on the type, the cooling system consists of up to four components with the climate condenser, the intermediate cooler, the water cooler, and the cooling fan. While the variation of the first three components appears statistical, a systematic over-dimensioning of the cooling fan also leads to larger dimensions of the overall cooling system. The tool uses a constant value of 97 mm for the cooling fan, which is derived from the A2Mac1 2D database. However, based on the 3D data used within the evaluation, the cooling fan of the AUDI A4 reference variant is only 35.5 mm thick. There are several reasons for explaining the high deviations. The main reasons for the deviations are inaccurate measurements and distorted images of this component in the A2Mac1 2D database (Figure 4.11). In this database, the cooling fan of the AUDI A4 is 75 mm thick. Because this value is similar to the implemented value, it shows the overall statistical significance of the derived constant value. But since the 75 mm are also more than twice the value derived from the vehicle's 3D data, inaccuracies in the 2D database become apparent during the evaluation. However, modeling with the available 3D database is not meaningful because of the limited number of datasets. Another factor is that the constant value does not differentiate between cooling fans with one or two radiators. Therefore, it is possible that in the database many cooling fans with two radiators and thus a higher thickness exists, while most of the reference vehicles within this evaluation have lower performances and only one radiator. The improvement of the cooling fans accuracy would thus require an extensive 3D database and distinctions between cooling fan types.

Figure 4.11: Original AUDI A4 cooling fan measurement from A2Mac1, based on [80]

In addition to the over-dimensioning of the engine height and cooling system, the tool outputs lower wheel house lengths and widths than in reality. The size of the wheel house is a function of the tire diameter, the tire width, and the turning radius. Within this function, the rotation of the tire is solely around the vertical y-axis in the center of the tire. Consequently, the tool simplifies the kinematics, as in reality, the tire turns around an instantaneous center of rotation [74, p. 852, 108, p. 21]. Also, the dimensioning of the wheel house usually considers the deflection and rebound of the suspensions [108, p. 396]. Another unconsidered aspect is the space required for snow chains. These factors explain the lower dimensions of the wheel house. However, a more detailed consideration of the kinematics would require further inputs not available at this stage of development.

Another significant underestimation is the distance between the bumper beam and the cooling system. Within the tool, this is 76.5 % lower on average than within the reference vehicles. One of the main reasons for the deviations is that the evaluation is based on the regulatory design. Consequently, the model uses a constant value between the bumper beam and the cooling system. For the insurance classification, a semi-physical model calculates the distance based on the vehicle weight and the presence of a lower stiffener. It is unrealistic that all reference vehicle variants consider the insurance classification. The higher distances are more likely to occur because the contemplated vehicle variants are not among the maximum performance classes in almost all cases. Due to the larger size of the cooling system, the distance to the bumper is likely to decrease within the maximum variants. Another reason for the increasing distance is the growing number of sensors in front of the bumper beam. Therefore, another objective in positioning the cooling system is to prevent the sensors from intrusion into the cooling system during a low-speed crash.

Comparing the gearboxes of electric vehicles shows a tendency to under-sizing, especially for the gearbox length. This is reasonable, as the semi-physical model for the one-speed gearboxes primarily dimensions the shafts and bearings statically with a dynamic load factor but without a dynamic load spectrum. However, the number of electric vehicles within the evaluation database is too small to identify a significant trend.

Comparing the deviations shows that only few of the multitude of dimensions deviate systematically. Some geometric substitute models, like the one of the combustion engine, are based on the data of over 200 vehicles. With only 14 reference variants, it is therefore still possible that the systematic deviations are only statistical deviations in the overall database. Besides, the geometric substitute models have the highest accuracy, under consideration of the available database and level of detail of the tool.

4.1.4 Second stage of the evaluation

As a result of the first evaluation stage, only 25.9 % of the existing architectures were a feasible output of the tool. Similar to the application of the tool, the evaluation is repeated in a second stage using continuous optimization parameters.

The continuous optimization parameters reduce the dimension of a component or distance by a percentage or absolute value. The definition of the optimization parameters is based on the error reports output by the tool and the gap between the required and the available installation space in the corresponding dimensional chains.

Using optimization parameters is necessary to overcome the statistical deviations since the evaluation vehicles only represent one data point within the implemented empirical and semi-physical substitute models. In addition, the parameters limit the impact of geometric substitute models with less accuracy and systematic deviations. Thus, it is possible to analyze the general functionality of the architecture generation.

Figure 4.12 shows the optimization parameters used in the second stage of the optimization. Hereby, the overall objective is to apply as few and as low optimization parameters as necessary to enable the feasibility of the architectures with the actual architectural standards of the evaluation vehicles and variants.

Almost all vehicles and variants use the optimization parameter of the engine height to overcome the systematic deviation. This already leads to the feasibility of most of the architectures. The optimization parameter for the engine displacement volume applies to the VW Passat and the VW Tiguan. Without the parameter, the tool creates a five-cylinder in-line engine for the maximum diesel variant, which is too long for transversal installation. The optimization parameter for the engine displacement also applies to the gas engines of the BMW 7 series, otherwise, no in-line engines are feasible. The remaining parameters for the engine length, gearbox length, cooling system thickness, underbody height, z-position of the side members, and the viewing angle only apply to a few vehicles in order to overcome statistical deviations. Due to the manifold dependencies of dimensions in dimensional chains, it would be possible to use other optimization parameters. However, to avoid an arbitrary selection, these are based on actual deviations. For example, as within the Hyundai Ioniq, the calculated engine length is higher than in reality because the stroke-bore ratio is 1.1 within the tool, and 1.35 in reality. Another example is the viewing angle, which at 5.6 °, is higher by 0.8 ° than the actual angle [99, p. 127]. Despite the multitude of statistical and systematic derivations analyzed during the first stage of the evaluation, it is not necessary to use more optimization parameters because deviations within larger components, such as the engine, have a greater impact on the vehicle architecture. Moreover, in a few cases, different deviations mutually cancel each other out, such as the under-dimensioned distance between the bumper beam and the cooling system and the over-dimensioned thickness of the cooling system.

Within this evaluation, the values of the optimization parameters are lower than the actual deviations. Therefore, the optimization parameters maximally resize the components or distances to the actual size, but not beyond. This is possible because, in order to generate a feasible architecture, only the required installation space needs to be reduced by the gap between the dimensional chain and the available installation space. This ensures that the optimization only limits the impact of deviations without simplifying the architecture generation.

		Engine Displacement Volume in %		Engine Height in %		Engine Length in %		Gearbox Length in %		Cooling System Thickn. in %	Viewing Angle in °	Unterbody Thickness in mm	Side Rail z-Position in mm
		Fuel 1	Fuel 2	Fuel 1	Fuel 2	Fuel 1	Fuel 2	Fuel 1	Fuel 2				
ICEV													
AUDI A4	Regular Variants	0	0	5	10	0	0	0	0	0	0	0	0
	Maximum Variants	0	0	10	11	0	0	0	0	0			
AUDI A6	Regular Variants	0	0	11	13	0	0	0	0	0	0	20	0
	Maximum Variants	0	0	10	7	0	0	0	0	0			
AUDI A8	Regular Variants	0	0	10	10	0	0	0	0	0	0	0	0
	Maximum Variants	0	0	10	18	0	0	0	0	0			
BMW 7 Series	Regular Variants	0	0	4	9	0	0	0	0	0	0.7	0	0
	Maximum Variants	11	4	9	13	0	0	0	0	0			
BMW X3	Regular Variants	0	0	0	0	0	0	0	0	0	0	0	0
	Maximum Variants	0	0	0	0	0	0	0	0	0			
MB C-Class	Regular Variants	0	0	2	4	0	0	0	0	0	0	0	0
	Maximum Variants	0	0	6	10	0	0	0	0	0			
MB E-Class	Regular Variants	0	0	0	6	0	0	0	0	0	0.8	0	0
	Maximum Variants	0	0	10	11	0	0	0	0	0			
VW Golf	Regular Variants	0	0	2	2	0	0	0	0	0	0	0	16
	Maximum Variants	0	0	3	3	0	0	0	0	0			
VW Passat	Regular Variants	0	0	0	3	0	4	0	0	0	0	0	0
	Maximum Variants	0	10	3	10	6	4	0	0	12			
VW Tiguan	Regular Variants	0	0	0	0	0	0	0	0	0	0	0	0
	Maximum Variants	0	10	0	0	0	0	0	0	0			
HEV													
BMW 5 Series	Regular Variants	0	-	1	-	0	0	0	-	0	0.6	0	0
	Maximum Variants	0	-	7	12	0	0	0	0	0			
Hyundai Ioniq	Regular Variants	0	-	0	-	12	-	10	-	0	1.6	0	0
	Maximum Variants	-	-	-	-	-	-	-	-	-			
BEV													
Renault Zoe	Regular Variants	-	-	0	0	0	0	0	0	0	0	0	0
	Maximum Variants	-	-	-	-								
VW e-Golf	Regular Variants	-	-	0	0	0	0	0	0	0	0	0	0
	Maximum Variants	-	-	-	-								

Figure 4.12: Continuous optimization parameters applied within the second evaluation stage (fuel type 1: gas, gas hybrid, or electric; fuel type 2: diesel, diesel hybrid, or electric)

As a result of only a few optimization parameters, the tool creates feasible architectures for 100 % of the actual architectures and architectural standards (Figure 4.13). The architectures are feasible for the reference variants but also the maximum variants with higher required installation spaces.

		Drive Type	Chassis Type	Engine Installation	Regular-Variants Fuel 1 Manual	Regular-Variants Fuel 1 Automatic	Regular-Variants Fuel 2 Manual	Regular-Variants Fuel 2 Automatic	Maximum-Variants Fuel 1 Manual	Maximum-Variants Fuel 1 Automatic	Maximum-Variants Fuel 2 Manual	Maximum-Variants Fuel 2 Automatic
ICEV												
AUDI A4	2015	Front	Multi-Link	Longitudinal	Ref. ✓	✓	✓	✓	n/a	✓	n/a	✓
AUDI A6	2018	Front	Multi-Link	Longitudinal	n/a	✓	n/a	✓	n/a	Ref. ✓	n/a	✓
AUDI A8	2018	Front	Multi-Link	Longitudinal	n/a	Ref. ✓	n/a	✓	n/a	✓	n/a	✓
BMW 7 Series	2015	Rear	Multi-Link	Longitudinal	n/a	✓	n/a	Ref. ✓	n/a	✓	n/a	✓
BMW X3	2017	Rear	McPherson	Longitudinal	n/a	✓	n/a	Ref. ✓	n/a	✓	n/a	✓
MB C-Class	2014	Rear	Multi-Link	Longitudinal	Ref. ✓	✓	✓	✓	n/a	✓	n/a	✓
MB E-Class	2016	Rear	Multi-Link	Longitudinal	n/a	✓	n/a	Ref. ✓	n/a	✓	n/a	✓
VW Golf	2013	Front	McPherson	Transversal	Ref. ✓	✓	✓	✓	✓	✓	✓	✓
VW Passat	2014	Front	McPherson	Transversal	✓	✓	✓	✓	n/a	✓	n/a	Ref. ✓
VW Tiguan	2016	Front	McPherson	Transversal	✓	✓	✓	Ref. ✓	n/a	✓	n/a	✓
HEV												
BMW 5 Series	2017	Rear	Multi-Link	Longitudinal	n/a	Ref. ✓	n/a	n/a	n/a	✓	n/a	✓
Hyundai Ioniq	2016	Front	McPherson	Transversal	n/a	Ref. ✓	n/a	n/a	n/a	n/a	n/a	n/a
BEV												
Renault Zoe	2012	Front	McPherson	Transversal	n/a	Ref. ✓	n/a	n/a	n/a	n/a	n/a	n/a
VW e-Golf	2013	Front	McPherson	Transversal	n/a	Ref. ✓	n/a	n/a	n/a	n/a	n/a	n/a

Reference Variant (Ref.) | Variant not Available in Reality (n/a) | ✓ Architecture Feasible | ✗ Architecture not Feasible

Figure 4.13: Feasible and infeasible architectures within the second stage of the evaluation (fuel type 1: gas, gas hybrid or electric; fuel type 2: diesel, diesel hybrid or electric)

The tool not only generates all architectures that match the evaluation vehicles. Instead, the tool can also create all kinds of architectures with different architectural standards. Appendix H visualizes all feasible and non-feasible architectures for the various evaluation vehicles and variants before and after the use of optimization parameters. The results show that even with the optimization parameters, not many architectures are feasible other than the actual ones. Consequently, it validates that the tool in general, as well as the use of optimization parameters, does not simplify the architecture generation. The limited amount of feasible architectures also indicates that the available installation space within today's series vehicles is extremely limited.

4.1.5 Discussion of the architecture generation

With the generation of feasible architectures for the actual architectures and architectural standards of the evaluation vehicles, the evaluation successfully confirms the overall applicability of the first two stages of the method.

Even for only 14 vehicles, the evaluation is based on a diversified database, with vehicles of different segments, body types, drivetrain, and drive types. As the architectural standards of existing vehicles vary, the evaluation shows that the tool is capable of generating all kinds of architectures. This demonstrates the functionality of the LDS, the synthesis of the architectures, the derivation of the available installation space as well as the comparison of the installation spaces with dimensional chains. However, while the tool can generate feasible architectures for the various architectural standards, it rarely outputs more feasible architectures than those used in reality. Generating all kinds of feasible architectures would indicate an oversimplification. Consequently, the large number of components and dimensional chains is well suited to represent the architecture generation.

The limited number of feasible architectures also shows that the available installation space is restrained within existing series vehicles. Statistical deviations of the implemented empirical or semi-physical geometric substitute models can therefore lead to not feasible architectures. Consequently, as intended, the application of the tool requires iterations and optimization parameters.

In contrast, the method does not intend the use of optimization parameters to overcome systematic deviations. However, today's data availability limits the accuracy of the geometric substitute models. Even with the extensive database of A2Mac1, it is not possible to precisely model every component and the distance between components. Nevertheless, as soon as new data becomes available, it is imperative to revise the engine’s geometric substitute model in terms of the engine displacement volume and the oil pan height. These systematic deviations currently have the greatest impact on the feasibility of architectures. However, other geometric substitute models with systematic deviations also need to be optimized. Until the geometric substitute models are updated, the tool is fully functional through the use of optimization parameters for both statistical and systematic deviations. The concept engineer can analyze the resulting component sizes and distances between components at any time and define optimization parameters accordingly.

4.2 Evaluation of Modular Systems

The first part of the evaluation analyzed the first two stages of the method and thus the functionality of the vehicle architecture generation. With the validated functionality, it is now possible to assess the derivation of modular systems by comparing a computed modular system with an existing modular system. Therefore, the focus of this part is mainly on the third stage with the identification of cross-vehicle modules and the derivation of unified architectural standards. Nevertheless, it evaluates the applicability of the entire method for the development of modular systems. The following section describes the database, the procedure, and the results of the second part of the evaluation.

4.2.1 Database of the evaluation

In this evaluation part, the database does not consist of vehicles from different manufacturers and with different architectural standards. Instead, the vehicles all belong to an existing modular system.

The modular system chosen for the evaluation is the “*Modularer Längsbaukasten*” in the second generation (MLBevo). As described in section 1.1, multiple vehicles from different manufacturers within the Volkswagen Group and various segments share architectures with front-drive type, multi-link suspension and longitudinal engine installation as architectural standards.

Despite the consideration of vehicles from different brands of the Volkswagen Group, AUDI AG is the lead developer of this modular system. Therefore, the evaluation is sufficient for the AUDI vehicles of the MLBevo. With low-ground body type, these are the A4, A5, A6, A7, and A8. As high-ground body type, Q5, Q7, and Q8 are available. Since A4 and A5, A6, and A7, as well as Q7 and Q8, vary only in more detailed vehicle shapes, which the tool does not consider, it is not necessary to include the A5, A7, and Q8 in the evaluation database. Each of the remaining five vehicles has several vehicle variants. However, the number of variants varies per vehicle, as for some vehicles like the A6 and the A8, not all variants are available on the market yet. Moreover, for some, only automatic transmissions exist. Nevertheless, this part of the evaluation considers all available vehicle variants, with combustion drivetrains, of the five vehicles. Although available in some of the vehicles, the evaluation does not include variants with hybrid drivetrains. Since variants with combustion drivetrains are the foundation for the derivation of hybrid variants, their consideration would not increase the solution space. As electric vehicles are not included in the MLBevo, they are also not part of this evaluation.

Consequently, the evaluation database for the five vehicles overall comprises 33 vehicle variants. For each of the vehicles and variants, it is important to gather the properties as the input of the tool, mainly using the ADAC [82] and AMS [83] databases as well as the homepage of the AUDI AG [109]. Due to the focus on the final stage of the method, it is not necessary to measure any dimensions for the vehicles and their variants. The previous evaluation part has already analyzed some vehicle variants of the A4, A6, and A8 in detail.

4.2.2 Procedure for the evaluation

The primary objective of the second evaluation part is to analyze whether with the vehicles and vehicle variants of the MLBevo as input, the tool can identify similar modules and derive the actual architectural standards.

The procedure of this evaluation is based on the second stage of the first evaluation part (4.1.2). Similarly, the inputs to the calculation are the properties of the vehicles as well as the discrete optimization parameters. To overcome statistical and systematic deviations, the evaluation also uses continuous optimization parameters. The values of the optimization parameters are similar to the previous evaluation, with on average of 10.7 % for the engine height and 2.7 mm for the underbody thickness.

Using these inputs, the tool generates a multitude of engine-gearbox combinations. In contrary to the previous evaluation, no filter applies to these. Consequently, a large number of engine-gearbox combinations remain for the architecture generation. This leaves a high solution space for the modularization.

Based on the engine-gearbox combinations, the tool generates all conceivable architectures with all kinds of architectural standards. Since this part of the evaluation does not apply a filter to the architectures, this results in a multitude of feasible architectures with different engine-gearbox combinations as well as component and installation position alternatives.

Subsequently, the tool identifies cross-vehicle modules within the architecture alternatives with the same architectural standards as described in section 3.5.1. This also means that the tool decides between modules with same coverage based on the minimum required installation space that is usually the module with the lowest engine power. In case no modules are possible, the tool also selects an architecture with individual components based on the minimum required installation space. In the evaluation, however, only the gas and diesel engines are modularized, and the modularization of other components like the gearbox are neglected.

