Efficient Design Space Exploration and Optimization Using the Example of Plug-In Hybrid Electric Vehicle Architectures

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1 Abstract

Plug-in Hybrid Electric Vehicles (PHEVs) are one alternative to significantly reduce fossil fuel consumption. The potential complexity of PHEV powertrains is high due to the countless combinations of combustion engines, electric motors, storage systems and control strategies. Previous studies have shown how to tune parameters according to customer requirements for a given PHEV architecture. However, most approaches do not cover the whole design space of possible PHEV configurations. This study presents a framework for powertrain generation, exploration and optimization. Formal engineering methods are used to generate conceptual PHEV configurations. To evaluate these configurations quantitatively, a parameterized model is defined, including component types and sizes as well as control strategy parameters that is linked to a multi-level simulation model. The parametric and simulation models can be used to generate and explore parametric variants of alternative PHEV architectures. The main design criteria explored are energy consumption and vehicle performance criteria. This research goes beyond prior work as it offers a comprehensive approach for the automated and rapid generation and evaluation of PHEV powertrains according to particular customer requirements including cost. This provides a first step towards an integrated and automated method for powertrain synthesis, simulation and optimization.

2 Introduction and Motivation

Due to the limited supply of fossil fuels and the common interest of politicians, OEMs and the general public to reduce vehicle-related $C0_2$-emissions, plug-in hybrid electric vehicles (PHEVs) are one promising step towards the electrification of the automotive powertrain. Numerous possibilities exist to choose, arrange and size the different powertrain components, i.e. the internal combustion engine, electric machine(s), transmission(s) and electric energy storage. This contribution presents a framework for the holistic generation and evaluation of powertrain concepts which also includes a cost model. Key elements of this framework are a synchronized parameterization as well as surrogate modeling and multi-criteria optimization techniques.

3 Background and Related Work

The following paragraphs introduce related work in the fields of generation, modeling, simulation and optimization related to PHEV architectures. The generation or synthesis part of possible PHEV configurations is based on previous work by Helms et al. [1]. Here, formal engineering methods are used with an underlying graph-grammar structure in order to generate unprejudiced configurations. In modeling a correct parameterization plays an important role [2] as it impacts subsequent processes including sampling techniques, e.g. design of experiments (DoE), approximation methods like response surfaces (RSM) and optimization. In the approach, this paper is based on, the parameter bandwidth spans from the requirement-level to vehicle-level to component-level. The parameterization of the vehicle is done according to the different driving resistance parameters [3], whereas the parameter selection for the different components requires domain specific knowledge, especially when continuous scaling is required. For electric machines this knowledge derives from Schöning et al. [4] who identified relevant properties to size with respect to electromagnetic and thermal aspects. For internal combustion engines (ICEs) an approach has been presented by Seibel et al. [5]. Sauer et al. [6] showed a model parameterization for electric energy storage systems while Lipman et al. [7] and Gorbea et al. [8] dealt with component costs and lifecycle cost aspects of (P)HEVs. On the PHEV technology side high level comparisons between particular configurations of the two different PHEV approaches displayed below in Figure 1 were accomplished e.g. by Toyota Motors Corporation [12], General Motors Corporation [13], Freyermuth et al. [14] and Hauffe et al. [15]

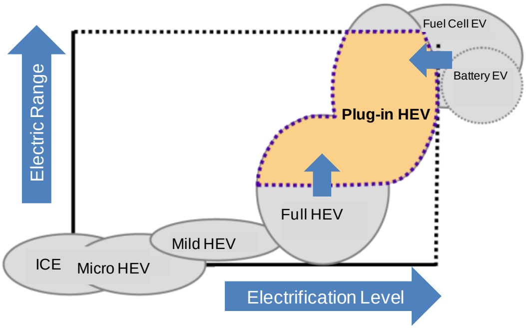

Figure 1: PHEV design space

Optimization plays an important role when component sizing or determination of control strategy parameters is concerned: An overview over the variety of optimization algorithms used in powertrain applications is given by Gobbi et al. [16]. Parametric optimization with regard to PHEVs has been conducted by Karbowski [17] [18] among others. Faron et al. [19] furthermore performed a robust simulation on PHEV fuel efficiency and cost by using a Monte-Carlo simulation.

4 Research Approach

According to the concept of frontloading the costs to resolve problems in a development process can be decreased by providing as much information as possible in the early concept phase. Figure 2 presents a two-staged approach to cope with the structure in a systematic way.

