Powertrain dimensioning of electrified vehicle concepts based on a synthesis

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Abstract—The amount of possible concepts for the electrification of conventional powertrains leads to an increasing complexity of the future powertrain developments. In order to find new promising concepts a tool chain for the simulation, evaluation and optimization is being developed by the Institute of Automotive Engineering (IAE) and the Audi AG. The tool chain allows a methodical examination of new powertrains.

In this paper we present the first two fundamental sections of the tool chain which are the synthesis of new topologies and an automated powertrain dimensioning. An outlook of the further tool chain sections are the simulation, evaluation and optimization of the powertrains which will be given as well. In addition an optimal electric range considering the WLTP is examined.

In the long term this methodical and reproducible approach can contribute to the fulfilment of product requirements, while reducing development time and cost.

Keywords: Drivetrain topologies, customer requirements, CO_2-efficiency

I. INTRODUCTION

Alternative and fuel-efficient drive systems have become an increasing focus of public perception. This development is caused by stricter legal emission, by uncertainty regarding the market for raw materials and in perspective rising fuel prices. Therefore at the core of current research and development is among others the electrification of the powertrain.

Between vehicles powered exclusively by an internal combustion engine and electric vehicles (EV) a broad field has opened for a variety of hybrid technologies with variable complexity and degree electrification. In order to achieve future emission requirements electrification and, therefore, complexity of the propulsion systems will continue to rise. But electrification of the powertrain or individual components also creates a high cost pressure. The following objectives, and their conflicts, must be addressed:

1. Legal regulations controlling emissions become gradually more stringent
2. Cost of development and implementation of additional technology in the vehicle
3. Relevant customer vehicle characteristics

To resolve a compromise, depending on regional and market conditions must be found. Besides dynamic key component development the predominant power industry and infrastructure, as well as the mobility demands and customer habits play a decisive role. Depending on parameters and requirements several drive concepts with variable degree of electrification may be relevant for the optimal use in the vehicle.

The variety of electrification concepts - starting with micro hybrids over plug-in hybrid electric vehicles (PHEV) to battery (BEV) and fuel cell electric vehicle (FCEV) - makes development highly complex, complicated and expensive. Thus the aim of this scientific work is to develop a computer-based tool chain for preliminary drivetrain dimensioning and methodological synthesis of electrified drive systems which subsequently are automatically analyzed and evaluated.

The overall project, to achieve this goal, is therefore divided into four subprojects:

Within the first subproject powertrain requirements are country-specific analyzed and determined. To determine the requirements driving cycles for different types of drivers and driving environments from EU, China, and United States are created. Based on the driving cycles, demand maps assess the relevance of the respective load ranges. Further dynamic requirements are identified that characterize the acceleration behavior in various speed ranges. In addition to the described country-specific requirements test procedure cycles such as NEDC or WLTC are taken as a basis as well.

The second subproject deals with the determination of functional hybrid requirements. Based on the results of the first subproject the different driving profiles and requirements are examined regarding hybrid functions. Since efficiency and performance increasing features of a hybrid drive work in different load ranges and are dependent on topology, the question arises as to what features are primarily relevant rather than subordinate. The result of the second subproject is a catalogue of evaluated hybrid functions for each of the three core regions.

The third subproject is the design of future powertrain concepts. The results of the previous subprojects are prerequisite for the design and evaluation of new powertrains and topologies. To find the best electrified drivetrain for the given requirements it is crucial to consider and evaluate the whole solution space of possible powertrains. Therefore key components are implemented using a methodical synthesis of drivetrain topologies. The computer-based synthesis allows it to analyze a large number of possible powertrains in an order of best fulfilment. For each core region the most promising powertrain topologies for electric and hybrid vehicles are defined and evaluated.

The last subproject concludes the powertrain development with parameter optimization. After design and selection of defined powertrain concepts the respective basic powertrain parameters are varied until an optimum in terms of a specified evaluation function is found. This includes not only performance variation of the drive machine, but also number and increment modification of transmission gears. The powertrains found by optimization are both analyzed and evaluated with respect to consumption and dynamics using simulation.

The main result of the project is a tool chain to create a selection of drivetrains that are optimized for the core markets EU, China, and United States according to the respective customer requirements.

II. Tool Chain

The structure of the tool chain is corresponding to the subprojects. The flowchart of the tool chain is shown in Figure 1. The tool chain consists of five basic tools. The tools are highlighted with a gear icon and will be described into detail later on.

