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Topology synthesis of hybrid electric vehicle drivetrains in the context of the integrated Product engineering Model

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Summary

In order to increase the overall efficiency of hybrid electric vehicle drivetrains, new topology concepts are investigated to identify unexploited potentials of CO_2 reduction. In contrast to the few different hybrid topologies, which are available on the vehicle market, there are thousands of possibilities to combine the components of a drivetrain. This leads to a high complexity in the development process. To support the developer within the development process with the aim of identifying more efficient hybrid vehicles topologies a new approach is presented in this paper, which makes automated topologies synthesis possible.

Keywords: HEV (hybrid electric vehicle), drivetrain, simulation

1 Introduction

The European Union defined the regulations on CO_2-emissions for the registration of new vehicles with 95 g/km coming into effect in 2020 [1]. This boundary condition forces the car manufacturers to develop drivetrains that are more efficient. Battery electric vehicles are in the focus of development and they are already in the market but customers have a restrained buying behaviour because of the high acquisition costs in relation to conventional driven vehicles. Another factor is the so-called 'Reichweitenangst', which means that customers are afraid of not being able to reach their destination with the given battery capacity and the long charging time compared to the fuelling time of a conventional vehicle [2]. For these reasons, the development of hybrid electric vehicles is getting into focus in order to combine the prejudices of conventional and electric vehicles. The topologies of hybrid electric vehicles that are in the market base on conventional drivetrain topologies. LI and WILLIAMSON [3] figured out that the drivetrain topology has a high impact on the efficiency of the drivetrain. There are different factors leading to the different efficiencies. On the one hand, there are different losses in the drivetrain, resulting from different gearboxes and arrangements of the drivetrain components. On the other hand, there are different functionalities and modes, which can be realized by different drivetrain topologies. This is pending on the hybrid vehicle classification whereby serial hybrid vehicles can only propel with the electric motor and recharge the battery by stationary operation of the combustion engine driving a generator. Parallel and power-split topologies offer different driving functionalities and modes as they offer the possibility to propel the vehicle in combined modes with the combustion engine and the electric machine, pure electric, or in the case of a parallel hybrid topology only with the combustion engine as well [4]. This offers more possibilities for efficient driving, because there are more degrees of freedom. Therefore, it is important to investigate new drivetrain topologies in order to improve the overall efficiency of hybrid electric vehicles. For this purpose, a suitable development method has to be identified and will be presented in this contribution.

2 State of the art

For the description of the development, process the iPeM (integrated Product engineering Model) has been developed and established for various procedures by ALBERS. This model is universally applicable to any development process and describes the transfer of the system of objectives by the operation system to the system of objects, as displayed in Fig.1 [5]. Regarding the drivetrain development of new hybrid electric vehicles, the system of objectives includes the requirements of the customers and the developer. Within the operation system, the developer performs different activities of product engineering in order to develop a new drivetrain, which fulfils the requirements as system of objects. To perform the activities of product engineering, the developer needs support to identify suitable activities of problem solving. At the IPEK the so-called InnoFox [6] has been developed in order to provide different methods to the developer according to the current activities of product engineering and problem solving, considering the system of resources. The activities of problem solving can be performed iteratively, which can be derived from the phase model. The phase model is kind of a project plan that displays the development procedure and which is unique for each development process. The activities of product engineering are "Manage projects: Sum of the activities at the beginning of a PDP (Product Development Process) - including planning of the initial system of objectives and operation system – as well as their continuous controlling and regulation. Validation and verification: continuous comparison of objects and their objectives. Manage knowledge: Gaining an overview of internal and external data, information and capabilities. Further elements are identification, acquisition and development of knowledge as well as distribution, use and maintenance of this knowledge. Manage changes: Including the coordination of technical, economic and social changes. The inherent elements are: the examination of early detection of errors and the potential as well as the implementation of respective measures. Profile detection: Identification of customer use and supplier's use as well as solution-neutral characterisation of the qualities of a future product. Idea detection: finding solutions for the holistic treatment of the profile. Model principle solution and embodiment: detailed elaboration of the product idea taking into account technical and economic aspects. Development of the physical connection of function and embodiment. Built up prototype: This activity is necessary to perform the activity "validate and verify". It is carried out at different maturity levels and can contain physical prototypes as well as virtual ones.