After the modularization, the tool only considers the modularized architectures further and neglects redundant ones. Finally, the tool outputs for all vehicles whether similar architectural standards and thus a modular system are feasible.

4.2.3 Results of the evaluation

Applying the presented procedure to the vehicles and variants of the MLBevo, the tool generates a multitude of vehicle architectures. For each vehicle variant, a variety of architectures with the actual architectural standards are feasible. These vary mainly in the engine power/torque. Consequently, this demonstrates that multiple engine-gearbox combinations can fulfill the requirements and thus provide the required bandwidth in the properties for the modularization.

In order to analyze the functionality of the modularization by comparison with the MLBevo, the following focuses on the modularization of the vehicle architectures with the actual architectural standards.

Figure 4.14 shows for the vehicle variants with gas engines the bandwidth of feasible architectures with different engine power/torque. A comparison of the bandwidth with the actual engine power of a vehicle variant shows that for a vehicle variant of the A4 and the Q5, the bandwidth does not include the actual engine power. For example, the bandwidth of the Q5 with 185 kW ranges from 235 to 260 kW and does not include the actual value. The differences arise due to differences between the scalable engine load curves integrated within the LDS and the actual load curves of the vehicle variants' engines. Nevertheless, applying the modularization to the different bandwidths leads to architectures with three modules and one single component for the 14 vehicle variants with gas engines and thus to a level of modularization of 76.9 %.

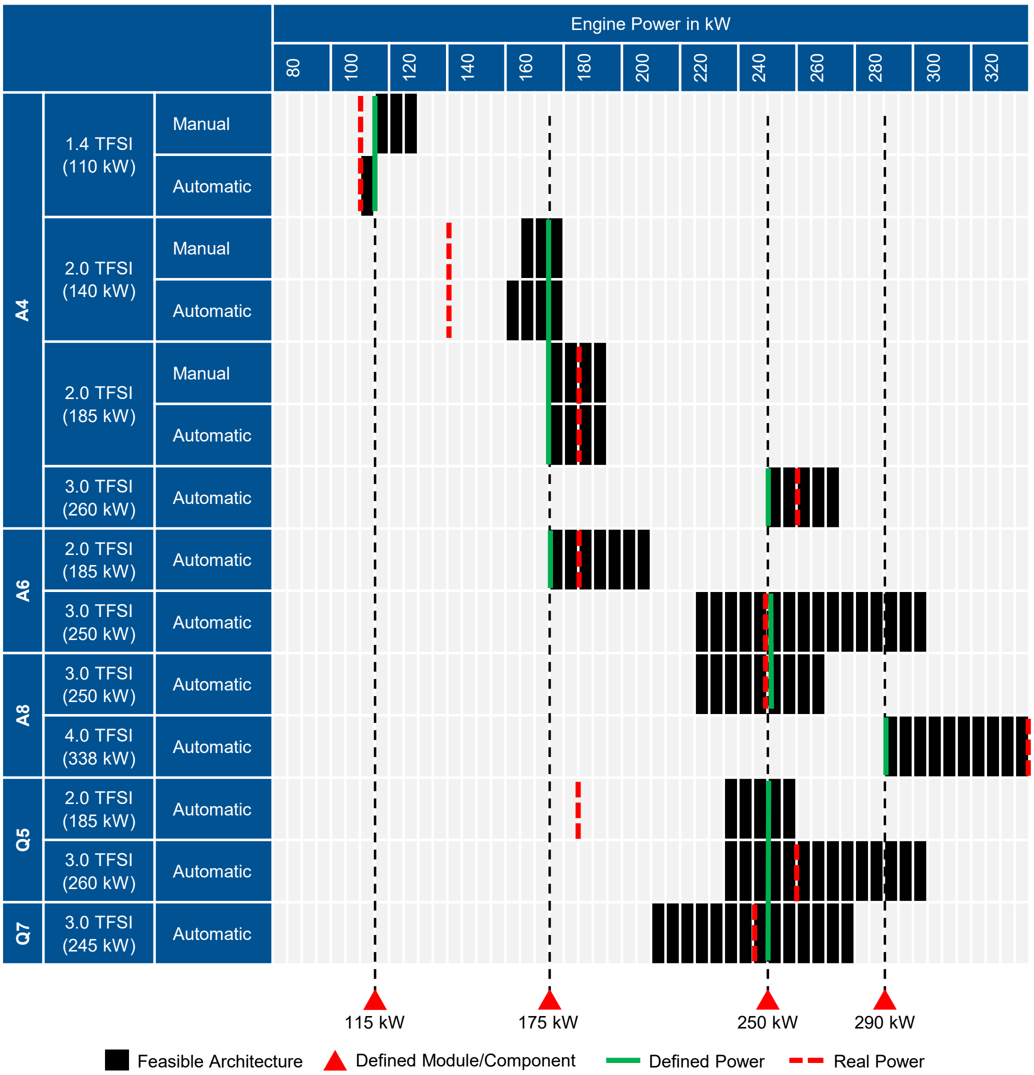


Figure 4.14: Modularization of the gas engines in comparison with the MLBevo

Figure 4.15 shows the possible bandwidth of feasible architectures with different engines and the resulting modules for the different vehicle variants with diesel engines. Similar to the gas engines, the actual power in two cases is also not within the bandwidth due to the different engine load curves. For the diesel engines, the level of modularization is 77.7 %, since there are architectures with four modules and a single component for the 19 vehicle variants with diesel engines.

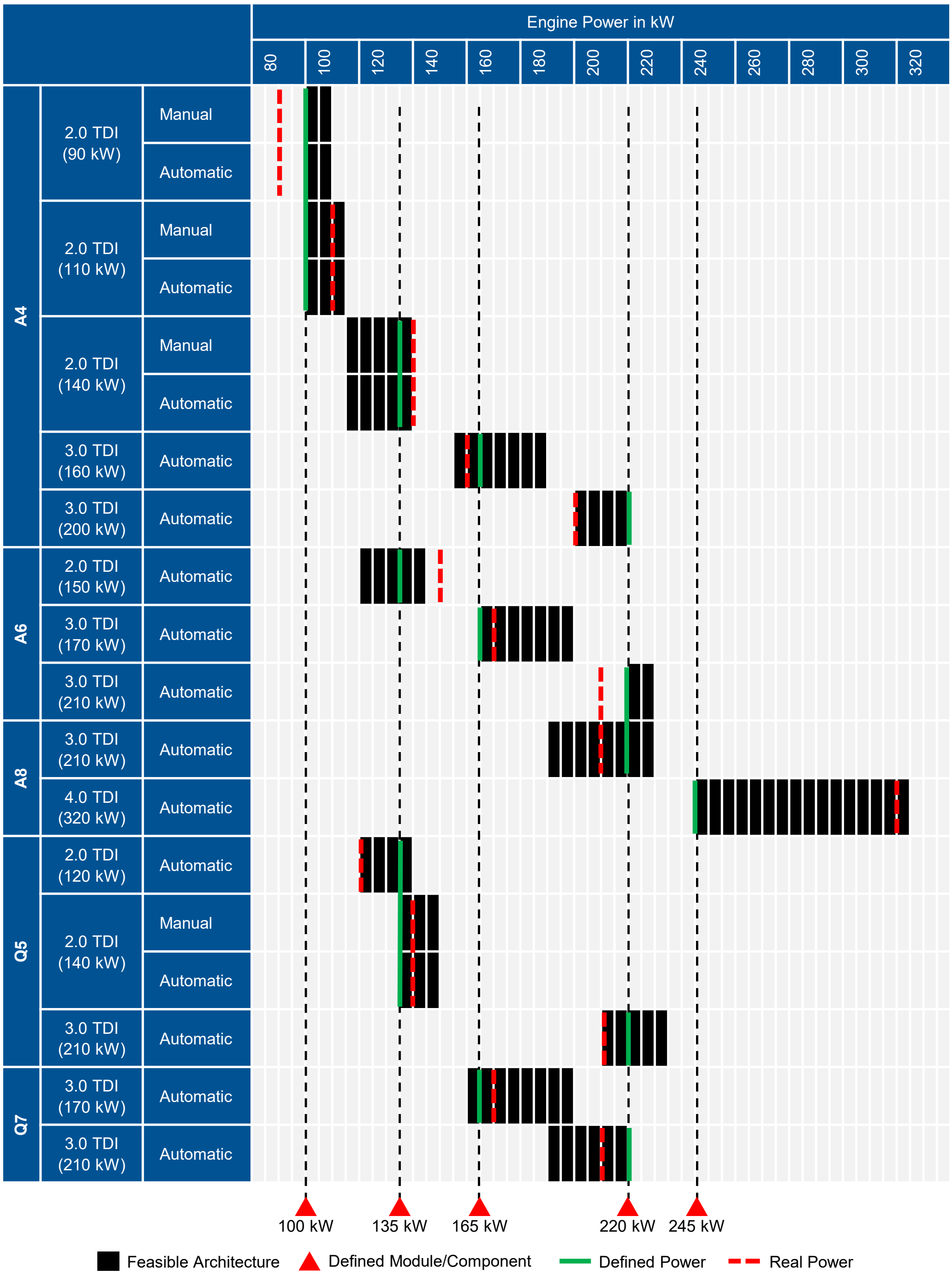


Figure 4.15: Modularization of the diesel engines in comparison with the MLBevo

The results for the gas and diesel engines show that the tool can identify cross-vehicle modules. With the resulting bandwidths in the engine power/torque of the different vehicle variants, the tool determines the highest possible level of modularization. No other combination of modules would lead to a higher level of modularization. But with an increase in the bandwidth, by offering additional installation space, or by the further use of optimization parameters, even higher levels of modularization would be feasible. This shows that the modularization can reduce the internal variance as intended.

However, the level of modularization is much lower in reality at 38.5 % for gas engines and 50.0 % for the diesel engines. The main reason for the large discrepancies is that the automotive manufacturers offer a wide variety of engine properties to increase the external variance. However, since the difference between the different variants is small, the tool detects the overlapping bandwidths and reduces the number of modules.

As the required variety depends heavily on the manufacturer's strategies, the implementation in the tool is not meaningful. Therefore, the modularization of the tool represents an orientation for the concept engineers by outputting the maximum level of modularization as a benchmark. If the level of modularization is too high, concept engineers can deviate from this solution by selecting different properties within the feasible bandwidths and thus increase the external variance. In case the resulting level of modularization is too low, it is necessary to iterate with adjustments of the requirements or external variance. However, the modularization only decides between architectures with the same architectural standards and different properties and thus does not impact the derivation of architectural standards.

The modularization has already shown that for each of the vehicle variants multiple architectures with the actual architectural standards are feasible. Consequently, the tool can derive and unify the same architectural standards as within the MLBevo. Architectures with other architectural standards are also feasible only for few variants. Thus, no other architectural standards are available across all vehicles.

4.2.4 Discussion of the Derivation of Modular Systems

By comparing the modularization and the derivation of architectural standards within the tool and the MLBevo, the second part of the evaluation shows that the tool can successfully conduct all three stages of the method.

Within the modularization, the tool identifies the highest level of modularization, aiming at a minimal internal variance. However, the evaluation shows that in reality, there is a larger variety. Due to the high dependence on the automotive manufacturer's strategies, an implementation of the modularization with higher variety and lower level of modularization does not make sense. Nevertheless, concept engineers can use the level of modularization output by the tool as a benchmark. In case the level of modularization is too high, they can increase the external variance by selecting further engine properties within the resulting bandwidths. If the level of modularization is lower than desired, the concept engineers need to adjust the requirements or external variance and iterate. Therefore, the modules output through the tool are not necessarily the final results and allow for modification by concept engineers.

Currently, the modularization identifies modules with the same properties. An extension of the current modularization would be the identification of modules with a range of properties. One example of these modules are modular engine systems [43, 110], which adapt a basic engine with different components, such as the engine control unit, to enable a range of properties. These modules overcome the conflict of interest between high external variance and low internal variance. However, an implementation is difficult because this modularization depends heavily on the adaptation measures and production volumes.

However, variations in the modularization strategy are not critical because the modularization only decides between architecture alternatives with the same architectural standards and different properties. Consequently, it does not affect the subsequent derivation of architectural standards.

In addition to modularization, the tool can derive the same architectural standards as within the existing modular system. However, as in the previous evaluation, this requires, above all, to overcome the systematic deviations, continuous optimization parameters. Due to the specific design of the MLBevo to these architectural standards, it is reasonable that the tool does not derive any other unified architectural standards.

Overall, the tool achieves the highest level of modularization and is able to derive unified architectural standards. Consequently, this part of the evaluation demonstrates the functionality of the entire method.

5 Discussion

The previous section evaluates and validates the intended functionality of the method for the automated development of modular systems. This section focuses on the overall applicability and the limitations of the method.

The method presented allows the development of modular systems from the ground up. This means that with the approximate requirements of entirely new and existing vehicles, it is possible to identify whether cross-vehicle modules and architectural standards are available. Fast iterations allow adjusting the input parameters to analyze the entire solution space. Consequently, with rigid vehicle requirements, the output is either a feasible or not feasible modular system. Otherwise, if adjusting the requirements is possible, the tool supports the identification of compatible requirements of a feasible modular system. The identification of compatible requirements is especially useful in defining multi-drivetrain modular systems. Due to the different components such as combustion engines and electric machines, as well as the fuel tank and battery, these are usually not possible if all drivetrains have the same requirements. Instead, with the same exterior dimensions, the requirements for the BEV, such as the maximum velocity or battery capacity, must be lower.

Due to the rapid variation of the input parameters, the tool also offers the possibility for parameter studies. In order to analyze changes in the architectural standards and the level of modularization, it is possible to vary the exterior dimensions, such as the overhang or the prestige measure, or other requirements like the acceleration time or velocity. Since the method contemplates all conceivable architectures, it is possible to identify coherences between the inputs and the resulting architectural standards and modules.

With the variance of vehicles, the previous evaluation already represents a discrete parameter study. It has been shown that the feasibility of longitudinal engine installation mainly depends on the length of the vehicle front. For example, the tool outputs feasible architectures with longitudinal engine installation for one variant of the Volkswagen Golf. The gas engine of this variant has a torque of 250 N m. However, in the other variants with more than 340 N m engine torque, a longitudinal engine installation is not possible due to the limited length of the vehicle front. Within the AUDI A4, the vehicle front is around 130 mm longer, which leads to feasible architectures with longitudinal engine installation for engines with up to 600 N m torque and thus higher performance requirements.

Further comparisons of the Volkswagen Golf and the AUDI A4 show that architectures with transversal engine installation are only possible in the Volkswagen Golf. A detailed analysis shows that the feasibility of transversal engine installation depends on the vehicle width, the chassis type, the wheel house width, and the performance requirements. It is understandable that the vehicle width needs to increase with the performance requirements for transversal engine installation. This explains that even with a 40 mm higher vehicle width, no feasible architectures with transversal engine installation are available for the maximum variants of the

AUDI A4. These variants have around 260 N m more engine torque than the maximum variants of the Volkswagen Golf. Consequently, transversal engine installation is not available for high-performance requirements because the vehicle width is more restricted than the length of the vehicle front. However, for the regular variants of the AUDI A4 which have similar performance requirements as the regular variants of the Volkswagen Golf, there are also no feasible architectures with transversal engine installation. One reason is that with high-performance requirements of the maximum variants, the vehicle weight and thus the tire and wheel house dimensions increase. This results in a reduction of the available installation space in the y-direction. Another influence is the chassis type since multi-link suspensions require around 100 mm more installation space compared to McPherson suspensions and thus further reduce the available installation space in the y-direction. Thus, neither with the AUDI A4 nor with the Volkswagen Golf, architectures with transversal engine installation and multi-link suspension are feasible. In contrast to the Volkswagen Golf, the McPherson chassis type is also not possible on the AUDI A4, as the H30 measure is lower by 20 mm. The resulting lower eye point of the driver in combination with the viewing angle reduces the distance between the hood and the strut mounting. Thus, in the AUDI A4, the remaining distance is not sufficient for pedestrian protection. Consequently, the higher performance of the maximum variants, as well as the infeasibility of the McPherson suspension, makes the transversal engine installation in the regular variants of the AUDI A4 impossible.

Analyzing the feasibility of the chassis types indicates that multi-link suspensions in combination with transversal engine installation led in only one of the combustion/hybrid vehicles to a feasible architecture. This is reasonable as the transversal installed engine and the higher width of this type of suspension conflict with each other. The McPherson suspension is smaller in width but higher. In order to provide enough distance between the hood and the strut mounting for pedestrian protection, the feasibility of this chassis type depends on the driver's eye points and the viewing angle. The driver’s eye point, for instance, depends on the H30 measure.

Another finding is the dependency between the front- and rear-drive types. While architectures with both drive types are feasible within the AUDI A4, the feasible outputs of the Mercedes-Benz C-Class only include rear-drive type architectures. At almost the same size of the vehicle front, the prestige measure of the Mercedes-Benz C-Class is around 110 mm longer. This makes it easier to position the engine behind the front axle, which allows an optimal load distribution for the rear-drive type. However, the lower overhang limits the possibilities to position the engine in front or above the axle, which makes a front-drive type not feasible.

Table 5.1 summarizes the dependencies of the different architectural standards.

Table 5.1: Overview of the dependencies of the different architectural standards

Architectural Standards	Dependencies
Longitudinal Engine Installation	Length of the vehicle front, performance requirements
Transversal Engine Installation	Vehicle width, performance requirements, wheel house width, chassis type
Multi-link Suspension	Engine installation position
McPherson Suspension	Viewing angle, driver's eye points
Front-Drive Type	Overhang and prestige measure
Rear-Drive Type	Overhang and prestige measure

It is important to note that the overall transferability of these insights is limited. With over 400 parameters influencing the architectures in the vehicle front, it is difficult to derive universally valid coherences. Depending on the expected benefits and the cost sensibility, it is possible to overcome most coherences with special concepts. The large number of influences, as well as the statistical and systematic deviations, therefore, always require concept engineers to analyze and iterate the results.