The start of the tool chain is in the top left corner. Main input variables of the tool chain are the vehicle, the requirements, the hybrid functions and the synthesis. In the vehicle input consists of all basic vehicle parameters such as the mass without the powertrain, the drag coefficient or the frontal area. The requirement and the hybrid function input were developed within the first two subprojects. The requirement input includes basic vehicle requirements such as maximum velocity or the electric range in a legal cycle. Within the hybrid function catalogue objectives arising from the hybrid functions such as recuperation or boosting are listed. An exemplary objective is the capability of the drivetrain to recuperate a certain amount of energy in a cycle or customer operations. The fourth and last necessary input to obtain discrete topologies is the synthesis tool.

The discrete topologies as well as the vehicle, the requirements and the hybrid function catalogue are the input for the second tool, the powertrain dimensioning. The dimensioned vehicles with their powertrains are input for the simulation tool, in which the fuel consumption in legal cycles and in customer cycles as well are measured. Subsequently after the simulation follows the rating tool, in which the

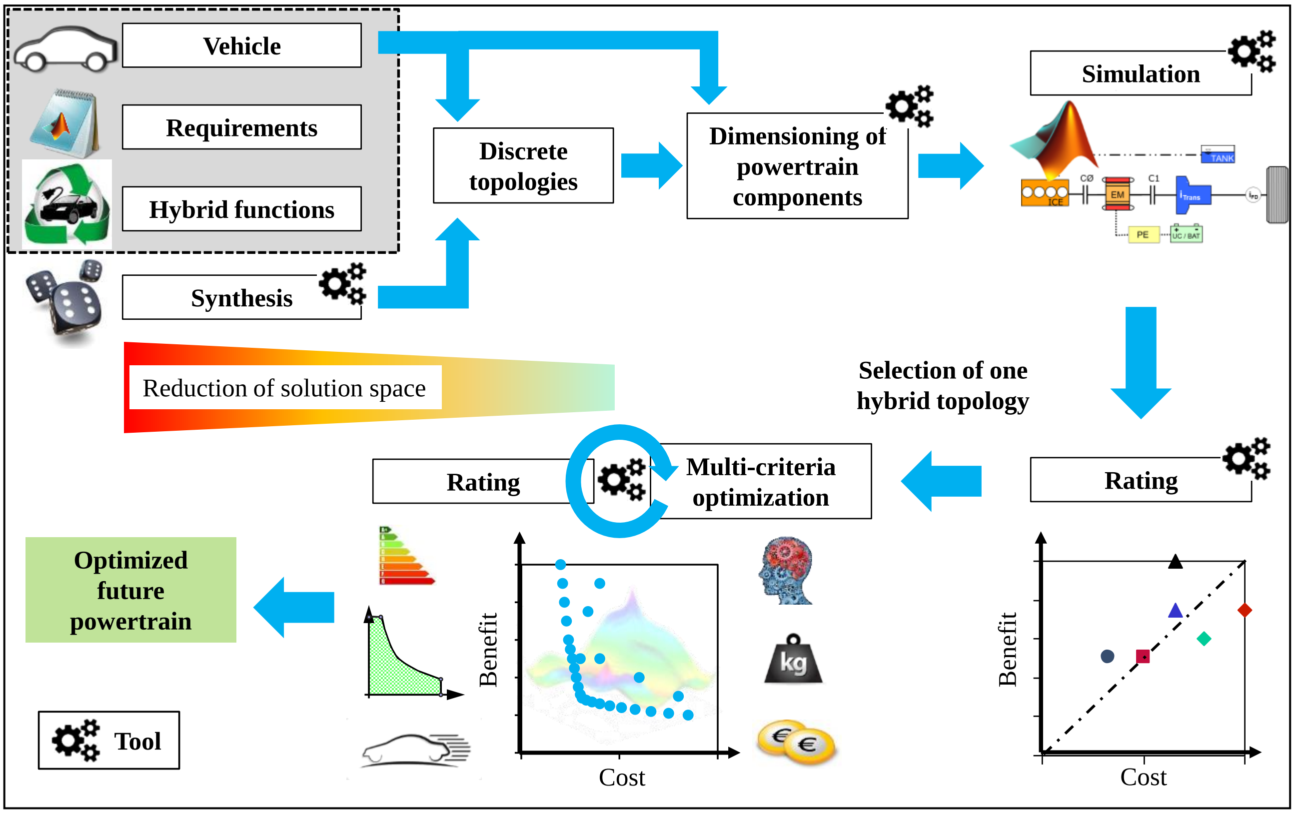

Figure 1: Tool chain for the identification of new optimized hybrid powertrains

different drive trains are evaluated. Evaluation criterions are for example the powertrain expenditure, the weight or the demand map coverage. Aim of the rating tool is to display the different powertrains in a two dimensional space which consists on the one hand of drivetrain benefits and on the other hand of the powertrain expenditure. Based on the evaluation one promising hybrid powertrain will be selected for further optimization and evaluation. The tool chain concludes with an optimized future powertrain.