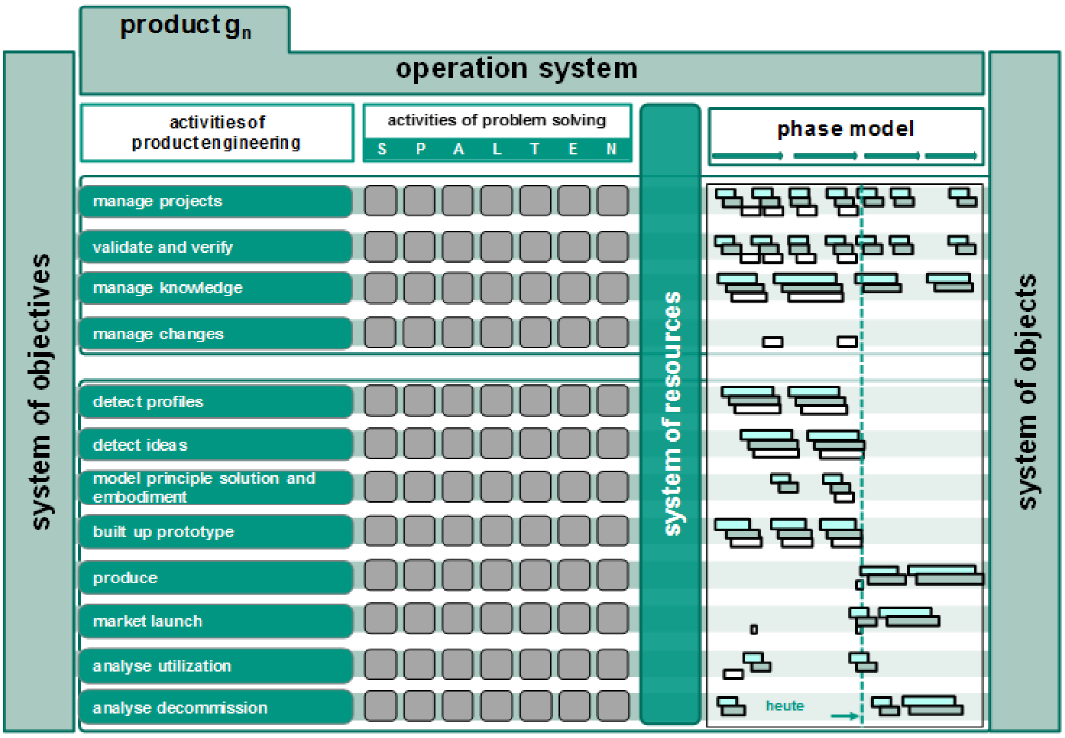

Figure 1: First layer of the integrated Product engineering Model in context of product generation engineering [5]

Production system engineering: Activities that are necessary to be able to produce the product. Production: Manufacturing activities for the realisation of the product. Market launch: Activities, which serve for the marketing of the product. They enclose the implementing of a distribution network, as well as the definition

of a marketing strategy. Analysis of Utilization: Anticipation of the future user's behaviour and identification of improvement potentials with existing products. Analysis of Decommission: Anticipation of the possibilities of recycling after the end of the product life cycle" [5]. The activities of problem solving are following the so-called SPALTEN-process, which is German and means 'to split something'. SPALTEN consists of the first letters of the seven activities in this process in German. These activities are: Situation analysis, problem containment, detection of alternative solutions, selection of solutions, analysis of consequences, deciding &implementing and recapitulation &learning [5]. For the investigation of new drivetrain topologies, especially the activities of "detecting ideas", "model principal solution and embodiment" and "validate and verify" are in focus. The last activity is very important because there is always an investigation whether the system of objects fulfills the system of objectives - if not, the detected topology is not suitable and therefore not considered in the further development process.
For the methodical support in this activity, the IPEK-X-in the-Loop-Framework (IPEK XiL) has been developed, which considers the investigated system within its environment and the user - in the case of a vehicle the driver - , as displayed in Fig.2 [7]. These three systems are in interaction with the manoeuvre and test cases, depending on the investigations, which have to be performed. The investigated System X is in the focus of the investigations. It can be the complete vehicle, a subsystem of the vehicle in different sizes as the whole drivetrain or only a part of it, or even only a friction contact or code of the controller software that has to be validated. The rest-vehicle model is getting more detailed, as the system in development is getting more into detail. Depending on the maturity of the investigated system, the rest vehicle model, has to be more accurate as well to achieve more meaningful validation results.