The described application possibilities of the tool focus on the early stage of the modular systems development. Consequently, the resulting architectures form the basis for further manual architecture and package development.

In the application, it is also important to take the limitations of the method into account. These mainly result from the use of geometric substitute models and dimensional chains as well as the level of detail and scope of the method.

The empirical and semi-physical geometric substitute models output the statistically most likely dimensions and not the best-of-benchmark solution. This ensures a robust design and gives design freedom in the subsequent development stages. In addition, the concept engineers can define optimization parameters to deviate from the most likely dimensions. Currently, however, the method does not help the concept engineers to estimate the maximum deviations. Furthermore, the geometric substitute models apply especially for the development from scratch. An evolutionary development requires concept engineers to consider existing components, such as engines, to save on development costs. Therefore, the tool would also require a database to load dimensions from existing components instead of always using the geometric substitute models. Also, the existing systematic deviations, as well as technology leaps, require improvement and continuous update of the models.

When deriving the available installation space and comparing the required and available installation spaces, the tool uses dimensional chains. The systematization of the dimensional chains and their variants, as well as the repositioning of components by distance elements with an additional degree of freedom, implements the logic of manual architecture development and enables the use in the tool. This offers a systematic and transparent approach. However, the resulting architectures are always limited to the implemented dimensional chains. Consequently, the dimensional chains also prevent the identification of completely new architectures with new component arrangements. The tool sacrifices on the innovation of the architectures for transparency in the generation of over 250,000 architectures. Also, using existing dimensional chains ensures the functionality of the architecture compared to new solutions.

Despite the high number of architectures, the tool does not cover all components and dimensional chains of vehicle front architectures. While the representation of the architectures is already extensive, the integration of the steering system or the brake booster remain. Also, the representation of the components and dimensional chains is based on simple shapes with cuboids or cylinders. Overall, this is sufficient for the intended use in the early stage of the modular system development and does not convey a higher level of detail and functionality.

Even at this level of detail, the considered number of components and dimensional chains creates a high degree of complexity and thus limits the scope of this thesis to the implementation of the method on the vehicle front. However, the current mix of drivetrains justifies the application of the method to the vehicle front. Moreover, the tool already considers some dependencies with the interior and the occupant cell. Nevertheless, only by contemplating the entire vehicle it is possible to cover all dependencies. This will be even more important in the future, due to the increasing development of electric vehicles with electric machines in the rear of the vehicle, for the rear-wheel or the all-wheel drive. Combustion engines in the middle or the rear are less important due to the niche application in sports vehicles [108, pp. 11-12].

In addition, the method is currently focused on the geometric feasibility of modular systems. Therefore, the architecture generation does not take into account the cost of the different component and installation position alternatives. Furthermore, the derivation of the modular system does not contemplate the production volumes of the different vehicles. However, this is an important criterion to decide on the external variance of the modular system and, therefore, the inclusion or exclusion of vehicles.

Despite these limitations, the method enables concept engineers to analyze the solution space and to develop modular systems quickly and holistically. Therefore, the use of the tool overcomes the high complexity and the limited resources of the current process and makes the identification of the best solution more likely. Existing methods and tools have not been capable of supporting the development of modular systems for passenger cars, as they lack considering either multiple vehicles, different drivetrains, or scalable substitute models. Consequently, the described work closes this research gap.

In addition to the described research gap, this method contributes overall to the systematization of the vehicle architecture design and the development of modular systems. In particular, the procedures developed for the dimensioning of components and the systematic use of dimensional chains of the vehicle architecture design, as well as their description in this thesis, set an essential foundation for further research on additional challenges in this field.

6 Conclusion and Outlook

The first and second chapter of this thesis presented the motivation and the current process for the development of modular systems. Since the current process is time-consuming and complex, it is not possible to consider the solution space holistically and to identify the overall best solution. Rather, the experiences of the concept engineers with predecessor vehicles have a high impact on the development. A literature review revealed that existing methods either only focus on the development of an individual vehicle, lack the consideration of multiple drivetrains and geometric substitute models, or are not suited to the automotive sector. Consequently, there is still no method for the development of modular systems for passenger cars, thus leading to the primary objective of this thesis.

Consequently, the author developed the presented method, which is divided into the requirement definition, the architecture generation, and the derivation of modular systems. The method requires only limited input parameters, allowing it to be used at the early stage of the modular systems development. This also includes combustion, hybrid, and electric drivetrains. Core elements for the holistic generation of over 250,000 architectures are the geometric substitute models and the dimensional chains. The geometric substitute models enable the continuous scaling of components and distances. With the dimensional chains, the generation of the high number of architectures is replicable and transparent. As a result, the tool can identify cross-vehicle modules and derive architectural standards from the vast solution space. If a modular system is not feasible, the tool will issue an error report. This helps the concept engineer to define targeted iterations and resolve various conflicts of interests. Consequently, the method enables concept engineers to fully analyze the solution space and to develop modular systems quickly and holistically.

To validate the functionality of the method, the author compared the generated results with the architectures, architectural standards, and modules of existing vehicles and modular systems. In some cases, it is necessary to use optimization parameters, as intended within the method, to overcome statistical deviations. Although the geometric substitute models with the available databases represent the highest available accuracy, the tool also requires optimization parameters to overcome systematic deviations within five component sizes and distances. Nevertheless, the evaluation validates the overall functionality of the tool as it can represent the actual vehicles and modular systems.

The discussion focuses on the overall application of the method and its limitations. By varying the input parameters, the tool enables concept engineers to fully analyze the solution space and to develop modular systems quickly and holistically. The resulting architectures set the foundation for further architecture and package development. Despite several limitations, due to the use of geometric substitute models and dimensional chains, as well as the level of detail and scope of the method, the presented method closes the derived research gap. In addition, the method is an important contribution to the vehicle architecture design and modular systems development through the development and application of geometric substitute models as well as the systematization and use of dimensional chains of the vehicle architecture design. The detailed description in this thesis sets the foundation for further research in this field.

Further research concerns the improvement and expansion of the existing method as well as its enhancement.

To increase the applicability of the existing tool, it is of utmost importance to continuously update the geometric substitute models. This is not only necessary to prevent systematic deviations, but also to adapt to technology leaps. Further expansions within the geometric substitute models and the dimensional chains should include the steering system, the brake booster as well as coaxially electric drivetrains and their power electronics as remaining elements of the architectures in the vehicle front. As current niche applications and new technologies such as wheel hub or hydrogen drivetrains evolve, it is essential to include the components and dimensional chains in the tool. At the same time, the goal is an extension to the overall vehicle. Another improvement is the automation of the iteration with optimization parameters. By considering the best-of-benchmark solution as the maximum deviation from the statistically most likely solution, it would be possible to optimize the feasibility automatically.

Besides these improvements and expansions, the overall functionality of the method increases by consideration of costs and production volumes. This would support decisions about the external variance of the modular system and thus the inclusion or exclusion of the vehicle.

Finally, it is possible to enhance the tool to contemplate not only the architecture generation but also the package generation. Positioning all remaining components in generated architectures, including cables and hoses, would greatly enhance the functionality of the tool. However, with the increasing number of components, the challenge is not to identify unified component positions in all vehicles of the modular system, but in platforms and vehicle models. Besides, the higher level of detail also enormously increases the number of dimensional chains. Therefore, it is possible that other methods, like topology optimizations, are more applicable.

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List of Publications

The foundation of this Ph.D. Thesis was set by different publications and student theses. These cover partial aspects of this work. The publications as the first author have the highest impact on this thesis. The different bachelor-, term- and master-theses originate from research questions and advising of the author. The author wants to thank the other authors and students for their contributions.

Journals; Scopus/Web of Science listed (peer-reviewed)

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Conferences; Scopus/Web of Science listed (peer-reviewed)

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[16] Matthias Felgenhauer, Johannes Stocker, Markus Lienkamp, "New approach for architecture design of high variable vehicle portfolios", International Mechanical Engineering Congress and Exposition, Tampa, 2017

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[27] Matthias Felgenhauer, Markus Lienkamp, "Automated Generation of Vehicle Architectures and Derivation of Modular Systems with-in the Vehicle Front", NordDesign2018, Linköping, 2018

[111] Johannes Stocker, Mesut Chavushoglu, Matthias Felgenhauer, Markus Lienkamp "Efficient Module Design for Chassis-Mounted Components of Commercial Vehicles", NordDesign2018, Linköping, 2018 *

[93] Christian Angerer, Matthias Felgenhauer, Isaak Eroglu, Maximilian Zähringer, Svenja Kalt, Markus Lienkamp, "Scalable Dimension-, Weight- and Cost-Modeling for Components of Electric Vehicle Powertrains", 21st International Conference on Electrical Machines and Systems, Jeju, 2018

[71] Matthias Felgenhauer, Lorenzo Nicoletti, Ferdinand Schockenhoff, Christian Angerer, Markus Lienkamp "Empiric Weight Model for the Early Phase of Vehicle Architecture Design", 14th International Conference on Ecological Vehicles and Renewable Energies, Monaco, 2019 (in review process)

Patents

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Journals, Conferences, Magazines, Reports, Conference-Presentations and -posters; not Scopus/Web of Science listed

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Advised Student Theses

[112] Martin Wolf, Term Thesis, “Zukünftige geometrische Veränderungen der packagerelevanten Komponenten verschiedener Antriebskonzepte“, 2016 *

[113] Andreas Billert, Bachelor Thesis, “Vergleich von Pkw-Antriebskonzepten und Konzeption eines parametrischen Baukastenmodells“, 2016 *

[114] Markus Schreiber, Bachelor Thesis, “Erfassung und Analyse des Packages und der Maßketten des Visio.M“, 2016 *

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[118] Christoph Mederer, Bachelor Thesis, “Aufbau eines Modells zur Bauraumberechnung und parametrischen Konzeptgenerierung“, 2017 *

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[97] Stephan Wagner, Master Thesis, “Erstellung geometrischer Ersatzmodelle für die Konzeptauslegung von Komponentenabständen im Vorderwagen“, 2018

[96] Andreas Krohn, Master Thesis, “Designing Geometric Substitute Models for Automated Concept Development“, 2018

[94] Tim Schröder, Term Thesis, “Entwicklung geometrischer Ersatzmodelle für Komponenten des Vorderwagens“, 2018

[121] Alexandre Baum, Term Thesis, “Statistische Evaluierung von empirischen Ersatzmodellen“, 2018

[122] Amin Siala, Bachelor Thesis, “Konzipierung einer Bauraumüberprüfung zur automatischen Generierung von Vorderwagenarchitekturen“, 2018

[123] Stephane Levrat, Term Thesis, “Entwicklung des Funktionsablaufs eines Tools zur automatischen Erstellung von Pkw-Konzeptalternativen“, 2018

[124] Frederik Massner, Term Thesis, “Analyse von Ansätzen zur Pkw-Konzeptgenerierung“, 2018

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* Publications or Student Thesis not relevant for this Dissertation

Appendices

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The following appendices provide further insights into the presented method and the tool. Due to the scope of this thesis, it does not illustrate all coherences within the method and tool. However, it is possible to access the tool at the Institute of Automotive Technology of the Technical University of Munich.

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Appendix A GUI of the Tool

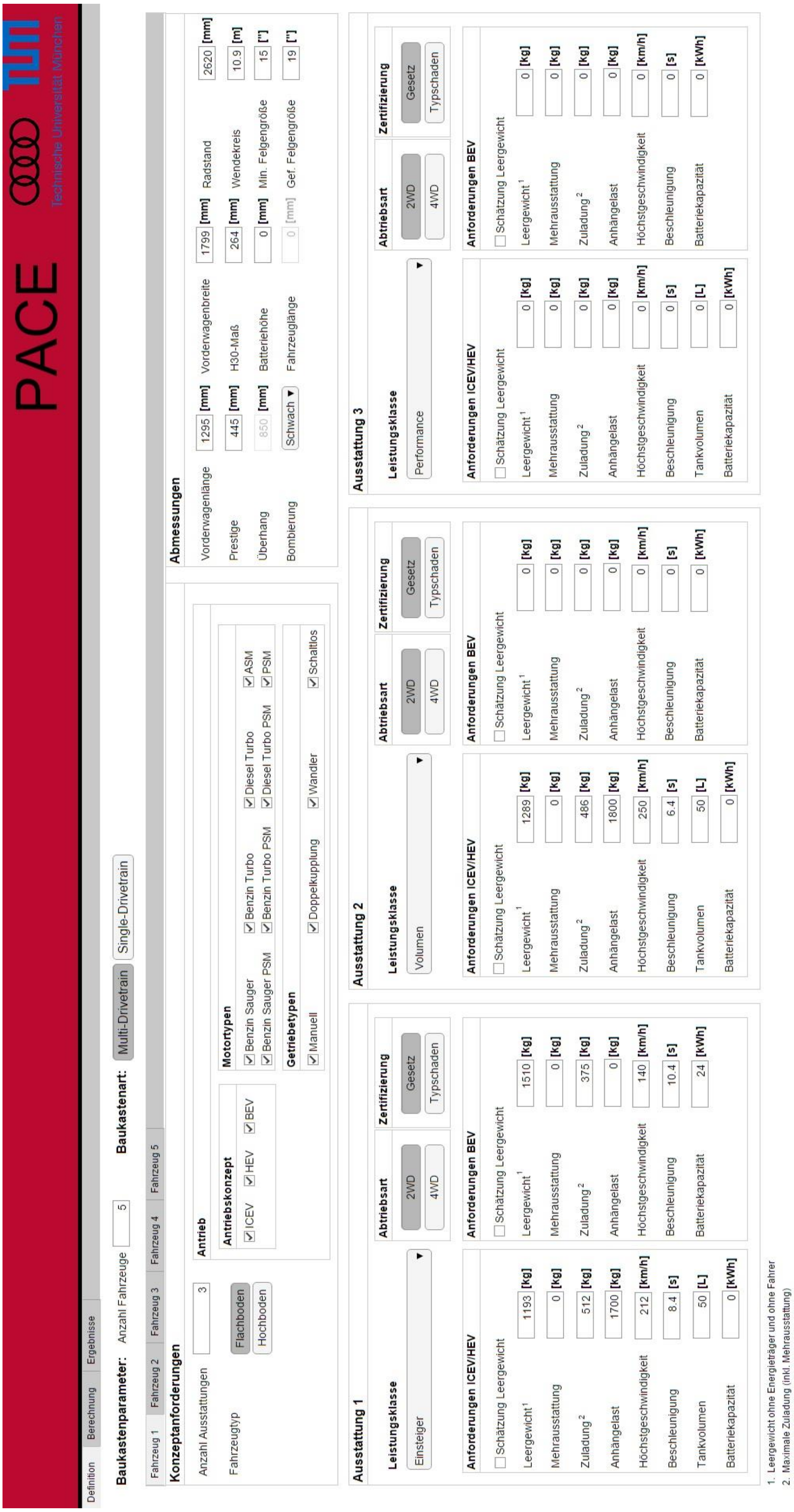

Figure A.1: GUI for the input of requirements

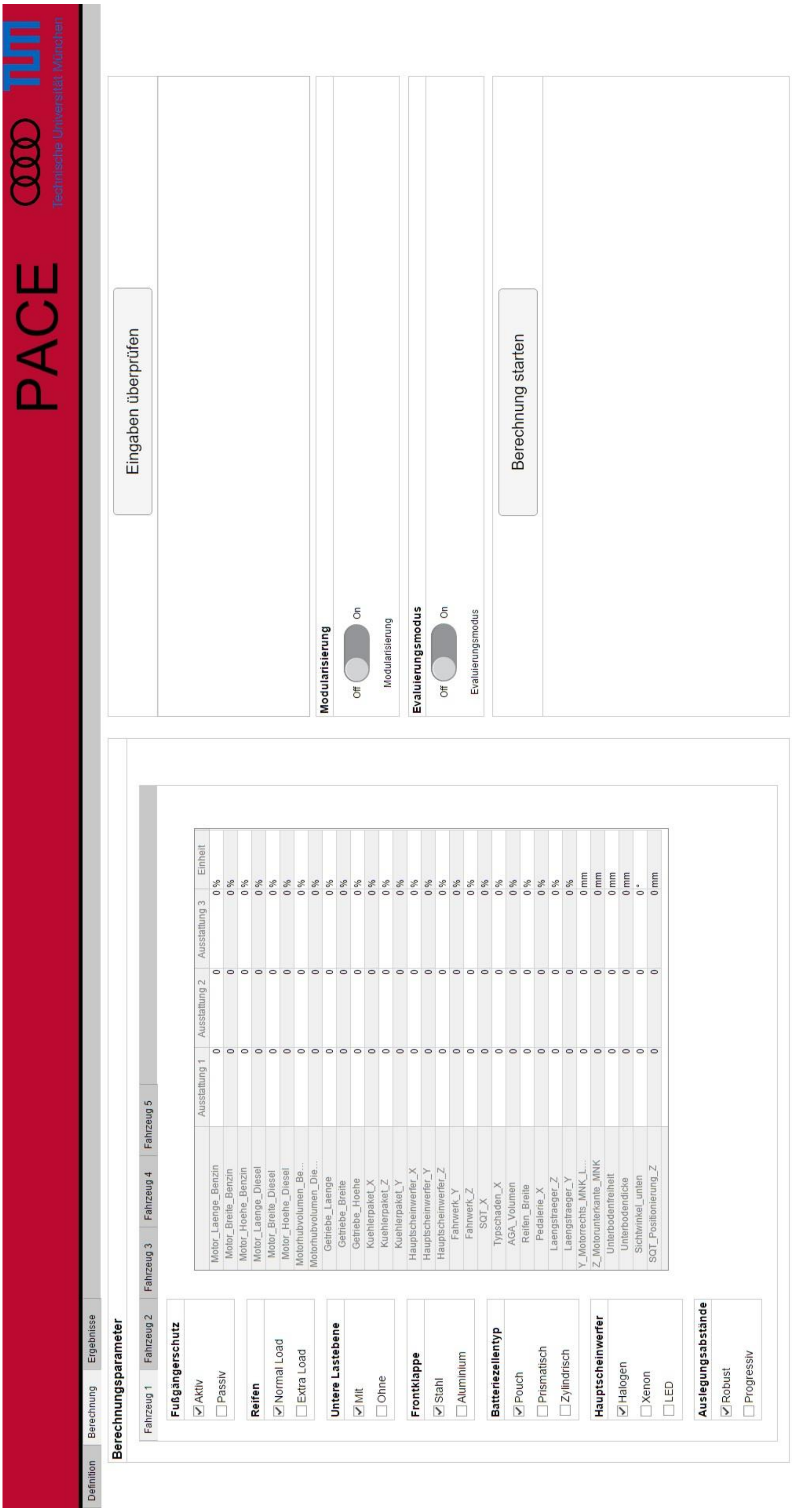

Figure A.2: GUI for the definition of optimization parameters and the start of the tool