III. SYNTHESIS

Introduction resp. General Synthesis Process

A variety of synthesis methods are used today for the development of powertrains. These can also be applied for the development of electrified vehicles by adaption and expansion. In most cases, there are methods for the development of individual components, such as transmission synthesis for power split hybrid transmissions [1] or the optimization of electric traction motors [2]. Other methods have their focus on energy optimization of given drive systems [3] or the spatial integration of drive components at minimum volume and cost (inter alia [4]). Therefore the existing methods emphasize certain drive components or known drive topologies.

The automated conceptual design of new drive topologies to address changing framework conditions has so far focused on a stringent and undivided flow of energy from the power source (e.g. tank) to the drive wheels (see [5]). Thus, a parallel or divided flow of energy, as it mostly is found in hybrid drive systems, cannot be considered. Hybrid vehicles are subdivided into micro- to plug-in hybrids by the level of electrification and into parallel, serial or power split hybrids by the component topology. Depending on the type of drive train and degree of electrification the interaction of various key components with different properties and parameters specify the electrified powertrain.

Basis and Development of a Topology Synthesis

In order to produce an automated synthesis of electrified powertrains, the system "electrified powertrain" and its limits has to be defined and all synthesis relevant drive components and assemblies has to be determined (see [6]). The components are assigned to the respective drivetrain concepts, their characteristics and functionalities, as well as their technological parameters and characteristics. The resulting component catalogue is then completed by a theoretical consideration of the components of different drive systems. For example, any power-split hybrid can be reduced to the three basic types input split, output split, and multi-mode power split. Power split drivetrains with varying complexity are always composed of at least one power-split element, a variator, node elements, and, optionally, gear sets and actuators [1]. By varying these and other basic elements, such as their number and arrangement, hybrid drive structures can be automatically analyzed and synthesized.

The Component Catalog

A component catalog can be produced by collecting information on various drive components or assemblies and the associated technology parameters and their characteristics. This would include energy converters and energy storage systems, actuators, gear sets and torque converters, therefore containing all kind of relevant powertrain components. The component catalog corresponds to a disordered “morphological matrix” [7] which can be reduced or expanded by the users filter settings according to the desired functionalities. Each component in this catalog is introduced with its "linking-relevant" parameters - inputs and outputs. For this purpose, a struct is created with the name of the component and all relevant input and output parameters are saved in an array format. From this point onward, the components are considered as black boxes, and therefore reduced to their inputs and outputs. Accordingly, two components can be combined, if the output parameters (for example, interval of speed and torque) of one component fits together with the corresponding inputs of the other component.

The Compatibility Matrix

In classic methodical engineering design working principles (possible physical implementation of a desired sub-function) must be combined manually into a theoretically possible overall solution. Each working principle or each component needs to be checked for compatibility. For large solution spaces it can take considerable time and resources to complete. After combining all sub-functions into a working structure, concretization will lead to a principle solution. [7] While this leads only to some solutions to the problem at hand, it does not guarantee to detect all theoretically possible working structures or even to create the optimal solution.

	Traction	Gear set	Knot	Electric motor	Battery	Generator	Split element	ICE	Tank
Traction		**1**	**1**	**1**	0	0	**1**	**1**	0
Gear set			**1**	**1**	0	0	**1**	**1**	0
Knot	**Traction interface**	**1**		**1**	0	0	**1**	**1**	0
Electric motor		0	0		**1**	**1**	0	0	0
Battery		0	0	0		**1**	0	0	0
Generator		**1**	**1**	**1**	0		**1**	**1**	0
Split element		**1**	**1**	**1**	0	0		**1**	0
ICE		0	0	0	0	0	0		**1**
Tank			**Energy storage**						

Figure 2: Simplified compatibility matrix for the Toyota Prius concept

On the basis of clearly defined input and output values of each component, the computer-aided synthesis automatically analyzes the compatibility of all selected components and stores the result in a compatibility matrix. If all valid and utilitarian combinations starting with an energy source and ending with the traction interface are created, the result is a variety of element chains – i.e. a stringent succession of components from a power source to the drive wheels (see [5]). By means of the synthesis of drive components to element chains, stringent drive concepts like the conventional drive, the serial hybrid drive and the purely electric drive can be achieved. Parallel and power-split drives are not taken into account by this method.