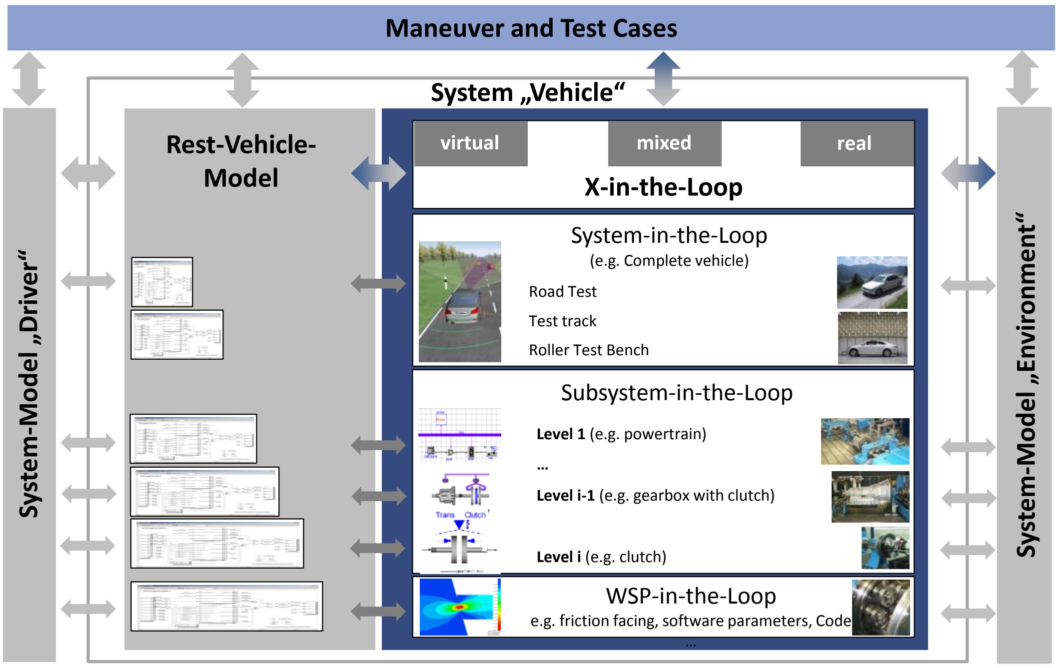

Figure 2: IPEK-X-in-the-Loop-Framework [7]

The investigation of new drivetrain topologies is in the early phase of the product generation development, which begins with the initiation of a project and ends with a rated technical solution, according to ALBERS ET AL. [8]. There is only few information about the complete series vehicle available, but the decisions that have to be met, have a high impact on the efficiency of the vehicle. Therefore, the validation can only be performed within a virtual environment into the simulation. The information about the rest-vehicle-model has to be derived from the previous vehicle generation, or - if this is not available - from comparable vehicles in this segment.

3 Current development approach

Due to the cost reducing effects in the development and production of hybrid electric vehicles, the focus within the current development process is on the integration of hybrid functionalities in conventional drivetrains and on the usage of similar subsystems in different drivetrains because the manufacturers have established construction kits to profit from scale effects [9]. This means that the main part of a hybrid drivetrain consists of subsystems, which are also used in conventional drivetrains, including the combustion engine, the gearbox and the differential unit. For example, the integration of the electric motor between the engine and the gearbox reduces the subsystems' development costs compared with the development of new topologies. It also avoids changes at the vehicle architecture that are possibly necessary with new topology designs. In the context of PGE (Product Generation Engineering), the so-called carryover share from the previous product generation is high [10]. The reference product is in this case the conventional vehicle of the previous generation. For this reason, there are only a few different hybrid topologies in the market. An exception is the Toyota Prius where Toyota has developed a new topology concept not basing on a conventional drivetrain; even the combustion process of the engine is adapted to the requirements of the power split topology.