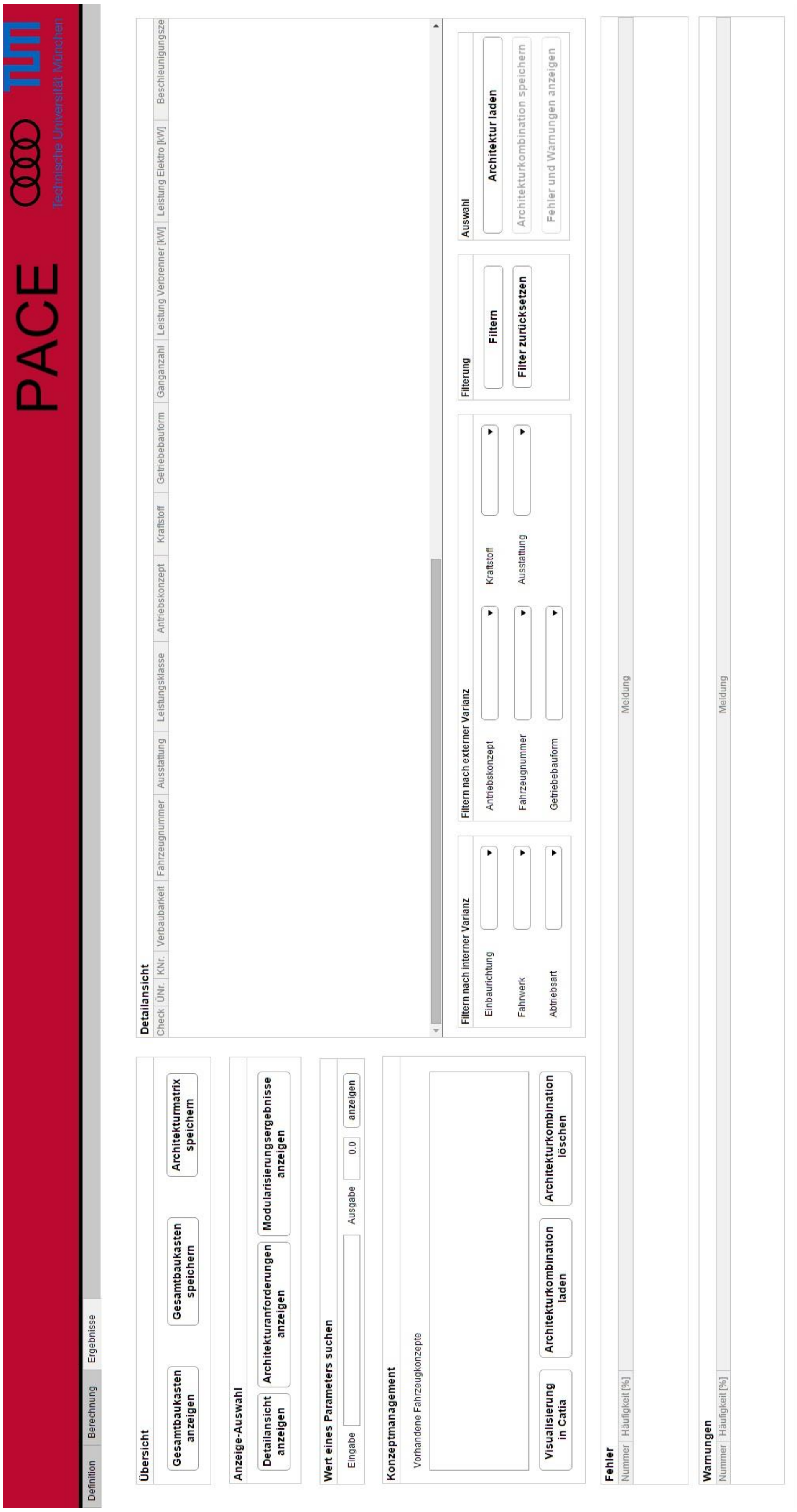

Figure A.3: GUI for the visualization and analysis of the results

Appendix B Regression Functions and Constant Values

Combustion Engine - Overall												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Engine Displacement Volume	cm³			Gas	Naturally Aspirated		Max. Torque	N m				$D = 71.16 + 9.82\ M_1$
				Diesel	Super-charged		Max. Torque	N m				$D = 497.58 + 3.99\ M_1$
				Gas	Super-charged		Max. Torque	N m				$D = 40.69 + 5.91\ M_1$
Optimal Cylinder Volume	cm³	In-Line									Engine Displacement Volume <1800cm³	400,00
		In-Line									Engine Displacement Volume >1800cm³	500,00
		V-Type										575,00
Stroke/Bore Ratio	-	In-Line										1,10
		V-Type										0,96
Cylinder Spacing	mm	In-Line					Bore	mm				$D = 17.42 + 0.89\ M_1$
		V-Type					Bore	mm				$D = -10.88 + 1.23\ M_1$
Connecting Rod Ratio	-	In-Line										0,31
		V-Type										0,28
Cylinder Bank Offset	mm	V-Type		Gas	Naturally Aspirated							38,40
				Diesel	Super-charged							33,60
				Gas	Super-charged							21,10
Cylinder Bank Angle	°					6 Clinders						60,00
						8 Cylinders						90,00
						10 Cylinders						72,00
						12 Cylinders						60,00

Figure B.1: Regression functions and constant values for the combustion engines

Combustion Engine – Length												
Dependent Variable		**Binary Variables**					**Metric Variables**				**Condition**	**Equation/Value**
D	**Unit**	**B1**	**B2**	**B3**	**B4**	**B5**	**M1**	**Unit**	**M2**	**Unit**		
Length Overhang	mm	In-Line										273,35
		V-Type										311,52

Combustion Engine – Width												
Dependent Variable		**Binary Variables**					**Metric Variables**				**Condition**	**Equation/Value**
D	**Unit**	**B1**	**B2**	**B3**	**B4**	**B5**	**M1**	**Unit**	**M2**	**Unit**		
Width Overhang	mm	In-Line		Gas	Naturally Aspirated		Max. Torque	N m				$D = 372.59 + 0.35\ M_1$
				Diesel	Super-charged		Max. Torque	N m				$D = 407.32 + 0.33\ M_1$
				Gas	Super-charged		Max. Torque	N m				$D = 372.59 + 0.51\ M_1$
		V-Type				6 Clinders						231,09
						8 Cylinders						90,50
						10 Cylinders						191,59
						12 Cylinders						231,09

Figure B.2: Regression functions and constant values for the combustion engines

Combustion Engine – Height												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Compression Height	mm	In-Line					Bore	mm				$D = 0.365\ M_1$
		V-Type					Bore	mm				$D = 0.562\ M_1$
Cylinder Head Height	mm											225,91
Lower Height Overhang	mm	In-Line	Longitudinal		Naturally Aspirated		Max. Torque	N m	Number of Cylinders	-		$D = 275.47 + 0.14\ M_1 - 12.83\ M_2$
			Longitudinal		Super-charged		Max. Torque	N m	Number of Cylinders	-		$D = 254.84 + 0.14\ M_1 - 12.83\ M_2$
			Transversal		Naturally Aspirated		Max. Torque	N m	Number of Cylinders	-		$D = 241.36 + 0.14\ M_1 - 12.83\ M_2$
			Transversal		Super-charged		Max. Torque	N m	Number of Cylinders	-		$D = 220.73 + 0.14\ M_1 - 12.83\ M_2$
Upper Height Overhang	mm	In-Line										39,44
Overall Height Overhang	mm	V-Type		Gas	Naturally Aspirated							$D = 163{,}49 + 0{,}57\ M_1$
	mm			Diesel	Super-charged							$D = 59.83 + 0.40\ M_1$
	mm			Gas	Super-charged							$D = 163{,}49 + 0.40\ M_1$

Figure B.3: Regression functions and constant values for the combustion engines

Electric Machine												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Machine Volume	dm³	PSM					Nom. Torque	N m				$D = 5.70 + 0.05\ M_1$
		ASM					Nom. Torque	N m				$D = 5.70 + 0.10\ M_1$
Length/Diameter Ratio	-						Max. Rotational Speed	1/min				$D = 0.26 + 7.02\ 10^{-5}\ M_1$
Overhang	mm											33,30

Hybrid Module												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Module Volume	dm³						Max. Electric Torque	N m				$D = 4.29 + 0.04\ M_1$
Length/Diameter Ratio	-						Max. Electric Torque	1/min				$D = 0.06 + 1.60\ 10^{-3} M_1$

Figure B.4: Regression functions and constant values for the electric machines and hybrid module

Combustion/Hybrid Gearbox - Longitudinal													
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Clutch Diameter	mm	Manual					Max. Torque	N m				$D = 294.50 + 0.10\ M_1$
		Double Clutch										359,32
		Automatic										343,08
Clutch Thickness	mm	Manual					Max. Torque	N m				$D = 148.68 + 0.10\ M_1$
		Double Clutch										207,55
		Automatic										179,94
Gearbox Length	mm	Manual										$D = 280.75 + 0.23\ M_1$
		Double Clutch										543,20
		Automatic										414,41
Gearbox Width Inlet	mm	Manual					Max. Torque	N m				$D = 131.50\ + 0.17\ M_1$
		Double Clutch										352,85
		Automatic										301,86
Gearbox Width Outlet	mm	Manual					Max. Torque	N m				$D = 131.50\ + 0.17\ M_1$
		Double Clutch										198,53
		Automatic										171,38
Gearbox Height Inlet	mm	Manual										273,31
		Double Clutch										356,09
		Automatic										325,15
Gearbox Height Outlet	mm	Manual										273,31
		Double Clutch										303,74
		Automatic										295,03

Figure B.5: Regression functions and constant values for the longitudinal gearboxes

Combustion/Hybrid Gearbox - Transversal												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Clutch Diameter	mm	Manual										316,13
		Double Clutch										320,66
		Automatic										315,73
Clutch Thickness	mm	Manual									Max. Engine Torque < 300 N m	136,70
											Max. Engine Torque > 300 N m	152,95
		Double Clutch										359,32
		Automatic										343,08
Gearbox Length	mm	Manual	Two Shafts								Max. Engine Torque < 300 N m	411,66
			Two Shafts								Max. Engine Torque > 300 N m	440,22
			Three Shafts									447,63
		Double Clutch										555,48
		Automatic										541,74
Gearbox Width	mm	Manual	Two Shafts									241,32
		Manual	Three Shafts									227,09
		Double Clutch										352,85
		Automatic										262,16
Gearbox Height	mm	Manual	Two Shafts								Max. Engine Torque < 300 N m	254,31
		Manual	Two Shafts								Max. Engine Torque > 300 N m	304,06
		Manual	Three Shafts									333,81
		Double Clutch										333,81
		Automatic									Max. Engine Torque < 380 N m	356,68
		Automatic									Max. Engine Torque > 380 N m	389,52

Figure B.6: Regression functions and constant values for the longitudinal gearboxes

Exhaust System												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Catalytic Converter Volume	l	In-Line		Gas							Max. Engine Power < 150 kW	1,62
				Gas							Max. Engine Power > 150 kW	2,90
				Diesel							Max. Engine Power < 150 kW	1,65
				Diesel							Max. Engine Power > 150 kW	1,97
		V-Type	Longitudinal	Gas							Max. Engine Power < 285 kW	2,82
			Longitudinal	Gas							Max. Engine Power > 285 kW	3,55
			Transversal	Gas								3,27
				Diesel							Max. Engine Power < 255 kW	1,91
				Diesel							Max. Engine Power > 255 kW	2,82
Particle Filter Volume	l	In-Line		Diesel							Max. Engine Power < 150 kW	3,10
				Diesel							Max. Engine Power > 150 kW	3,44
		V-Type		Diesel							Max. Engine Power < 255 kW	3,44
				Diesel							Max. Engine Power > 255 kW	5,66

Figure B.7: Regression functions and constant values for the exhaust system

Climate Condenser												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Net Surface	m²						Interior Space Volume	m³				$D = 0.07 + 0.17\, M_1$
Height/Width Ratio	-	Fullface										1,46
		IC Below/Ahead										1,66
		IC Below/Behind										1,66
		Lateral IC										1,46
Overhang Height	mm											0,00
Overhang Width	mm											65,35
Thickness	mm											12,00
Overhang Thickness	mm											21,10

Watercooler												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Net Surface	m²						Max. Engine Power	kW	Vehicle Width	m		$D = -0.32 + 3.73\, 10^{-4}\, M_1 + 6.01\, 10^{-4}\, M_2$
Height/Width Ratio	-	Fullface										1,45
		IC Below/Ahead										1,45
		IC Below/Behind										1,57
		Lateral IC										1,45
Overhang Height	mm											0,00
Overhang Width	mm											92,05
Thickness	mm										Max. Engine Power < 155 kW	24,75
											155 kW > Max. E. P. > 255 kW	33,03
											Max. Engine Power > 255 kW	57,89
Overhang Thickness	mm											22,02

Figure B.8: Regression functions and constant values for the climate condenser and water cooler

Intercooler (Combustion/Hybrid)												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Net Surface	m²	Fullface					Engine Displacement Volume	cm³	Vehicle Width	m		$D = 0.069 + 1.81\ 10^{-5}\ M_1 + 8.92\ 10^{-5}\ M_2$
		IC Below/Ahead					Engine Displacement Volume	cm³	Vehicle Width	m		$D = -0.11 + 1.81\ 10^{-5}\ M_1 + 8.92\ 10^{-5}\ M_2$
		IC Below/Behind					Engine Displacement Volume	cm³	Vehicle Width	m		$D = 0.11 + 1.81\ 10^{-5}\ M_1 + 8.92\ 10^{-5}\ M_2$
		Lateral IC					Engine Displacement Volume	cm³	Vehicle Width	m		$D = 0.15 + 1.81\ 10^{-5}\ M_1 + 8.92\ 10^{-5}\ M_2$
Height/Width Ratio	-	Fullface										1,51
		IC Below/Ahead										4,56
		IC Below/Behind										4,56
		Lateral IC										1,07
Overhang Height	mm	Fullface										0,00
		IC Below/Ahead										0,00
		IC Below/Behind										0,00
		Lateral IC										128,90
Overhang Width	mm	Fullface	Direct									117,14
			Indirect									73,05
		IC Below/Ahead	Direct									216,18
			Indirect									140,40
		IC Below/Behind	Direct									216,18
			Indirect									140,40
		Lateral IC										0,00
Thickness	mm	Fullface										20,60
		Fullface										20,60
		IC Below/Ahead										68,37
		IC Below/Behind										68,37
		Lateral IC										64,50
Overhang Thickness	mm	Fullface										18,42
		IC Below/Ahead										13,67
		IC Below/Behind										13,67
		Lateral IC										17,54

Figure B.9: Regression functions and constant values for the intercooler of ICEV and HEV

Intercooler (Electric)												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Width	mm											Takeover from Climate Condenser
Height	mm											Takeover from Climate Condenser
Thickness	mm											30,00
Overhang Thickness	mm											20,00

Cooling Fan												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Thickness	Mm											96,83

Figure B.10: Regression functions and constant values for the intercooler of BEV and the cooling fan

Tire													
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Brake Disc Diameter	mm						Weight on Front Axis during Breaking	kg	Acceleration Time to 100 km/h	s		$D = 261.98 + 0.077\ M_1\ - 5.66\ M_2$
Minimal Offset Brake Disc to Rim	mm	Low-Ground										111,00
		High-Ground										138,90
Average Offset Brake Disc to Rim	mm	Low-Ground										90,00
		High-Ground										123,80
Tire Volume	mm^3	Normal Load										$D = -1.1\ 10^7 + 8.49\ 10^4\ M_1$
		Extra Load										$D = -1.26\ 10^7 + 7.68\ 10^4\ M_1$

Chassis													
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
Suspension Strut Mounting Length	mm	McPherson										229,70
		Multi-Link										287,60
Suspension Strut Mounting Width	mm	McPherson										155,60
		Multi-Link										204,90
Suspension Strut Mounting Height	mm	McPherson	Low-Ground									537,60
			High-Ground									574,60
		Multi-Link										501,50

Figure B.11: Regression functions and constant values for the tires and the suspensions

Body												
Dependent Variable		**Binary Variables**					**Metric Variables**				**Condition**	**Equation/Value**
D	**Unit**	**B1**	**B2**	**B3**	**B4**	**B5**	**M1**	**Unit**	**M2**	**Unit**		
Bumper Beam Thickness	mm											51,60
Bumper Beam Height	mm											97,90
Side Member Thickness	mm											67,00
Side Member Height	mm											121,30
Bumper Beam and Side Rail Vertikal Position	mm	Low-Ground										469,50
		High-Ground										523,50
Bulk Wall Thickness	mm											2,00

Distances												
Dependent Variable		**Binary Variables**					**Metric Variables**				**Condition**	**Equation/Value**
D	**Unit**	**B1**	**B2**	**B3**	**B4**	**B5**	**M1**	**Unit**	**M2**	**Unit**		
Minimal Distance between Bumper Beam and Cooling System	mm	Robust									Regulatory Design Type	33,93
		Progressive									Regulatory Design Type	21,97
Minimal Distance between Cooling System and Engine	mm	Robust										12,03
		Progressive										1,60
Minimal Distance between Engine and Bulk Wall	mm	Robust										61,93
		Progressive										48,24
Minimal Distance between Engine and Side Rails	mm	Robust										12,55
		Progressive										7,84
Minimal Crash Length	mm	Robust	Average									264,13
			Error									223,30
		Progressive	Average									251,75
			Error									206,40