To create power-split and parallel hybrids it is necessary to define power splitting elements and node elements which must be added to the component catalog. A node element may be a shaft which is driven by both the combustion engine and an electric motor. Among other things, a road can also be a node

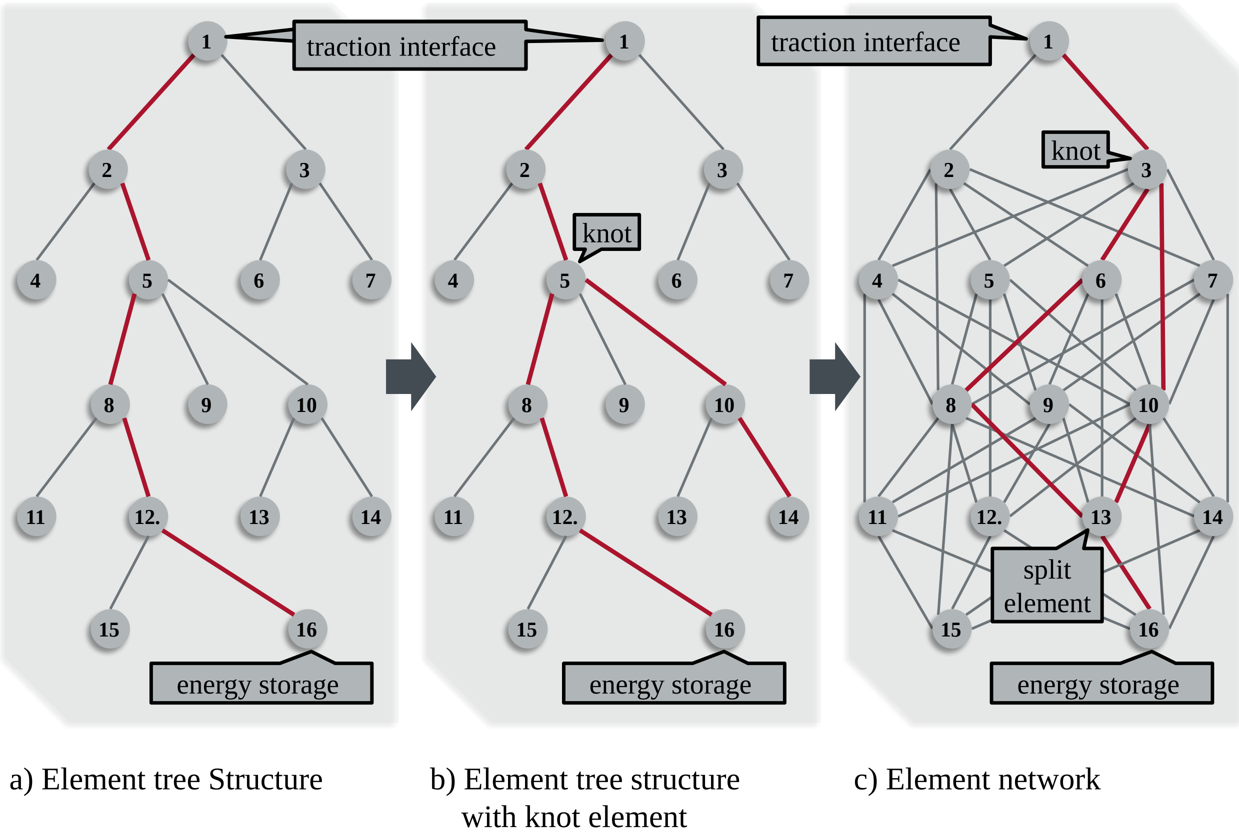

Figure 3: Element tree and element network

element by combining the power of axle-split concepts or the wheel hub drive. In addition to the classical planetary gear set, it is necessary for the power split element to also allow the access of different electrical components (e.g. electric motors) to a single component (e.g. battery). The variety of combination possibilities, including a limited number of power split and node elements for the synthesis tool are constituted mathematically in form of an n x n matrix. This compatibility matrix contrasts the inputs relative to the outputs of all components. With a simple binary display all combination options can be stored and methodically varied for the following synthesis. As an example, Figure 2 shows the components and combination possibilities of a simplified Toyota Prius concept. In the rows of the compatibility matrix the outputs of the components can be found and in the columns the inputs. Those components with non-zero entry labels can be combined.