There are a few approaches published dealing with the investigation of different hybrid topologies development. Whereby, their focus is not on the whole drivetrain or even on the investigation of completely new topology structures. There are different levels of drivetrain topology optimization, starting at the development of parallel hybrid drivetrains by integrating an electric machine in a mechanically not further optimized drivetrain [11] [12]. The next level is the optimization of single drivetrain components in an already existing hybrid drivetrain as described in various papers where the combustion engine, the transmission, the electric machine or the battery is optimized [13]. Much more complex is the use of multicriterial optimization considering all drivetrain components in order to identify the best parameter sets for a given drivetrain topology [14] [15]. If this is combined with a set of available topologies as described by DANZER [16], there is already a much greater chance to identify suitable drivetrain solution for a given scenario. The next step is now to widen the solution space in order to identify more efficient drivetrain topologies.

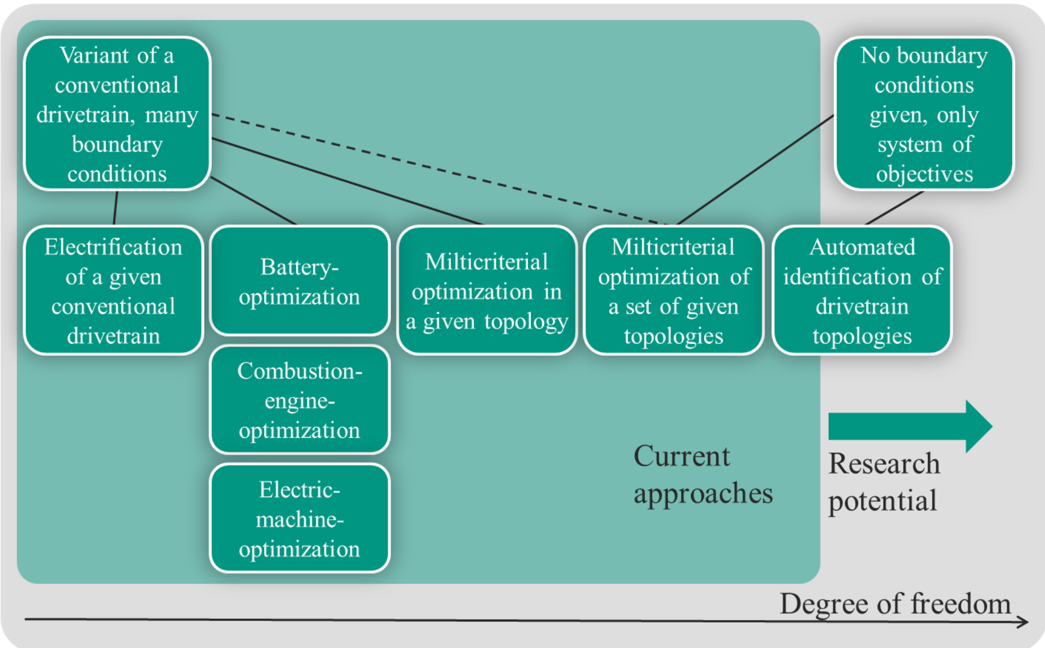

Figure 3: Degree of freedom in the drivetrain development depending on the boundary conditions

4 Methodical approach

Regarding the number of drivetrain components in a hybrid electric drivetrain, there are thousands of possibilities to combine them. For a combination problem with one engine, two gearboxes, three planetary gears and three electric machines, investigations have shown that there are already 386 mechanically realisable topologies without considering the various possible orientations of the planetary gears within the topologies. To reduce the complexity and to be able to handle the high variety of possible drivetrains in the development process, the developer needs methodical support. ALBERS ET AL. have identified in a study that 78% of the developers of the construction department of an automotive supplier do avoidable development activities by creating additional variants and doing changes on parts, which are no further pursued in the development process. From the same developers, 63% have the opinion that they could work more efficient if there was methodical support to avoid unnecessary variants [17]. Therefore, it is necessary to provide a method that enables the developer to meet a decision in the early phase of the product development regarding the identification of promising drivetrain topologies. PIECHOTTKA ET AL. [18] also identified this demand and described an alternative method for premium vehicles.

Based on the iPeM, which relates the generic activities of problem solving with the activities of product engineering [5], as displayed in Fig. 4, the method supports the developer in the activity of modelling principle solutions and embodiment and in the activity of validation and verification.