Figure B.12: Regression functions and constant values for the body and distances

Headlights												
Dependent Variable		Binary Variables					Metric Variables				Condition	Equation/Value
D	Unit	B1	B2	B3	B4	B5	M1	Unit	M2	Unit		
		Halogen										465,04
Headlight Length	mm	Xenon										476,30
		LED										440,30
		Halogen										404,49
Headlight Width	mm	Xenon										404,37
		LED										441,25
		Halogen										227,63
Headlight Height	mm	Xenon										221,00
		LED										227,33

Figure B.13: Regression functions and constant values for the headlights

Appendix C Dimensional Chains

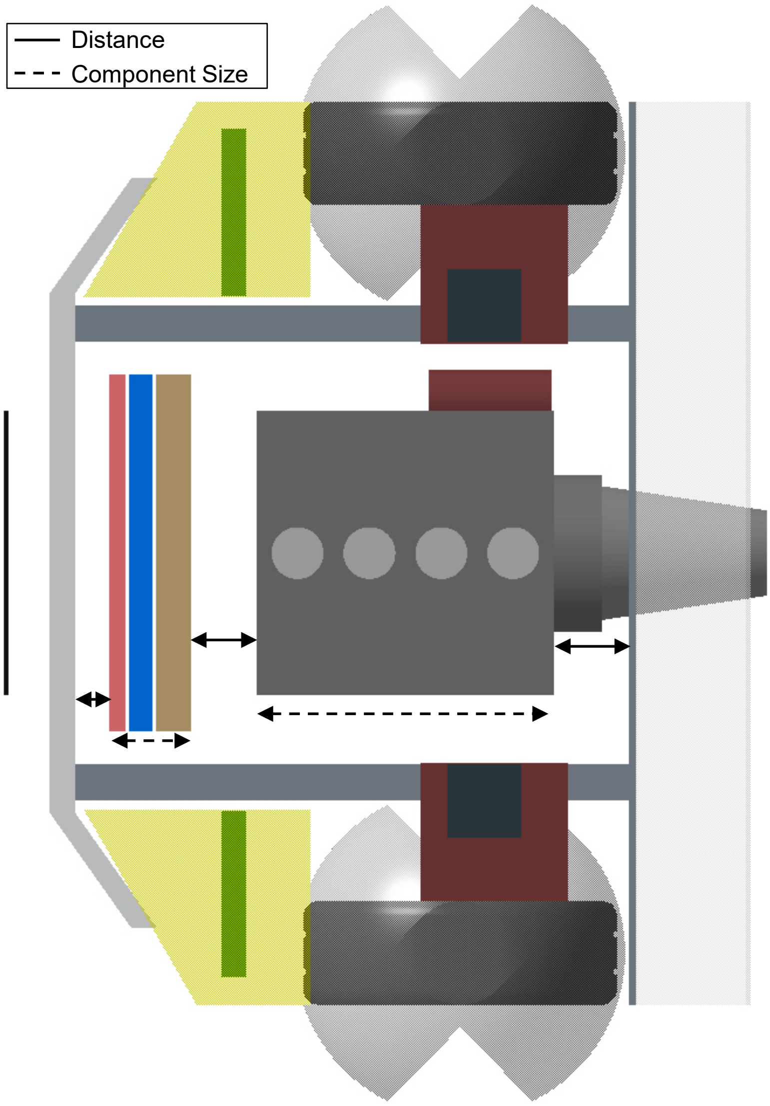

Figure C.1: Dimensional chain over the cooling system and the engine in the x-direction

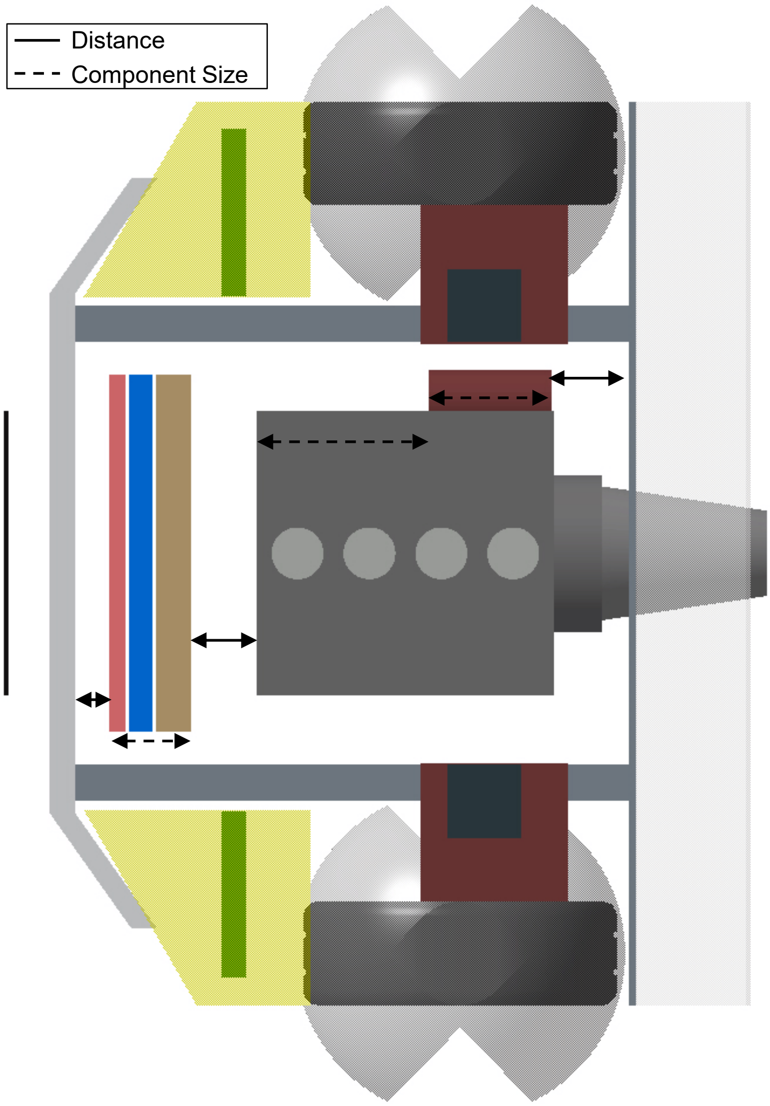

Figure C.2: Dimensional chain over the cooling system, engine, and exhaust system in the x-direction

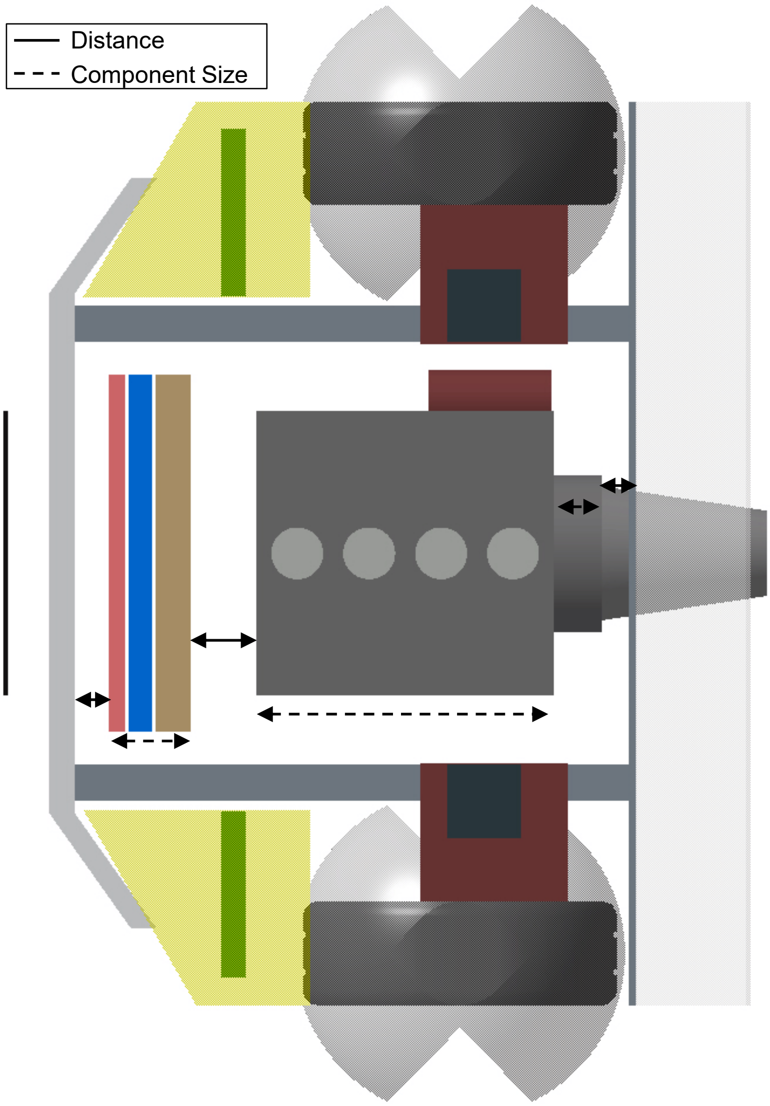

Figure C.3: Dimensional chain over the cooling system, engine and gearbox in the x-direction

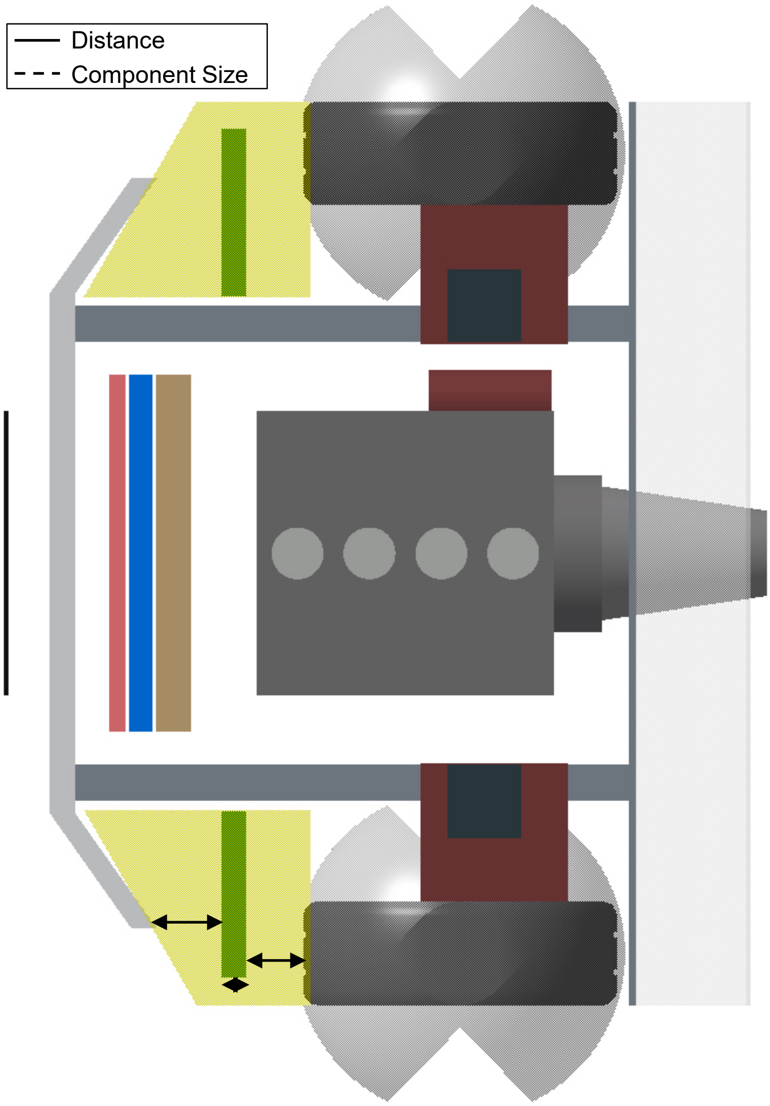

Figure C.4: Dimensional chain over the lateral intercooler in the x-direction

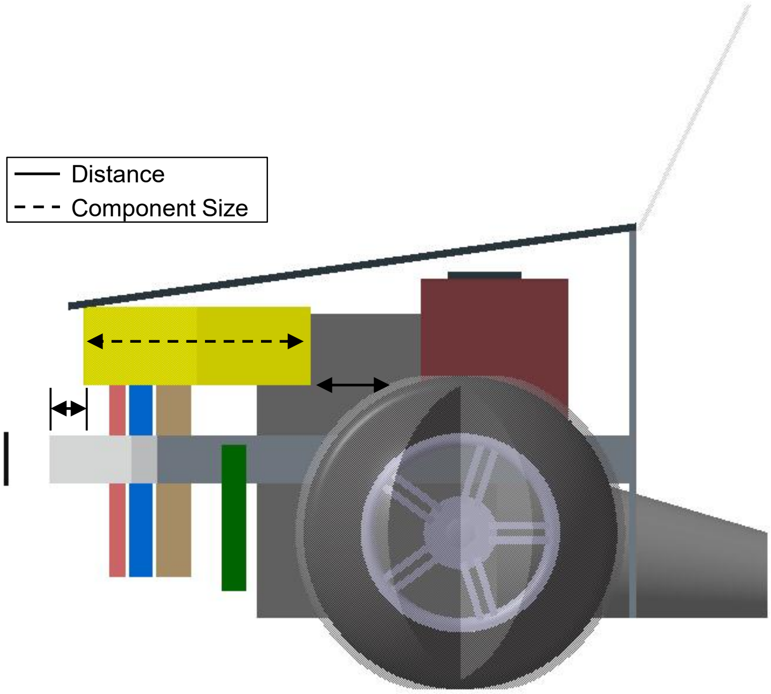

Figure C.5: Dimensional chain over the headlight in the x-direction

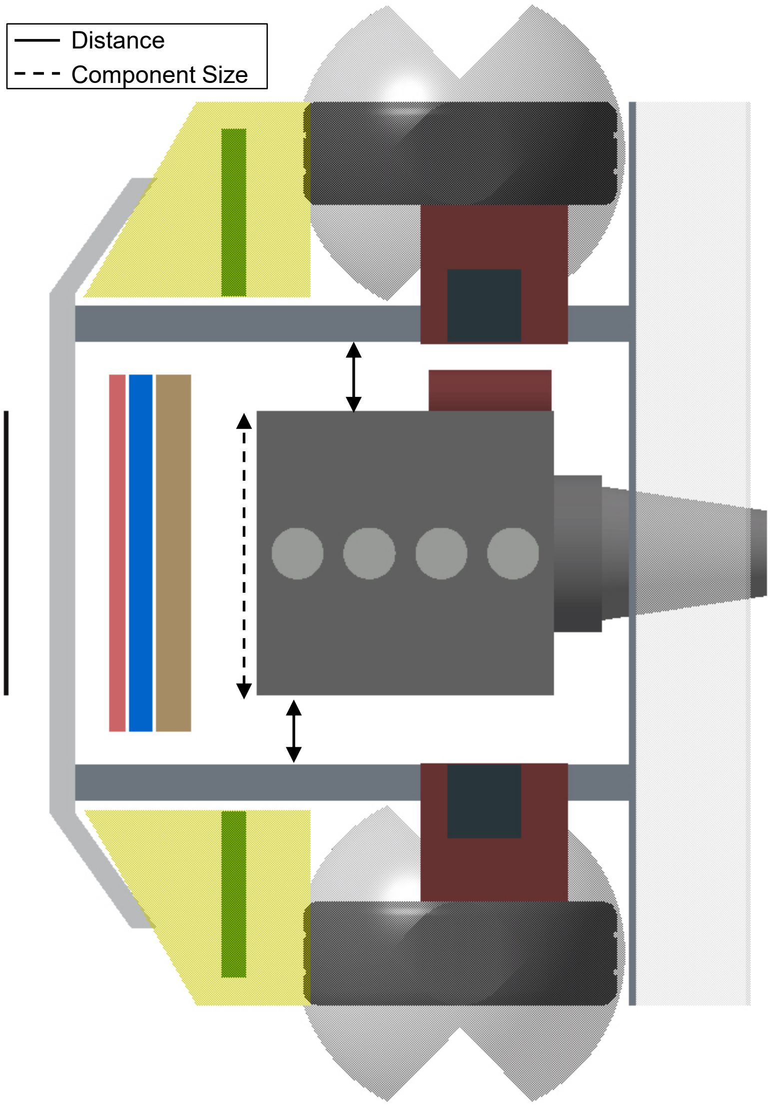

Figure C.6: Dimensional chain over the engine in the y-direction

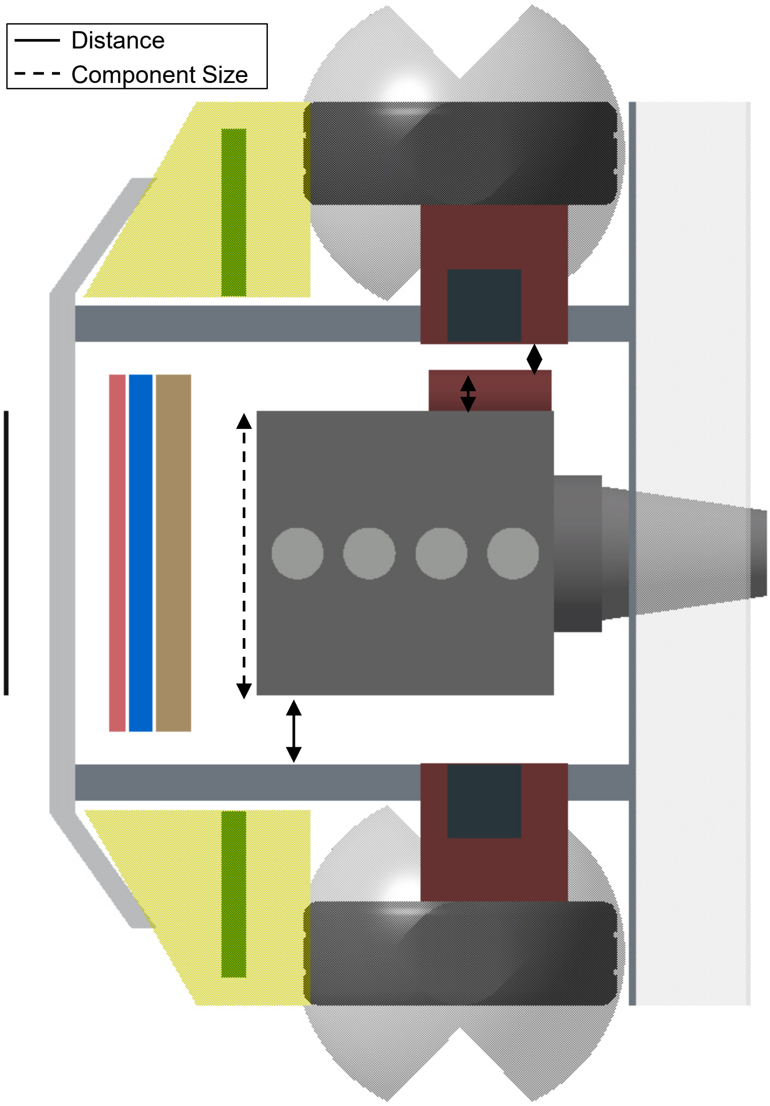

Figure C.7: Dimensional chain over the engine and exhaust system in the y-direction