The Synthesis Process

The starting point of the computer-aided synthesis is always the traction interface of the vehicle, herein defined as a pair of drive wheels or as a group of individually driven wheels. All common forms of propulsion such as front-wheel, rear-wheel and four-wheel drive can be chosen. Regardless of the complexity of future powertrains, the traction interface provides a constant and unchanging common denominator, which must be present in any topology. Based on the stored data in the compatibility matrix, all possible combinations between the traction interface and the other components are determined. Each combination is saved as a new possible solution and serves as a starting point for the next step of the synthesis. According to the compatibility matrix, this process will be continued until all combination options have reached a source, i.e. a tank, a battery, or other energy storage systems. All combination options form an element tree structure (see Figure 3: a). Therefore, each combination path starting from the traction interface to a source provides a solution for a possible propulsion topology. In Figure 2 the development from an element tree structure to an element network is shown and described hereafter.

The synthesis process detects all possible stringent combination variants which already represent conventional and serial hybrid drives. In addition, each variant is not only checked to see which component can be combined with the last element in a path. If a node element is installed, the two single-paths and the junction path itself will be stored as a variant. Thus the possible alternative solutions are being extended by parallel drive topologies. Figure 3: b) Element tree structure with knot element

In addition, with each new combination is also tested whether other existing element chains can be merged via a power split element. If this is the case, the examined element chains can also be saved as a power-split drive variant. Compared to the element tree structure all the elements, including within existing element chains are now checked for compatibility among themselves. Starting from the traction interface an element network is generated, which can include serial, parallel, power-split hybrid drive topologies and also a composition of them. Thus the synthesis allows to generate not only common hybrid drives like a P2-Hybrid, but "Dedicated Hybrid Drives", which includes Dedicated Hybrid Transmission (DHT) as well. Figure 3: c) Element network structure

Complementary Logic

In the first step the pure synthesis process detects all combination paths and takes only the compatibility of the components with one another into consideration. After every combination process the best solution out of all the combination paths will be identified. The identification is based on a multi-stage-optimize search strategy (see [6]). The expansion of the element tree structure to a network element may be referred to as a complex network-optimize search strategy. In a further step, the actual assessment and evaluation of the found variants is preceded by a preliminary analysis. By the user specified constraints can be implemented that affect the synthesis process directly. Topologies with more than two electric motors or energy transformations may be excluded or a respective drive form for the front and the rear axle may be approved. The user has the possibility to vary freely these and other limitations. The synthesis process is cyclically performed and therefor the impact of user-defined guideline implemented directly. So it is a cyclical network-optimize search strategy.

Save and Transfer Synthesis Data

Similar to the compatibility matrix the synthesized driving topologies are stored in matrix format. Using dynamic variables the component combinations are written into a matrix. This data format enables the following programs in the toolchain to read out all the necessary information. On the basis of empty rows or columns traction interface and energy storage can be identified, because they do not have an exit or rather an entrance. If there are several nonzero entries in a row, this element has more than one exit, therefore it has to be a power split element. If there are several non-zero entries in a column, it has to be a node element.

IV. Powertrain Dimensioning Tool

For the simulation, evaluation and optimization of different hybrid powertrains the main components (drivetrain, engine, electric motor and battery) have to be dimensioned according to the vehicle requirements and objectives arising from hybrid functions. The dimensioning of the components is constrained to the vehicle as well, resulting in different components for different vehicles in different vehicle classes. In order to analyze a variety of hybrid powertrains for several vehicles a tool was developed at the Institute of Automotive Engineering (Braunschweig University of Technology) to automatically