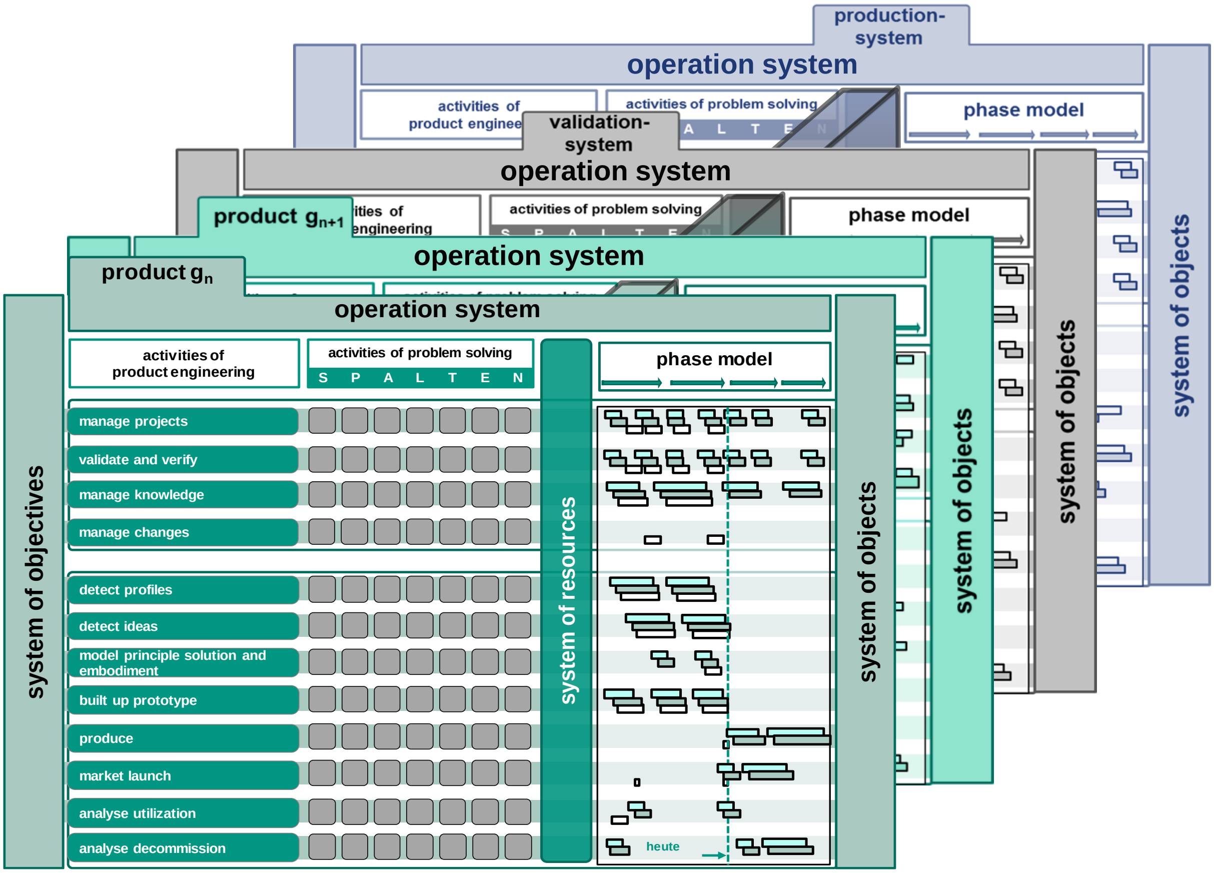

Figure 4: Integrated Product engineering Model (iPeM) in context of product generation engineering [5]

In order to identify the best drivetrain topology for a specified use case for the product generation n+1, it is necessary to do the activities of problem solving 'identification of alternative solutions' and 'selection of solutions'. To support the developer in these activities methodically, a procedure is described taking the vehicle segment for which the drivetrain is developed, the estimated usage profile, the target market and the performance requirements into account to identify alternative topologies and to evaluate them. For this procedure, an automated tool has been developed by the autors, which aim to guide the developer though the process and to make the high complexity through digitalisation manageable. Fig. 5 displays the general description of the approach.