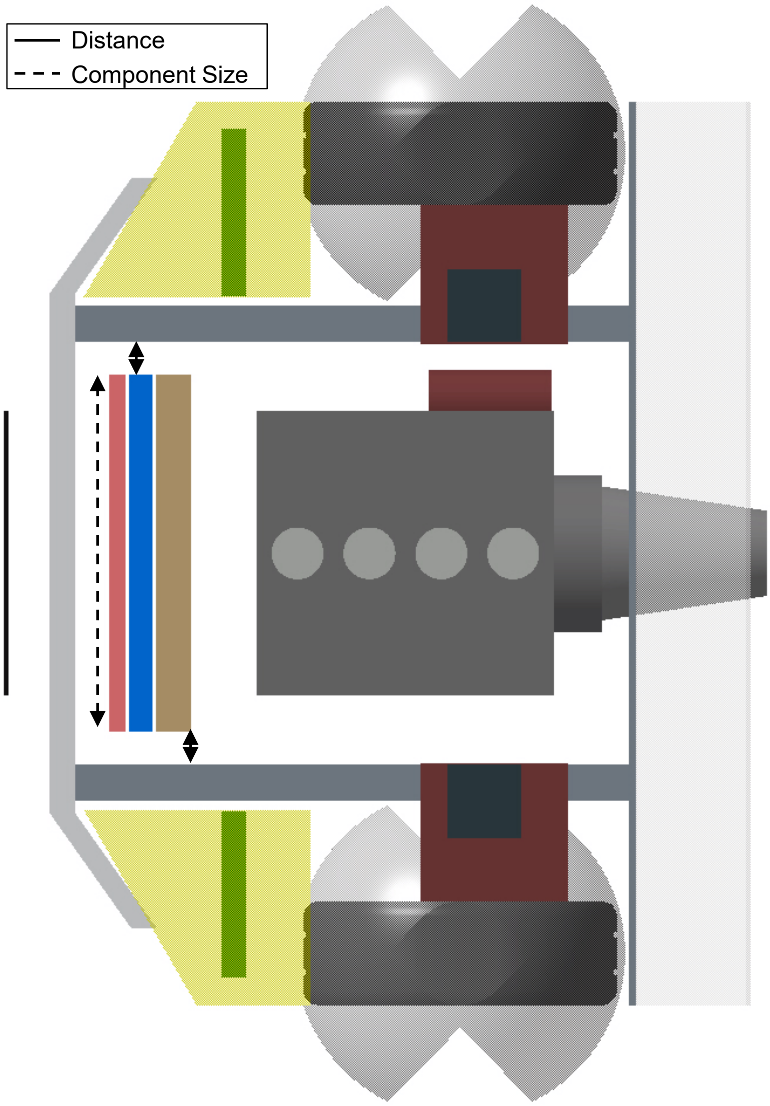

Figure C.8: Dimensional chain over the cooling system in the y-direction

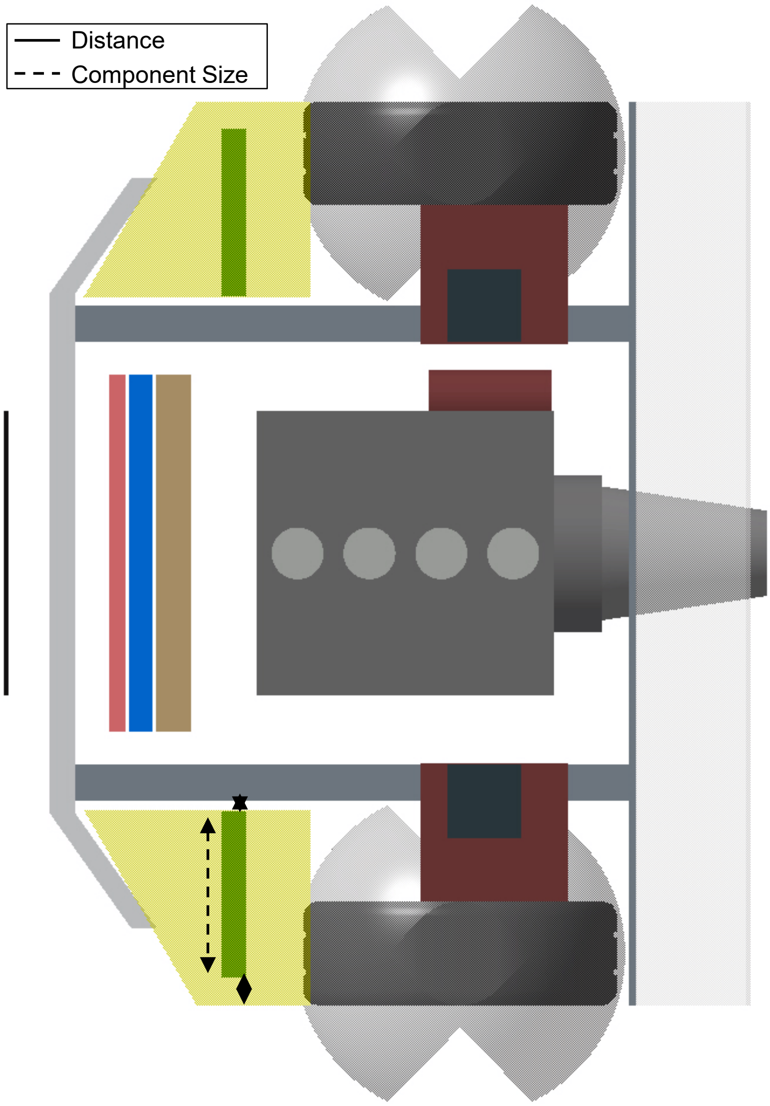

Figure C.9: Dimensional chain over the lateral intercooler in the y-direction

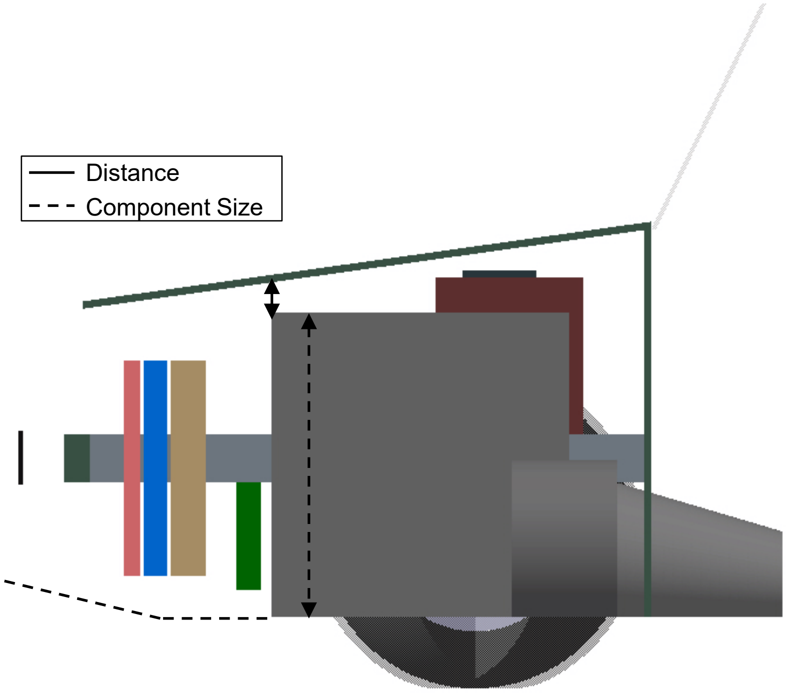

Figure C.10: Dimensional chain over the engine in the z-direction

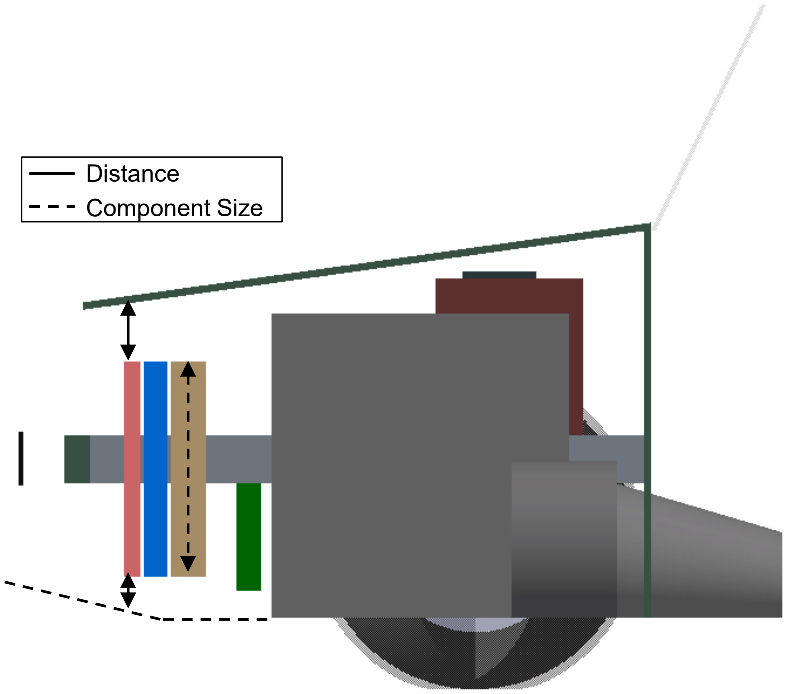

Figure C.11: Dimensional chain over the cooling system in the z-direction

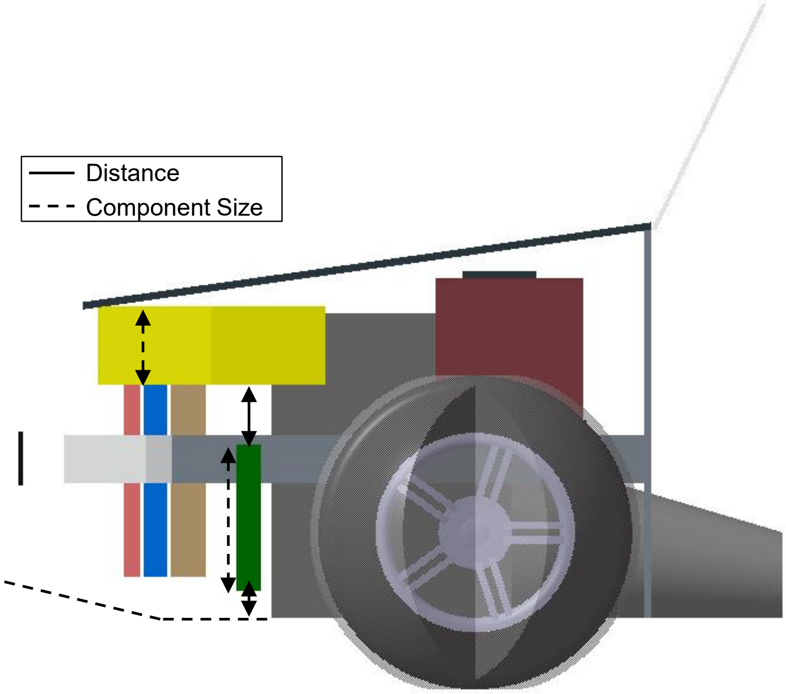

Figure C.12: Dimensional chain over the lateral intercooler and headlight in the z-direction

Appendix D Modular System Matrix

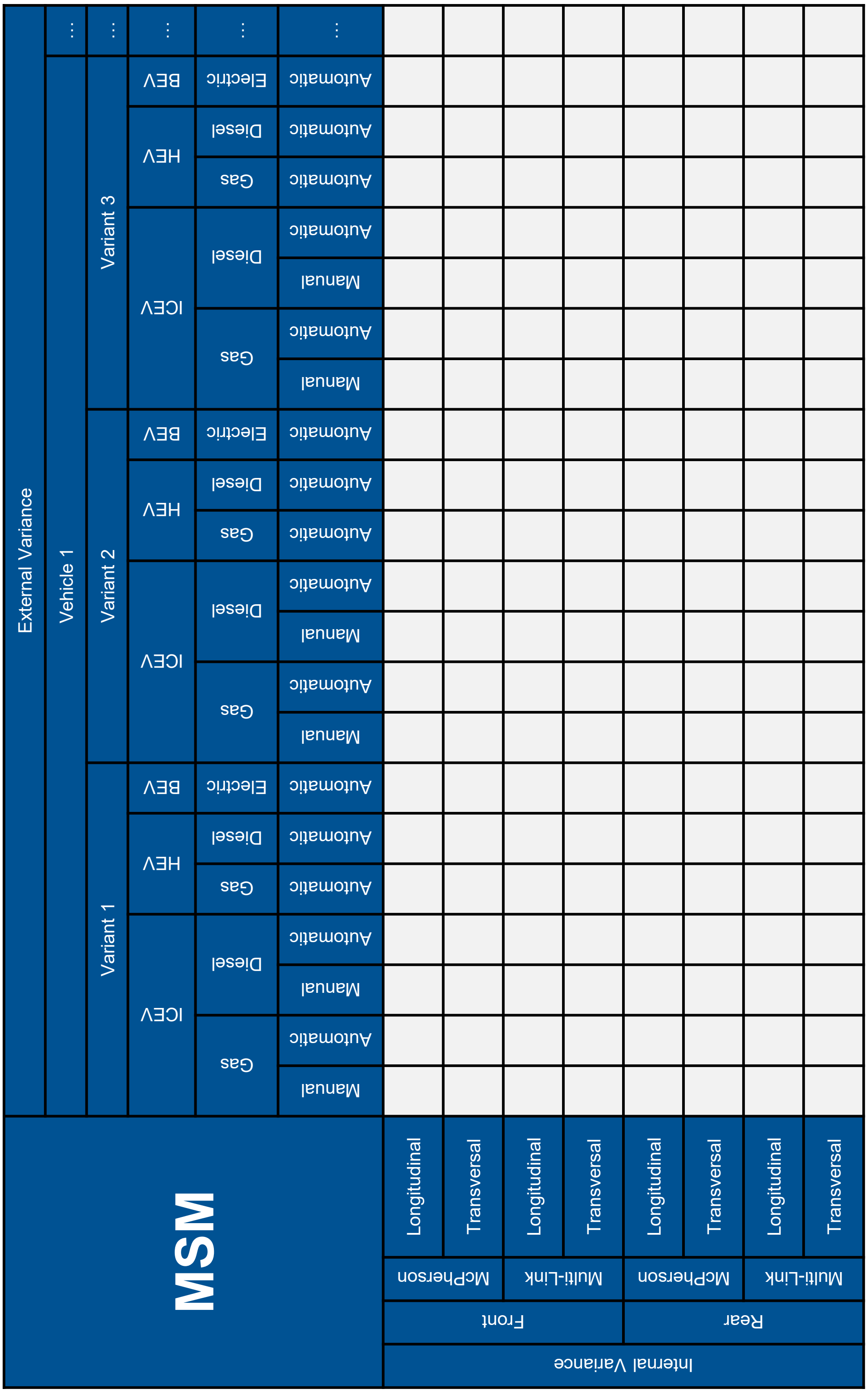

Figure D.1: Modular Systems Matrix with all external variants of one vehicle

Appendix E Evaluation Vehicles

Table E.1: Vehicle Data of the AUDI A4

AUDI A4, MY2015						
Body type	-	Low-Ground				
Basic Price	€	35.400				
Exterior Dimensions			**Discrete Optimization Parameters**			
Front Overhang	mm	885	**Tire Type**	-	Normal Load	
Prestige Measure	mm	545	**Lower Stiffener**	-	Without	
Wheelbase	mm	2820	**Hood Material**	-	Steel	
Vehicle Width	mm	1842	**Hood Mechanism**	-	Active	
H30-Measure	mm	242				
Turning Circle	m	11.6				
Rim Size	"	19				
Vehicle Variants						
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**	
		Fuel 1	Fuel 2	Fuel 1	Fuel 2	
		1.4 TFSI	2.0 TDI	3.0 TFSI	3.0 TDI	
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV	
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance	
Drive type	-	2WD	2WD	4WD	4WD	
Engine Type	-	R	R	V	V	
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged	
Power	kW	110	110	260	200	
Torque	N m	250	320	500	600	
Battery Type	-	-				
Gearbox Type	-	Manual/Double-Clutch	Manual/Double-Clutch	Automatic	Automatic	
Cooling System Type	-	L-Pack Front	-	-	-	
Headlight Type	-	Halogen				
Red. Curb Weight	kg	1320	1430	1630	1660	
Load Capacity	kg	495	525	495	495	
Trailer Load	kg	1600	1600	2100	2100	
Maximum Velocity	km/h	210	210	250	250	
Acceleration Time	s	8.7	9.2	4.7	5.3	