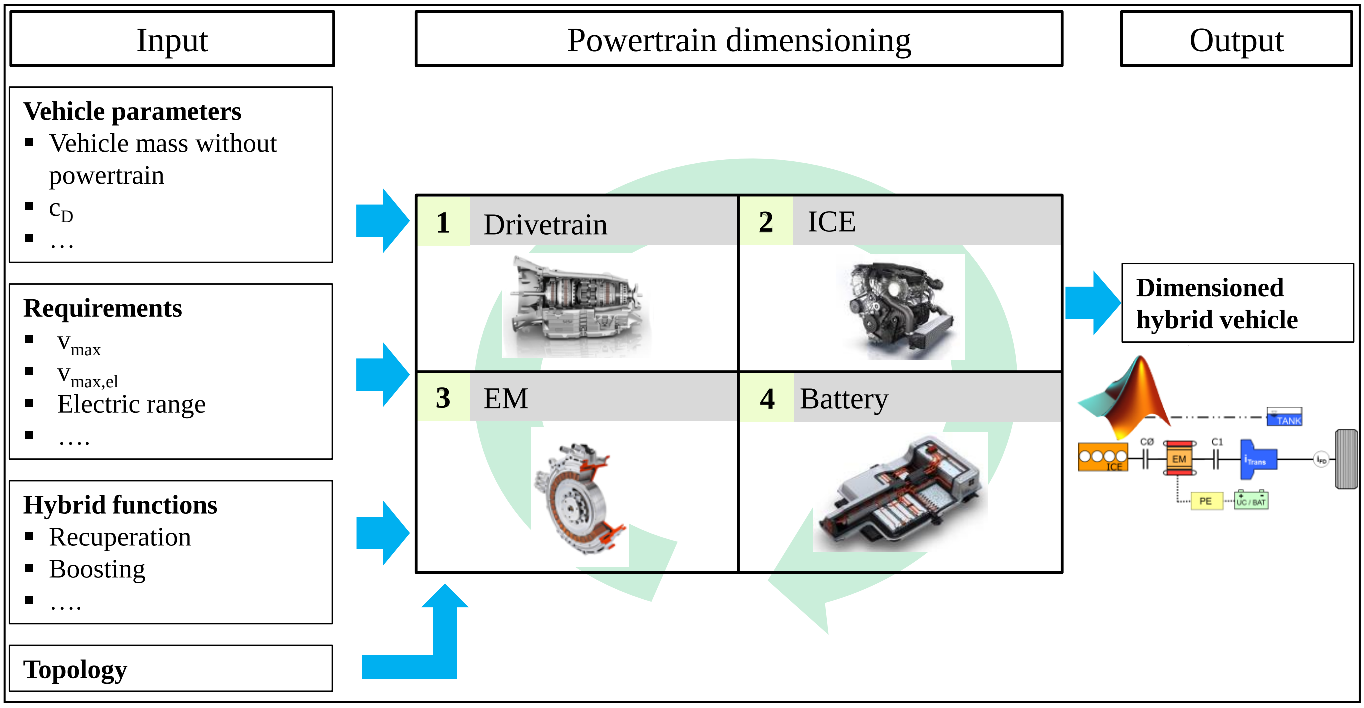

Figure 4: Tool for automated powertrain dimensioning

dimension the powertrain components regarding the given input. The flowchart of the tool is shown in Figure 4.

Four input cluster are necessary for the automated powertrain dimensioning tool. The first cluster consists of the basis vehicle parameters such as the mass without the powertrain or drag coefficient. Within the second cluster the vehicle requirements are listed such as the maximum velocity, the maximum electrical velocity or the electric range within a legal cycle. The third cluster includes the objectives arising from the hybrid functions such as recuperation or boosting. An exemplary objective is the capability of the drivetrain to recuperate a certain amount of energy in a cycle or customer operations. The fourth and last required input is the hybrid powertrain topology.

The configuration of the powertrain components consists of four steps which follow one another. In each step the necessary performance and the connected mass are calculated by the use of constant weight factors as well as constant efficiency factors for the drivetrain. In the first step the masses for drivetrain components such as transmission, crank shaft, clutches or axle transmission are calculated. In the second step, the peak power of the ICE is calculated regarding the maximum velocity and boosting potential. The ICE dimensioning is succeeded by the electric motor dimensioning. Thereby the recuperation potential as well as the maximum electrical velocity are taken into account. In the final step the battery of the hybrid vehicle is calculated. The crucial factor for the battery dimensioning is the electric range achieved in a legal cycle or customer use. In order to dimension the battery the usable capacity is considered as well as recuperation in the cycle to avoid an oversizing. The four powertrain dimensioning steps are carried out in a loop to include spiral effects and to ensure that the vehicle requirements are met. The battery for example has to include the capacity for its own weight. Furthermore the necessary ICE performance rises with an increasing weight. The output of the tool is a dimensioned hybrid vehicle powertrain which can be simulated with a simulation tool and further evaluated.