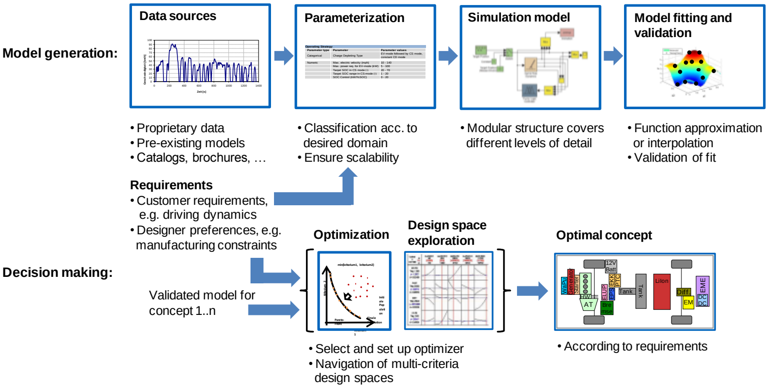

Figure 2: Model generation and decision making process

4.1 Model Generation

The upper part of Figure 2 shows the general steps necessary in order to generate valid models of PHEV architecture concepts. In this context data mining studies as proposed in [2] play a major role. Also, to search the powertrain design space in an unbiased way, an automated synthesis method [1] can be used to automatically generate possible PHEV configurations. High level functional requirements are gradually translated into powertrain components by using a modified Function-Behaviour-Structure (FBS) modeling approach with a graph-grammar to generate valid concepts.

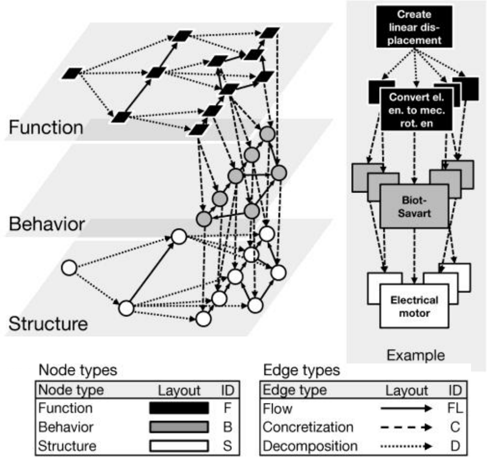

Figure 3: Representation based on FBS [2]

Figure 3 illustrates the representation that is used based on a FBS hierarchy. The figure on the right shows an exemplary decomposition process. At first the high-level function *Create linear displacement* is decomposed into subfunctions; among them *Convert electrical energy to mechanical rotational energy*. Behaviors describe working principles that realize the functions from a physical and component-independent point of view. Design catalogues, such as those by Koller [20] or Roth [21] provide a large source of knowledge for physical working principles. In this example the law of *Biot-Savart,* which contains the relation of a conductor in a magnetic field and the resulting force, is proposed. The lowest degree of abstraction is achieved on the structural level where specific components embody the behaviors required. At this point a design catalogue indicates potential solutions, e.g. using an *Electrical motor* for realizing the law of Biot-Savart. The FBS approach allows many mappings between function and behavior but also between behavior and structure. Using three levels of abstraction, a high diversity in the consideration of different powertrain configurations is possible. More information on product synthesis based on graph-grammars can be found in [2] and [22]. With this method around 100 different PHEV architectures have been generated. The configurations differ in terms of component arrangement and sizing. Three selected architectures covering alternatives currently considered in industry are selected from those generated by the graph grammar based method. Each of these architectures is implemented in hardware and thus the simulation model can be validated. Figure 4 shows the three architectures that are considered in this paper:

- a Parallel PHEV with rear wheel drive (RWD)
- a Series PHEV with rear wheel drive
- a Combined PHEV with rear wheel drive

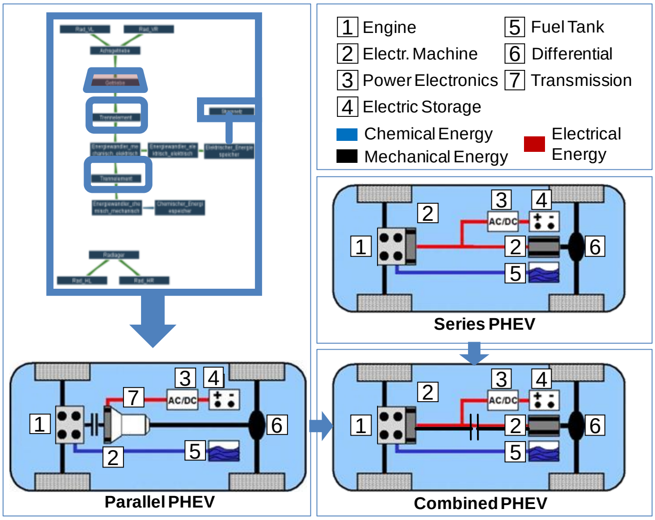

Figure 4: PHEV configurations considered

In a parallel configuration, both the electric machine and the engine can be used to propel the vehicle directly. The series configuration is considered to be closer to a pure electric vehicle compared to a parallel configuration. The vehicle is propelled solely by electrical energy and the engine speed and torque requirements are completely decoupled from the wheels. The combined configuration features characteristics of both, parallel and series PHEVs.