Table E.2: Vehicle Data of the AUDI A6

AUDI A6, MY2018						
Body type	-	Low-Ground				
Basic Price	€	49.150				
Exterior Dimensions			**Discrete Optimization Parameters**			
Front Overhang	mm	921	**Tire Type**	-	Normal Load	
Prestige Measure	mm	562	**Lower Stiffener**	-	Without	
Wheelbase	mm	2924	**Hood Material**	-	Aluminum	
Vehicle Width	mm	1886	**Hood Mechanism**	-	Active	
H30-Measure	mm	242				
Turning Circle	m	12.1				
Rim Size	"	21				
Vehicle Variants						
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**	
		Fuel 1	Fuel 2	Fuel 1	Fuel 2	
		2.0 TFSI	2.0 TDI	**3.0 TFSI**	**3.0 TDI**	
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV	
Performance Class	-	Performance	Performance	Performance	Performance	
Drive type	-	2WD	2WD	4WD	4WD	
Engine Type	-	R	R	V	V	
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged	
Power	kW	180	150	250	210	
Torque	N m	370	400	500	620	
Battery Type	-	-				
Gearbox Type	-	Automatic	Automatic	Automatic	Automatic	
Cooling System Type	-	-	-	L-Pack	-	
Headlight Type	-	LED				
Red. Curb Weight	kg	1640	1645	1760	1825	
Load Capacity	kg	575	535	565	575	
Trailer Load	kg	2000	2000	2000	2000	
Maximum Velocity	km/h	249	246	250	250	
Acceleration Time	s	6.8	8.1	5.1	6.3	

Table E.3: Vehicle Data of the AUDI A8

AUDI A8, MY2018		
Body type	-	Low-Ground
Basic Price	€	90.600

Exterior Dimensions			Discrete Optimization Parameters		
Front Overhang	mm	1533	**Tire Type**	-	Extra Load
Prestige Measure	mm	544	**Lower Stiffener**	-	With
Wheelbase	mm	1998	**Hood Material**	-	Aluminum
Vehicle Width	mm	1945	**Hood Mechanism**	-	Active
H30-Measure	mm	264			
Turning Circle	m	12.5			
Rim Size	“	20			

Vehicle Variants

Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		<u>3.0 TFSI</u>	**3.0 TDI**	4.0 TFSI	4.0 TDI
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Performance	Performance	Performance	Performance
Drive type	-	4WD	4WD	4WD	4WD
Engine Type	-	V	V	V	V
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	250	210	338	320
Torque	N m	500	600	600	900
Battery Type	-	-			
Gearbox Type	-	Automatic	Automatic	Automatic	Automatic
Cooling System Type	-	L-Pack	-	-	-
Headlight Type	-	LED			
Red. Curb Weight	kg	1920	1975	2050	2170
Load Capacity	kg	685	640	640	630
Trailer Load	kg	2300	250	2300	2300
Maximum Velocity	km/h	250	250	250	250
Acceleration Time	s	5.6	5.9	4.3	4.7

Table E.4: Vehicle Data of the BMW 5

BMW 5, MY2017					
Body type	-	Low-Ground			
Basic Price	€	48.400			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	862	**Tire Type**	-	Extra Load
Prestige Measure	mm	680	**Lower Stiffener**	-	With
Wheelbase	mm	2975	**Hood Material**	-	Aluminum
Vehicle Width	mm	1868	**Hood Mechanism**	-	Active
H30-Measure	mm	252			
Turning Circle	m	12.1			
Rim Size	“	20			

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		530e (9.2 kWh)		540i	540d
Drivetrain Type	-	PHEV		ICEV	ICEV
Performance Class	-	Performance		Performance	Performance
Drive type	-	2WD		4WD	4WD
Engine Type	-	R		R	R
Fuel and Charging Type	-	Gas Supercharged		Gas Supercharged	Diesel Supercharged
Power	kW	135/83 (Max./Max.)		250	235
Torque	N m	290/250 (Max./Max.)		450	680
Battery Type	-	-			
Gearbox Type	-	Automatic		Automatic	Automatic
Cooling System Type	-	L-Pack		-	-
Headlight Type	-	LED			
Red. Curb Weight	kg	1695		1520	1675
Load Capacity	kg	650		675	690
Trailer Load	kg	2000		2000	2000
Maximum Velocity	km/h	235		250	250
Acceleration Time	s	6.2		5.1	4.9

Table E.5: Vehicle Data of the BMW 7

BMW 7, MY2015					
Body type	-	Low-Ground			
Basic Price	€	90.600			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	880	**Tire Type**	-	Extra Load
Prestige Measure	mm	681	**Lower Stiffener**	-	With
Wheelbase	mm	3070	**Hood Material**	-	Aluminum
Vehicle Width	mm	1902	**Hood Mechanism**	-	Active
H30-Measure	mm	257			
Turning Circle	m	12.3			
Rim Size	“	20			
Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		730i	**730d**	750i	750d
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Performance	Performance	Performance	Performance
Drive type	-	2WD	2WD	4WD	4WD
Engine Type	-	R	R	R	R
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	190	195	330	294
Torque	N m	400	620	650	760
Battery Type	-	-			
Gearbox Type	-	Automatic	Automatic	Automatic	Automatic
Cooling System Type	-	-	L-Pack	-	-
Headlight Type	-	LED			
Red. Curb Weight	kg	1725	1755	1870	1940
Load Capacity	kg	600	620	630	615
Trailer Load	kg	2100	2100	2300	2300
Maximum Velocity	km/h	250	250	250	250
Acceleration Time	s	5.5	6.1	4.4	4.6

Table E.6: Vehicle Data of the BMW X3

BMW X3, MY2017						
Body type	-	High-Ground				
Basic Price	€	44.900				
Exterior Dimensions			**Discrete Optimization Parameters**			
Front Overhang	mm	856	**Tire Type**	-	Normal Load	
Prestige Measure	mm	678	**Lower Stiffener**	-	With	
Wheelbase	mm	2864	**Hood Material**	-	Aluminum	
Vehicle Width	mm	1891	**Hood Mechanism**	-	Active	
H30-Measure	mm	315				
Turning Circle	m	12.0				
Rim Size	“	21				
Vehicle Variants						
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**	
		Fuel 1	Fuel 2	Fuel 1	Fuel 2	
		20i	**20d**	30i	30d	
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV	
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance	
Drive type	-	4WD	4WD	4WD	4WD	
Engine Type	-	R	R	R	R	
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged	
Power	kW	135	140	185	195	
Torque	N m	290	400	350	620	
Battery Type	-	-				
Gearbox Type	-	Automatic	Automatic	Automatic	Automatic	
Cooling System Type	-	-	L-Pack	-	-	
Headlight Type	-	LED				
Red. Curb Weight	kg	1715	1750	1715	1820	
Load Capacity	kg	610	595	610	605	
Trailer Load	kg	2400	2400	2400	2400	
Maximum Velocity	km/h	215	213	240	240	
Acceleration Time	s	8.3	8.0	6.3	5.8	

Table E.7: Vehicle Data of the Hyundai Ioniq

Hyundai Ioniq, MY2016					
Body type	-	Low-Ground			
Basic Price	€	29.900			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	876	**Tire Type**	-	Normal Load
Prestige Measure	mm	425	**Lower Stiffener**	-	With
Wheelbase	mm	2700	**Hood Material**	-	Aluminum
Vehicle Width	mm	1820	**Hood Mechanism**	-	Passive
H30-Measure	mm	233			
Turning Circle	m	10.6			
Rim Size	"	18			

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		1.6 PHEV (8.9 kWh)			
Drivetrain Type	-	PHEV			
Performance Class	-	Entry/Medium			
Drive type	-	2WD			
Engine Type	-	R			
Fuel and Charging Type	-	Gas Nat. Aspirated			
Power	kW	77/45 (Max./Max.)			
Torque	N m	147/170 (Max./Max.)			
Battery Type	-	-			
Gearbox Type	-	Double Clutch			
Cooling System Type	-	Fullface			
Headlight Type	-	Xenon			
Red. Curb Weight	kg	1505			
Load Capacity	kg	390			
Trailer Load	kg	0			
Maximum Velocity	km/h	178			
Acceleration Time	s	10.6			

Table E.8: Vehicle Data of the Mercedes-Benz C-Class

Mercedes-Benz C-Class, MY2014					
Body type	-	Low-Ground			
Basic Price	€	34.914			

Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	789	**Tire Type**	-	Normal Load
Prestige Measure	mm	658	**Lower Stiffener**	-	Without
Wheelbase	mm	2840	**Hood Material**	-	Aluminum
Vehicle Width	mm	1810	**Hood Mechanism**	-	Active
H30-Measure	mm	260			
Turning Circle	m	11.2			
Rim Size	"	19			

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		C180	C180d	C400	C300d
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance
Drive type	-	2WD	2WD	4WD	4WD
Engine Type	-	R	R	V	R
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	115	85	245	180
Torque	N m	250	280	480	500
Battery Type	-	-			
Gearbox Type	-	Manual/Automatic	Manual/Automatic	Automatic	Automatic
Cooling System Type	-	Fullface	-	-	-
Headlight Type	-	Halogen			
Red. Curb Weight	kg	1320	1410	1570	1630
Load Capacity	kg	565	565	565	580
Trailer Load	kg	1400	1400	1800	1800
Maximum Velocity	km/h	225	205	250	250
Acceleration Time	s	8.2	11.1	4.9	5.7

Table E.9: Vehicle Data of the Mercedes-Benz E-Class

Mercedes-Benz E-Class, MY2016					
Body type	-	Low-Ground			
Basic Price	€	49.150			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	841	**Tire Type**	-	Normal Load
Prestige Measure	mm	656	**Lower Stiffener**	-	Without
Wheelbase	mm	2939	**Hood Material**	-	Aluminum
Vehicle Width	mm	1730	**Hood Mechanism**	-	Active
H30-Measure	mm	265			
Turning Circle	m	11.5			
Rim Size	“	20			

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		E200	**E220d**	E400	E400d
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance
Drive type	-	2WD	2WD	4WD	4WD
Engine Type	-	R	R	V	V
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	135	143	235	250
Torque	N m	300	400	480	700
Battery Type	-	-			
Gearbox Type	-	Automatic	Automatic	Automatic	Automatic
Cooling System Type	-	-	Fullface	-	-
Headlight Type	-	Halogen			
Red. Curb Weight	kg	1500	1640	1745	1830
Load Capacity	kg	640	635	640	640
Trailer Load	kg	1500	1500	2100	2100
Maximum Velocity	km/h	240	240	250	250
Acceleration Time	s	8.1	7.3	5.2	4.9

Table E.10: Vehicle Data of the Renault Zoe

Renault Zoe, MY2012					
Body type	-	Low-Ground			
Basic Price	€	32.990			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	836	**Tire Type**	-	Normal Load
Prestige Measure	mm	400	**Lower Stiffener**	-	With
Wheelbase	mm	2588	**Hood Material**	-	Steel
Vehicle Width	mm	1730	**Hood Mechanism**	-	Passive
H30-Measure	mm	359			
Turning Circle	m	10.6			
Rim Size	"	17			
Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		Q90 (22kWh)			
Drivetrain Type	-	BEV			
Performance Class	-	Entry			
Drive type	-	2WD			
Engine Type	-	SSM			
Fuel and Charging Type	-	-			
Power	kW	43 (Nom.)			
Torque	N m	145 (Nom.)			
Battery Type	-	Pouch			
Gearbox Type	-	Axially Parallel			
Cooling System Type	-	Fullface			
Headlight Type	-	Xenon			
Red. Curb Weight	kg	1427			
Load Capacity	kg	463			
Trailer Load	kg	0			
Maximum Velocity	km/h	135			
Acceleration Time	s	13.2			

*Evaluation as PSM, which is the only implemented synchronous machine type.

Table E.11: Vehicle Data of the Volkswagen Golf

Volkswagen Golf, MY2013						
Body type	-	Low-Ground				
Basic Price	€	18.075				
Exterior Dimensions			**Discrete Optimization Parameters**			
Front Overhang	mm	850	**Tire Type**	-	Normal Load	
Prestige Measure	mm	445	**Lower Stiffener**	-	With	
Wheelbase	mm	2620	**Hood Material**	-	Steel	
Vehicle Width	mm	1799	**Hood Mechanism**	-	Passive	
H30-Measure	mm	264				
Turning Circle	m	10.9				
Rim Size	"	19				
Vehicle Variants						
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**	
		Fuel 1	Fuel 2	Fuel 1	Fuel 2	
		1.4 TSI	2.0 TDI	2.0 GTI	2.0 GTD	
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV	
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance	
Drive type	-	2WD	2WD	2WD	2WD	
Engine Type	-	R	R	R	R	
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged	
Power	kW	103	110	169	135	
Torque	N m	250	340	350	380	
Battery Type	-	-				
Gearbox Type	-	Manual/Double-Clutch	Manual/Double-Clutch	Manual/Double-Clutch	Manual/Double-Clutch	
Cooling System Type	-	Fullface	-	-	-	
Headlight Type	-	Halogen				
Red. Curb Weight	kg	1193	1279	1289	1302	
Load Capacity	kg	512	506	486	473	
Trailer Load	kg	1700	1700	1800	1800	
Maximum Velocity	km/h	212	216	250	230	
Acceleration Time	s	8.4	8.6	6.4	7.5	

Table E.12: Vehicle Data of the Volkswagen e-Golf

Volkswagen e-Golf, MY2013					
Body type	-	Low-Ground			
Basic Price	€	34.900			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	850	**Tire Type**	-	Normal Load
Prestige Measure	mm	445	**Lower Stiffener**	-	With
Wheelbase	mm	2620	**Hood Material**	-	Steel
Vehicle Width	mm	1799	**Hood Mechanism**	-	Passive
H30-Measure	mm	264			
Turning Circle	m	10.9			
Rim Size	"	19			

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		e-Golf (24 kWh)			
Drivetrain Type	-	BEV			
Performance Class	-	Entry			
Drive type	-	2WD			
Engine Type	-	PSM			
Fuel and Charging Type	-	-			
Power	kW	50 (Nom.)			
Torque	N m	147 (Nom.)			
Battery Type	-	-			
Gearbox Type	-	Axially Parallel			
Cooling System Type	-	Fullface			
Headlight Type	-	Halogen			
Red. Curb Weight	kg	1510			
Load Capacity	kg	375			
Trailer Load	kg	0			
Maximum Velocity	km/h	140			
Acceleration Time	s	10.4			

Table E.13: Vehicle Data of the Volkswagen Passat

Volkswagen Passat, MY2014						
Body type	-	Low-Ground				
Basic Price	€	31.674				
Exterior Dimensions			**Discrete Optimization Parameters**			
Front Overhang	mm	879	**Tire Type**	-	Normal Load	
Prestige Measure	mm	433	**Lower Stiffener**	-	With	
Wheelbase	mm	2786	**Hood Material**	-	Steel	
Vehicle Width	mm	1832	**Hood Mechanism**	-	Passive	
H30-Measure	mm	261				
Turning Circle	m	11.7				
Rim Size	“	19				

Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		1.8 TSI	2.0 TDI	2.0 TSI	**2.0 TDI**
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance
Drive type	-	2WD	2WD	4WD	4WD
Engine Type	-	R	R	R	R
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	132	110	206	176
Torque	N m	250	340	350	500
Battery Type	-	-			
Gearbox Type	-	Manual/Double-Clutch	Manual/Double-Clutch	Double-Clutch	Double-Clutch
Cooling System Type	-	-	-	-	Fullface
Headlight Type	-	Halogen			
Red. Curb Weight	kg	1430	1465	1599	1660
Load Capacity	kg	585	600	576	575
Trailer Load	kg	2000	2000	2200	2200
Maximum Velocity	km/h	230	211	250	238
Acceleration Time	s	8.1	8.9	5.7	6.3

Table E.14: Vehicle Data of the Volkswagen Tiguan

Volkswagen Tiguan, MY2016					
Body type	-	High-Ground			
Basic Price	€	26.975			
Exterior Dimensions			**Discrete Optimization Parameters**		
Front Overhang	mm	896	**Tire Type**	-	Normal Load
Prestige Measure	mm	437	**Lower Stiffener**	-	With
Wheelbase	mm	2677	**Hood Material**	-	Steel
Vehicle Width	mm	1839	**Hood Mechanism**	-	Active
H30-Measure	mm	344			
Turning Circle	m	11.5			
Rim Size	“	19			
Vehicle Variants					
Vehicle Variant		**Regular 1**	**Regular 2**	**Maximum 1**	**Maximum 2**
		Fuel 1	Fuel 2	Fuel 1	Fuel 2
		1.4 TSI	**2.0 TDI**	2.0 TSI	2.0 TDI
Drivetrain Type	-	ICEV	ICEV	ICEV	ICEV
Performance Class	-	Entry/Medium	Entry/Medium	Performance	Performance
Drive type	-	4WD	4WD	4WD	4WD
Engine Type	-	R	R	R	R
Fuel and Charging Type	-	Gas Supercharged	Diesel Supercharged	Gas Supercharged	Diesel Supercharged
Power	kW	110	110	162	176
Torque	N m	250	340	350	500
Battery Type	-	-			
Gearbox Type	-	Manual/Double-Clutch	Manual/Double-Clutch	Double-Clutch	Double-Clutch
Cooling System Type	-	-	Fullface	-	-
Headlight Type	-	LED			
Red. Curb Weight	kg	1495	1590	1680	1805
Load Capacity	kg	600	645	605	550
Trailer Load	kg	2200	2200	2500	2500
Maximum Velocity	km/h	200	201	223	228
Acceleration Time	s	9.4	9.3	6.8	6.7