For the validation of the tool, two existing hybrid vehicles were dimensioned on the basis of the given requirements by the manufacturer. Two vehicles are dimensioned with the tool and compared with the real vehicles, shown in Table 1 and Table 2.

Table 1: Dimensioning comparison of a compact vehicle

	Unit	Tool	Real vehicle	Deviation
Vehicle mass	[kg]	1536	1599	-4 %
ICE Performance	[kW]	106	110	-3.7 %
EM Performance	[kW]	65	75	-15.4 %
Battery capacity	[kWh]	9.6	8.8	8.3 %

The dimensioned vehicles obtained from the developed tool match the real vehicles very well with slight differences. A deviation between the real vehicle and the dimensioned vehicle occurs by the dimensioning of the electric motor. An explanation is the dimensioning target which differs between the tool and the dimensioning realized by the manufacturer. The other deviations can be explained by the use of constant efficiency and weight factors within the tool.

Table 2: Dimensioning comparison of a mid-sized vehicle

	Unit	Tool	Real vehicle	Deviation
Vehicle mass	[kg]	1733	1722	0.6 %
ICE Performance	[kW]	116	115	0.9 %
EM Performance	[kW]	79	85	-7.6 %
Battery capacity	[kWh]	10.5	9.9	5.7 %

The automated drivetrain dimensioning tool offers the possibility to examine different requirements for PHEV such as the maximum velocity, recuperation potential or the electric range reached in legal cycles.

In the next step following the powertrain dimensioning is the simulation of the powertrains in legal cycles and customer operations. The simulation tool is built up as a reverse simulation. The selection of suitable operation points is done by the operation strategy. In order to achieve very good fuel consumption for all investigated concepts the equivalent consumption minimization strategy (ECMS) was taken into account. This strategy also ensures SOC neutral operation through an iterative and cycle related adjustment of the strategy parameters.

Optimal electric range of PHEV considering WLTP

Within the project the optimal electric range within the WLTP was examined and determined. In this example the optimal electric range is determined for a middle class vehicle with a P2-hybrid topology. The vehicle parameters are shown in Table 3.

Table 3: Design parameters for the vehicle (mid-sized, front-wheel drive)

Parameter	Unit	Value
$m_{without\ powertrain}$	[kg]	1250
c_d*A	[m²]	0,62
f_R	[-]	$8*10^{-3}$
λ	[-]	1,05
F_{Fric}	[N]	40
r_{dyn}	[m]	0,31
v_{max}	[kph]	220

In order to examine different ranges the vehicle is dimensioned on the basis of customer requirements obtained from the 3D-parameter[1] space and different electric ranges in the WLTC reaching from 1 up to 200 kilometers. After dimensioning the vehicles, using the automated drivetrain dimensioning tool, a charge sustaining simulation in the WLTC is carried out. A charge-sustaining simulation is not necessary due to the fact that the emissions during the electric drive are assumed with zero and the SOC break-off criterion is displayed by the electric range used for the dimensioning of the vehicles.

[1] acronym for the customer classification: driving style, driven vehicle, driving environment, see appendix for further detail

The used utility factor is derived from the ECE R101 since the utility factors for the different markets are not yet elaborated.

With the results obtained from the simulations of the different electric range specifications in the WLTP the combined carbon dioxide emissions can be calculated in connection to the electric range in the WLTC. Two points of view for the examination of an optimal electrical range of PHEV in the WLTC will be discussed in this paper. The first are legal guidelines and benefits obtained by reaching a certain value of combined carbon dioxide emissions. Beyond that the cost of hybridization compared to a conventional powertrain and the effort of a lower deviation of the manufacture carbon dioxide limit value will be considered as well. Both curves are shown in Figure 5. In addition the optimal electric range is emphasized by the filled area.

Taking legal guidelines and benefits into account an undercut of combined carbon dioxide emissions of 50 g CO_2/km is reasonable since super-credit regulation will apply to vehicles with emissions below [8]. From 2020 to 2022 vehicles with emissions below 50 g CO_2/km will be counted as 2 vehicles in 2020, as 1.67 in 2021 and as 1.33 in 2022. In order to reach emissions below 50 g, a middle class vehicle has to be dimensioned with an electric range of at least 24 km.