Also potential data sources like proprietary data, pre-existing models and component catalogs can been sourced in order to have a data basis that provides the relevant information to meet the requirements. The requirements can be rather high-level and more customer-oriented or more detailed, when incorporating the engineers' preferences. Thus they determine the level of detail of the parameterization and are consequently synchronized with the latter. Table 1 shows the customer requirements that set the constraints for the simulation model. There are criteria relating to the vehicle's longitudinal performance like top speed or acceleration and thus influence mainly the dimensions of the electric and conventional drivetrains, compassing electric machine, engine and transmission, which are responsible for power level and torque characteristics. Other criteria like the average daily driving distance are more related to electric energy storage and the overall electrification level, which is predominantly defined by the chosen PHEV architecture.

Table 1: Customer requirements

Requirements		
Description	**Values**	**Direct influence on**
Minimum top speed	60 - 125 mph	i_{n_max}, P_{EM_max}
Minimum required climbing capability	5 - 100 %	i_{n_min}
Maximum tolerable 0 - 60 mph time	5 - 30 sec	i_n, n_i, P_{EM_max}, T_{EM_max}
Average daily driving distance	5 - 100 km	$C_{EES,}$ architecture
Number of days exceeding the daily driving distance	0 - 200	$C_{EES,}$ architecture
Total driving distance per year	3,000 - 20,000 mls	$C_{EES,}$ architecture
Percentage of urban driving	0 - 100 %	$C_{EES,}$ architecture

A parameterization approach with two types of numeric values has been chosen: on the one hand continuous numerical values to ensure scalability of components for searching the design space in an unbiased way and on the other hand discrete numerical values, e.g. to take advantage of standard parts. Further categorical parameters are introduced and allow the switching between already existing components or concepts. The key parameters that influence the manufacturing process and the cost have been identified for each component by consulting expert knowledge, e.g. the parameterization of the electric motor(s) follows the ideas laid out by [3], whereas the internal combustion engine has been parameterized according to [4].

An exemplary parameterization of the electric machines and the cost model is specified is shown in Tables 2 and 3. Generally two different types of parameters are used, covering categorical and numeric values. For electric propulsion permanent magnet synchronous motors (PSMs) and asynchronous motors (ASMs) are simulated. The data sets are based on the ADVISOR electric machine library and the parameterization of the motors uses an approach presented in [4] in order to ensure scalability of the characteristic machine maps. Besides the categorical variable "Motor type", three numeric design variables can be adapted, see Table 2: The maximum machine speed, the characteristic machine speed and the maximum motor power. Depending on the maximum motor power, additional mass is added to the vehicle glider mass.

Table 2: Electric machine variables

Electric Motor		
Parameter type	**Parameter**	**Parameter values**
Categoric	Motor type	PSM, ASM
Numeric	Max. speed (rpm)	4000 - 12000
	Charact. engine speed (rpm)	2500 - 8000
	Max. motor power (kW)	10 - 100

Table 3: Cost model variables

Cost	
Parameter	**Parameter values**
Electricity price ($/kWh)	0.07 - 0.30
Fuel price ($/gal)	1.50 - 8.00
Electric machine (ASM) cost ($/kW)	7 - 30
Electric machine (PSM) cost ($/kW)	10 - 50
Production volume electric machine	2,000 - 200,000
Electric storage power/energy ratio (kW/kWh)	9 - 20
Electric energy storage cost [$/kWh]	200 - 1500
Production volume electric energy storage	2,000 - 200,000

The parametric cost model is based on work done by Lipman et al. [7] and Gorbea et al [8] and is seamlessly integrated into the simulation model. There is a strong correlation with the requirements, concerning the performance- as well as the energy related requirements.

A modular simulation model allows the calculation of results for different layers of complexity, according to the respective set of parameters. For component sizing an automated sizing process was developed. Figure 5 illustrates the logic. The electric machine and the engine are sized to meet the gradeability, top speed and acceleration requirements of the example configuration in Table 8. To meet the all-electric range (AER) requirements, the electric storage power is sized to follow the respective driving cycle. Fuel and electricity consumption are calculated by the simulation tool and the running costs in conjunction with the additional component costs allow the calculation of break-even times. The modeling and simulation work for the PHEV powertrains is implemented in a hybrid environment of Matlab/Simulink for simulation and Microsoft Excel for requirement and parameter definition.