Appendix F LDS Results

		Regular-Variants				Maximum-Variants			
		Fuel 1		Fuel 2		Fuel 1		Fuel 2	
		Manual	Automatic	Manual	Automatic	Manual	Automatic	Manual	Automatic
ICEV									
AUDI A4	∆ Max. Engine Power in %	18	18	-5	-5	-	0	-	11
	∆ Max. Engine Torque in %	0	0	-2	-2	-	0	-	0
AUDI A6	∆ Max. Engine Power in %	-	8	-	-10	-	4	-	-10
	∆ Max. Engine Torque in %	-	1	-	1	-	0	-	-8
AUDI A8	∆ Max. Engine Power in %	-	4	-	-5	-	-8	-	-6
	∆ Max. Engine Torque in %	-	0	-	0	-	-1	-	0
BMW 7 Series	∆ Max. Engine Power in %	-	11	-	3	-	2	-	-13
	∆ Max. Engine Torque in %	-	1	-	-3	-	-1	-	1
BMW X3	∆ Max. Engine Power in %	-	11	-	7	-	0	-	5
	∆ Max. Engine Torque in %	-	-1	-	12	-	2	-	-1
MB C-Class	∆ Max. Engine Power in %	13	13	0	0	-	2	-	-8
	∆ Max. Engine Torque in %	0	0	-9	-9	-	0	-	-1
MB E-Class	∆ Max. Engine Power in %	-	15	-	15	-	2	-	-6
	∆ Max. Engine Torque in %	-	-1	-	24	-	0	-	1
VW Golf	∆ Max. Engine Power in %	26	26	5	5	7	7	-7	-7
	∆ Max. Engine Torque in %	0	0	1	1	-1	-1	-1	-1
VW Passat	∆ Max. Engine Power in %	-2	-2	0	0	-	-8	-	-6
	∆ Max. Engine Torque in %	0	0	-3	-3	-	4	-	-1
VW Tiguan	∆ Max. Engine Power in %	14	14	5	5	-	11	-	-6
	∆ Max. Engine Torque in %	-4	-4	1	1	-	-1	-	-4
HEV									
BMW 5 Series	∆ Max. Engine Power in %	-	4	-	-	-	-6	-	-4
	∆ Max. Engine Torque in %	-	-7	-	-	-	0	-	-1
	∆ Nom. Machine Power in %	-	-28	-	-	-	-	-	-
	∆ Nom. Machine Torque in %	-	3	-	-	-	-	-	-
Hyundai Ioniq	∆ Max. Engine Power in %	-	-35	-	-	-	-	-	-
	∆ Max. Engine Torque in %	-	-18	-	-	-	-	-	-
	∆ Nom. Machine Power in %	-	11	-	-	-	-	-	-
	∆ Nom. Machine Torque in %	-	26	-	-	-	-	-	-
BEV									
Renault Zoe	∆ Nom. Machine Power in %	-	-13	-	-	-	-	-	-
	∆ Nom. Machine Torque in %	-	-22	-	-	-	-	-	-
VW e-Golf	∆ Nom. Machine Power in %	-	-2	-	-	-	-	-	-
	∆ Nom. Machine Torque in %	-	0	-	-	-	-	-	-

Figure F.1: Deviation between the calculated and the actual engine power and torque (Fuel Type 1: Gas or Gas Hybrid; Fuel Type 2: Diesel or Diesel Hybrid)

Appendix G Dimension Deviations

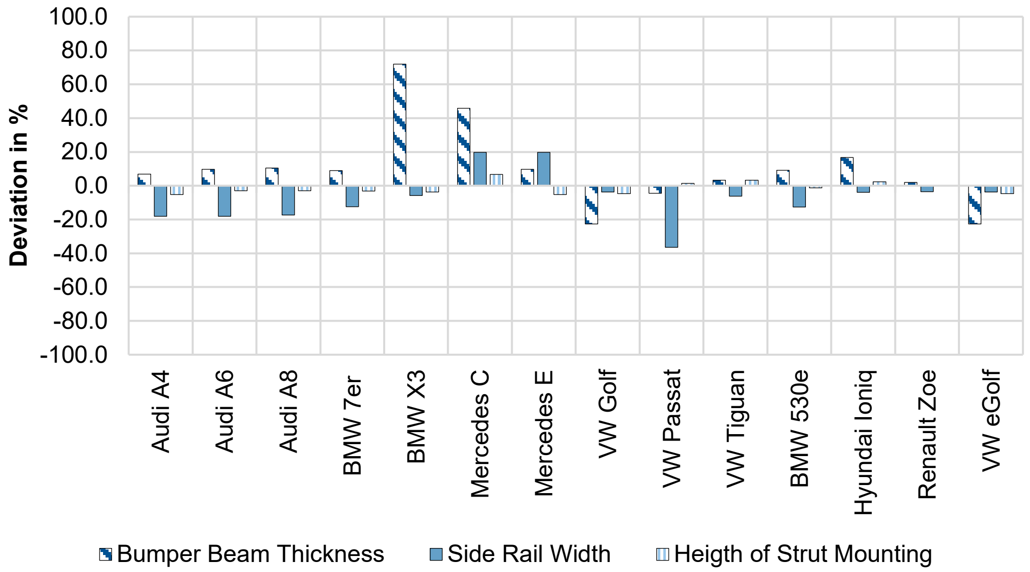

Figure G.1: Deviations between the calculated and the actual body dimensions

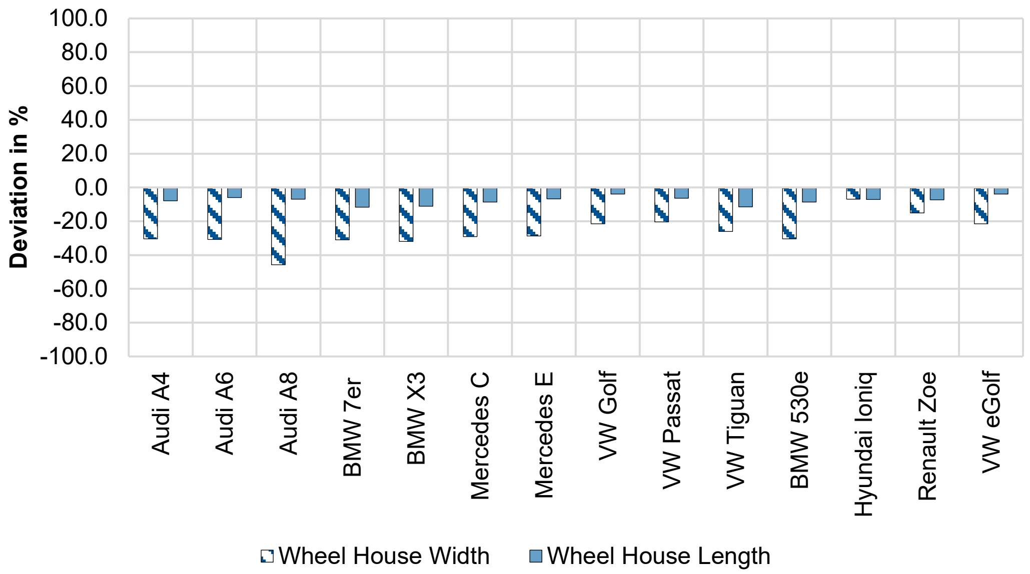

Figure G.2: Deviations between the calculated and the actual wheel house dimensions

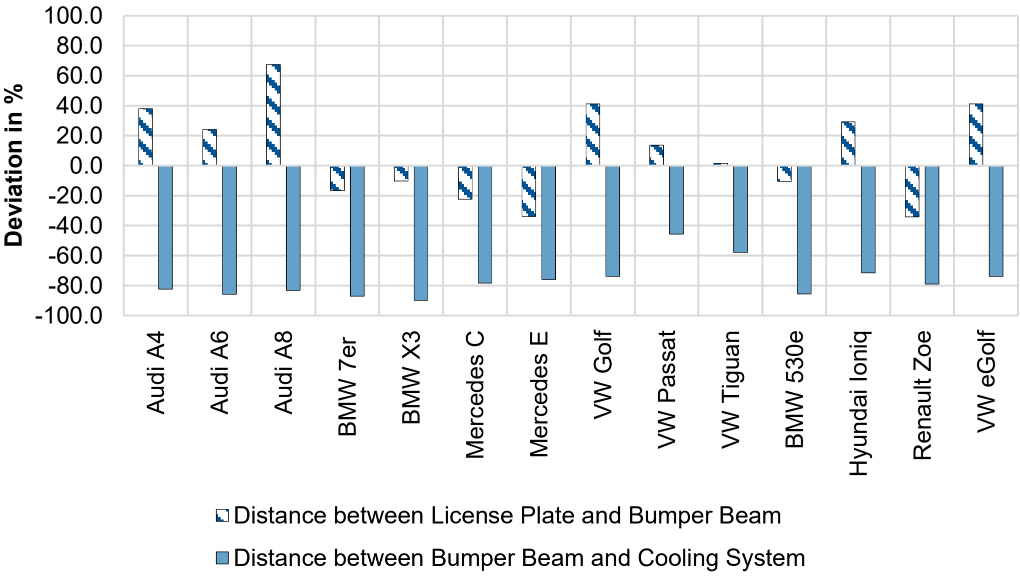

Figure G.3: Deviations between the calculated and the actual distances in front and behind the bumper beam

Appendix H Architecture Results

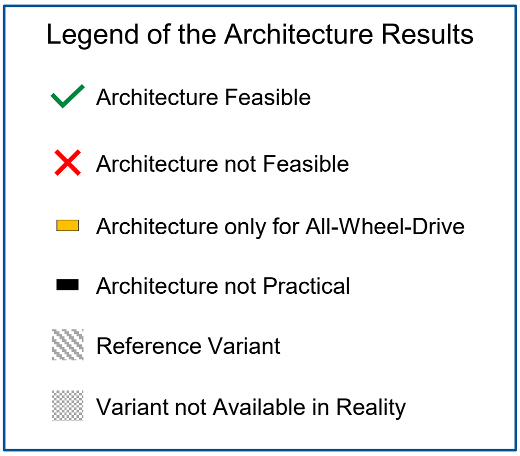

Figure H.1: Figure caption for the following architecture results

MSM			AUDI A4 – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

MSM			AUDI A4 – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✓	✓	✓	✓					✓		✓			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✓	✓	✓	✓					✓		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

Figure H.2: Resulting vehicle architectures for the AUDI A4

MSM			AUDI A6 – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
Front	McPherson	Transversal		✗		✗					✗		✗			
Front	Multi-Link	Longitudinal		✗		✗					✗		✗			
Front	Multi-Link	Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
Rear	McPherson	Transversal		✗		✗					✗		✗			
Rear	Multi-Link	Longitudinal		✗		✗					✗		✗			
Rear	Multi-Link	Transversal		✗		✗					✗		✗			

MSM			AUDI A6 – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
Front	McPherson	Transversal		✗		✗					✗		✗			
Front	Multi-Link	Longitudinal		✓		✓					✓		✓			
Front	Multi-Link	Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
Rear	McPherson	Transversal		✗		✗					✗		✗			
Rear	Multi-Link	Longitudinal		✓		✓					✓		✗			
Rear	Multi-Link	Transversal		✗		✗					✗		✗			

Figure H.3: Resulting vehicle architectures for the AUDI A6

MSM			AUDI A8 – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			

MSM			AUDI A8 – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✓		✓					✓		✓			
		Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✓		✗					✗		✗			
		Transversal		✗		✗					✗		✗			

Figure H.4: Resulting vehicle architectures for the AUDI A8

MSM			BMW 5 – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
	Multi-Link	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
Rear	McPherson	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
	Multi-Link	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			

MSM			BMW 5 – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
	Multi-Link	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
Rear	McPherson	Longitudinal					✗				✗		✗			
		Transversal					✗				✗		✗			
	Multi-Link	Longitudinal					✓				✓		✓			
		Transversal					✗				✗		✗			

Figure H.5: Resulting vehicle architectures for the BMW 5 Series

MSM			BMW 7 – Stage 1														
			Regular							Maximum							
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
Front	McPherson	Transversal		✗		✗					✗		✗			
Front	Multi-Link	Longitudinal		✗		✗					✗		✗			
Front	Multi-Link	Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
Rear	McPherson	Transversal		✗		✗					✗		✗			
Rear	Multi-Link	Longitudinal		✗		✗					✗		✗			
Rear	Multi-Link	Transversal		✗		✗					✗		✗			

MSM			BMW 7 – Stage 2														
			Regular							Maximum							
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
Front	McPherson	Transversal		✗		✗					✗		✗			
Front	Multi-Link	Longitudinal		✗		✓					✗		✗			
Front	Multi-Link	Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
Rear	McPherson	Transversal		✗		✗					✗		✗			
Rear	Multi-Link	Longitudinal		✓		✓					✓		✓			
Rear	Multi-Link	Transversal		✗		✗					✗		✗			

Figure H.6: Resulting vehicle architectures for the BMW 7 Series

MSM			BMW X3 – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✓		✗					✗		✗			
		Transversal		✓		✓					✓		✗			
	Multi-Link	Longitudinal		✓		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✓		✓					✓		✓			
		Transversal		✓		✓					✓		✓			
	Multi-Link	Longitudinal		✓		✓					✓		✓			
		Transversal		✗		✗					✗		✗			

Figure H.7: Resulting vehicle architectures for the BMW X3

MSM			Hyundai Ioniq – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal					✗									
		Transversal					✗									
	Multi-Link	Longitudinal					✗									
		Transversal					✗									
Rear	McPherson	Longitudinal					✗									
		Transversal					✗									
	Multi-Link	Longitudinal					✗									
		Transversal					✗									

MSM			Hyundai Ioniq – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal					✓									
		Transversal					✓									
	Multi-Link	Longitudinal					✓									
		Transversal					✗									
Rear	McPherson	Longitudinal					✗									
		Transversal					✗									
	Multi-Link	Longitudinal					✗									
		Transversal					✗									

Figure H.8: Resulting vehicle architectures for the Hyundai Ioniq

MSM			MB C-Class – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

MSM			MB C-Class – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✓	✓	✓	✓					✓		✓			
		Transversal	✗	✗	✗	✗					✗		✗			

Figure H.9: Resulting vehicle architectures for the Mercedes-Benz C-Class

MSM			MB E-Class – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			

MSM			MB E-Class – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
Rear	McPherson	Longitudinal		✗		✗					✗		✗			
		Transversal		✗		✗					✗		✗			
	Multi-Link	Longitudinal		✓		✓					✓		✓			
		Transversal		✗		✗					✗		✗			

Figure H.10: Resulting vehicle architectures for the Mercedes-Benz E-Class

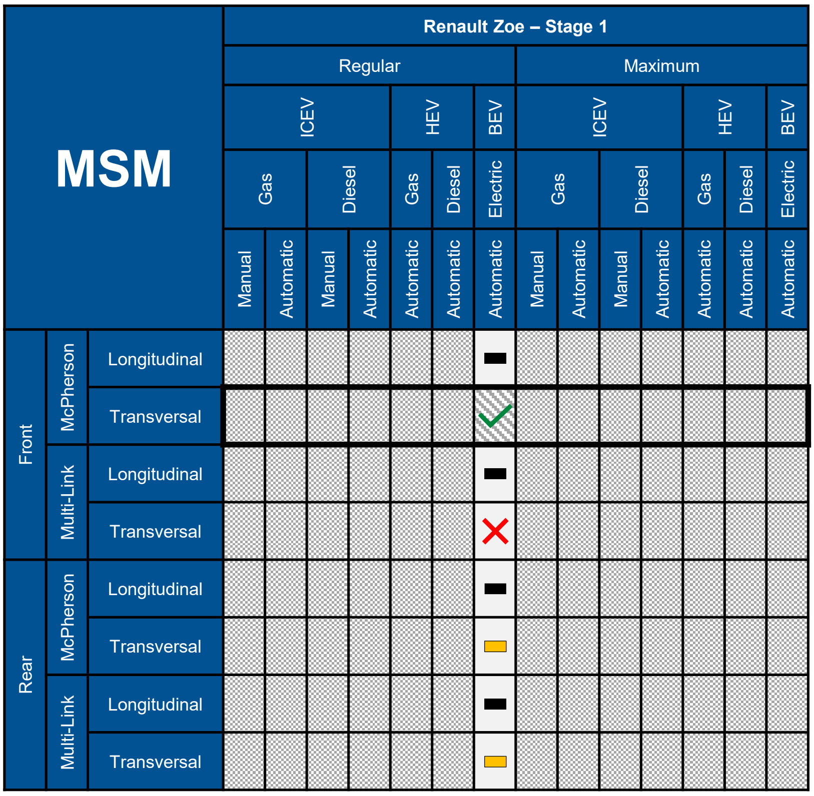

Figure H.11: Resulting vehicle architectures for the Renault Zoe

MSM			Volkswagen Golf – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✓	✗	✓	✗			▬	✗	✗	✗	✗			
		Transversal	✓ (hatched)	✗	✗	✗			✓	✓	✗	✗	✗			
	Multi-Link	Longitudinal	✓	✗	✓	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			✓	✗	✗	✗	✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			▬ (yellow)	✗	✗	✗	✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			▬ (yellow)	✗	✗	✗	✗			

MSM			Volkswagen Golf – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✓	✗	✓	✗			▬	✗	✗	✗	✗			
		Transversal	✓ (hatched)	✓	✓	✓			✓	✓	✓	✓	✓			
	Multi-Link	Longitudinal	✓	✗	✓	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			✓	✗	✗	✗	✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			▬ (yellow)	✗	✗	✗	✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗			▬	✗	✗	✗	✗			
		Transversal	✗	✗	✗	✗			▬ (yellow)	✗	✗	✗	✗			

Figure H.12: Resulting vehicle architectures for the Volkswagen Golf

MSM			Volkswagen Passat – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✓	✗	✓	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

MSM			Volkswagen Passat – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✓	✓	✓	✓					✓		✓			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

Figure H.13: Resulting vehicle architectures for the Volkswagen Passat

MSM			Volkswagen Tiguan – Stage 1													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✓	✓	✓	✓					✓		✗			
		Transversal	✓	✓	✓	✓					✓		✗			
	Multi-Link	Longitudinal	✓	✓	✓	✓					✓		✗			
		Transversal	✓	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

MSM			Volkswagen Tiguan – Stage 2													
			Regular							Maximum						
			ICEV				HEV		BEV	ICEV				HEV		BEV
			Gas		Diesel		Gas	Diesel	Electric	Gas		Diesel		Gas	Diesel	Electric
			Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic	Manual	Automatic	Manual	Automatic	Automatic	Automatic	Automatic
Front	McPherson	Longitudinal	✓	✓	✓	✓					✓		✓			
		Transversal	✓	✓	✓	✓					✓		✓			
	Multi-Link	Longitudinal	✓	✓	✓	✓					✓		✓			
		Transversal	✓	✗	✗	✗					✗		✗			
Rear	McPherson	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			
	Multi-Link	Longitudinal	✗	✗	✗	✗					✗		✗			
		Transversal	✗	✗	✗	✗					✗		✗			

Figure H.14: Resulting vehicle architectures for the Volkswagen Tiguan