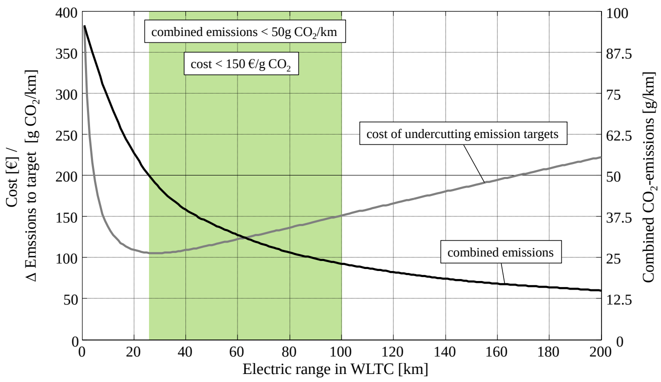

Figure 5: Optimal electric range of PHEV in the WLTC

The increase of the battery capacity is the main cost driver of hybridization of the conventional powertrain. For this cost analysis basic costs of hybridization are assumed with 2500 € [9]. These include the cost for integrating electrical components into the vehicle such as wires and power electronics. The cost of the electric motor with an integrated inverter are assumed with 25 €/kW [9]. The cost of the battery depends on its capacity and is assumed with 380 €/kWh [10]. In order to evaluate the investment for the hybridization of the powertrain to obtain the emissions difference towards the manufacturer limit value the total cost for the electrification of the drivetrain are set into proportion with the difference of the emissions, resulting in the gray graph in Figure 5.

If cost for undercutting the emission target values are determined to be below 150 € for every gram CO_2 the electric range has to be between 5 and 100 kilometers. If both factors are considered the dimensioned electric range of a middle class vehicle has to be between 24 and 100 kilometers.

V. Conclusion and Outlook

In this paper a tool chain for the simulation, evaluation and optimization of electrified drivetrains was introduced. Two of the fundamental tools, the synthesis and the automated drivetrain dimensioning, were described. The synthesis tool allows to generate different powertrains, ranging from simple topologies like parallel hybrids up to complex topologies with multiple power split elements. In order to simulate the drivetrains in different cycles, the main components have to be dimensioned. The drivetrains have to reach the different requirements as well as ensure the functions and effectiveness of the different hybrid functions. The dimensioning of the drivetrains is automated to enable the examination of a plurality of drivetrains generated by the synthesis. The first part of the tool chain was used to examine an optimal electric range in the WLTC. For a middle class vehicle an optimal electric range has to be between 24 and 100 kilometers in the WLTC, by taking the combined emissions and the cost of undercutting the manufacture limit value into account.

In further research the evaluation tool and methodology will be elaborated. Following that step the drivetrains obtained by the synthesis will be simulated and rated, in order to find the most promising drivetrains under the given criterion. Afterwards one selected drivetrain will be chosen for the optimization.

VI. APPENDIX

3D-parameter space

The 3D-parameter space consists of three axes each displaying one central element of the 3D-method and displays the influence of customer driving behavior on the complete vehicle and on the individual components and assemblies.

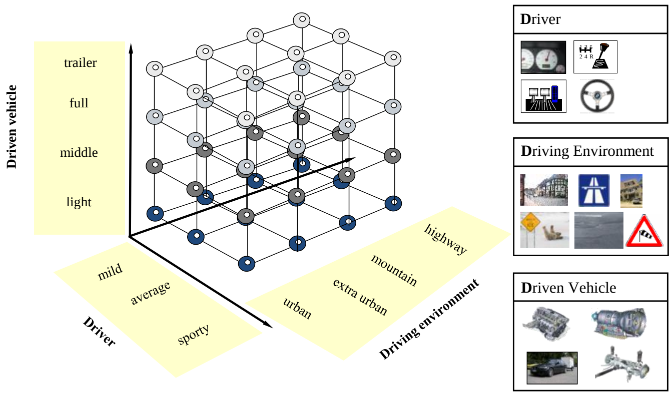

Figure 6: The 3D-parameter space for drivetrains

The representative 3D-parameter space for the development of drivetrains consists of the axes driver, driven vehicle, and driving environs. The driver is displayed by the driving style and divided into a mild, an average and a sporty driving style. The driven vehicle is described by the four dimensions light, middle, fully loaded and trailer. The driving environs are distributed into the type's urban, extra urban, highway and driving on the ascent of a mountain. A typical customer can be described by a combination of the three axes. This can be for instance a driver with a mild driving style and a light loaded vehicle driving in the city, resulting overall in 48 different combinations as shown in Figure 6.

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