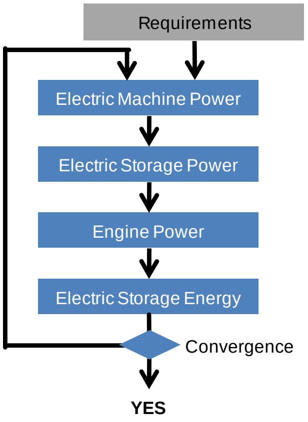

Figure 5: PHEV component sizing logic

Subsequently the solution space has been sampled in order to minimize the number of required simulations. The fit of data is done by regression models or artificial neural networks, depending on the number and quality of training data. Statistical analyses and cross-validation approaches with already validated high-fidelity simulation models are used to ensure the quality of the fit and generate a valid surrogate model of the respective architecture concept. Comparisons with actual validated simulation data of an industrial partner have been accurate to within 5 % of the actual energy consumption, SOC measurements and acceleration performance. Once these validated surrogate models have been generated the decision making phase starts.

4.2 Decision Making

These models provide the basis for the time-efficient application of decision-making methods and tools. Depending on the requirements a single- or a multi-criteria objective function has to be solved by optimization or search routines. As surrogate models have a relatively simple algebraic structure the selection and set up of optimization and search algorithms and the creation of Pareto-frontiers is comparatively quick. The decision making process is further supported by the possibility to navigate the design space, so that the resulting concept fulfills the requirements. Figure 6 exemplifies the easy and rapid navigation in the generated and validated approximated solution spaces for an application example.

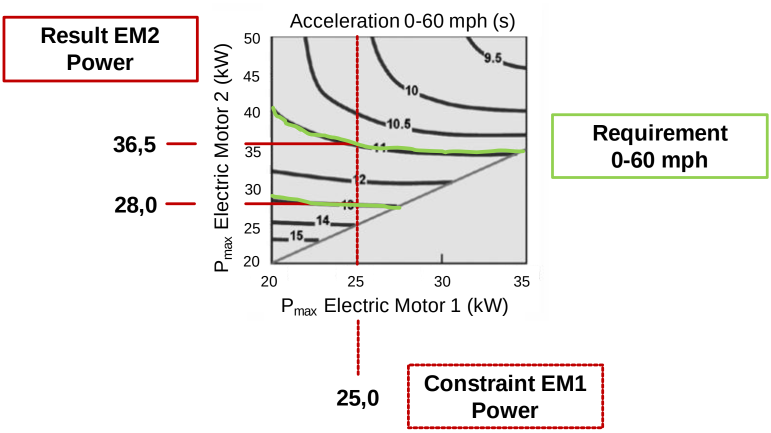

Figure 6: PHEV component sizing process.

Assuming the requirement for vehicle 0-60 mph acceleration changes from 13 sec to 11 sec while the power of electric motor 1 is set to be constant, the necessary power increase of electric motor 2 can be evaluated rapidly.

5 Discussion and Conclusion

With this approach the basis of a framework for automated synthesis, exploration and optimization of PHEV architectures has been laid. The parameterized model and simulation tool allows the generation of PHEV configurations according to particular requirements and allows initial design space exploration on different levels of details. The creation and validation of the parametric model and related simulation model presented here provide a firm foundation for the application of surrogate modeling methods in order to search the entire design space in an efficient way. A sampling method furthermore generates training data points for approximation methods. The obtained approximate model uses polynomial functions and thus allows for rapid configuration of powertrain and control strategy properties according to the particular requirements. For validation purposes optimization runs are also carried out with data from the actual simulation model. The results in the end demonstrate the applicability for top-down approaches from the overall-vehicle side or bottom-up approaches from the component side. The formalized synthesis responds to needs for an unbiased generation of architectures while the parameterized model and the simulation tool are indispensible for the application of optimization and approximation techniques in order to further automate the design process.

6 References

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7 Definitions and Abbreviations

AER: All electric range

DoD: Depth of discharge

DoE: Design of experiments

EV: Electric vehicle

FBS: Function-Behavior-Structure

FTP72: EPA urban drive cycle

HEV: Hybrid electric vehicle

HWFEDS: EPA highway drive cycle

ICE: Internal combustion engine

PHEV: Plug-in HEV

RWD: Rear wheel drive

SOC: State of charge

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