The information about the vehicle segment, basing on the information about the product generation n, allows to estimate the available design space in order to set limits to the amount of drivetrain components, which are taken into account at the topology synthesis process. Furthermore, there is the possibility to estimate the vehicle mass of the vehicle without drivetrain and further parameters to calculate the driving resistances in the automated simulation. The purpose of usage is needed to calculate the fuel consumption and the electricity consumption under more realistic boundaries. Whereby, different types of vehicle drivers are considered by the adaption of the driving profiles to various driver types. One of the most important requirements in today's drivetrain development is the observance of the CO_2 exhaust limits that are relating to the fuel consumption. To meet these limits and to consider the observance in the rating, the developer can select different target markets for which he wants to develop the new drivetrain and the limits are loaded from a database and directly displayed to him. The most important input parameters are the performance requirements because they are responsible for the customer satisfaction and the primarily dimensioning of the propulsion machines for the simulation, which have an impact on the topology ranking [19]. Therefore, the maximum velocity of the vehicle and the maximum acceleration for combined and electric driving are taken into account. The roughly dimensioning of the battery capacity for the simulation considers the expected electric range from the usage scenario.

To generate the alternative solutions automatically into the next step, the drivetrain components are described mathematically with the amount of mechanical interfaces, which can be connected when modelling the topology by using graph theory. As described before, the maximum amount of used components in the topology depends on the vehicle segment and a rule-based algorithm identifies all mechanically realisable topologies with this amount of components. To handle these solutions easier a new description has been developed to generate the topologies in an acceptable time and to enable the tool chain to access the information in an easy way in the following simulation process.

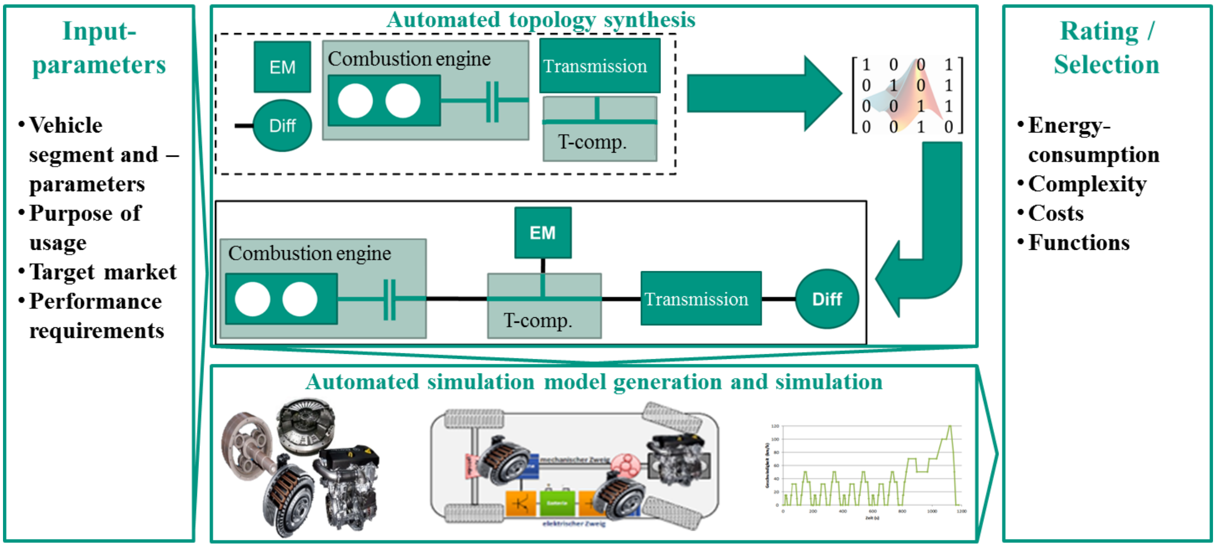

Figure 5: Proceeding for the automated topology synthesis, simulation and rating

The amount of realisable topologies can be very high. Therefore, the framework has an integrated simulation model builder that automatically builds up a simulation model for each identified topology and performs various simulations with each topology. The automated simulation model generation bases on the matrices, generated in the automated topology synthesis, and accesses a component library to build up all topologies, described in the matrices, in the simulation model with their mechanical connections. The propulsion machines are modeled by consumption maps under the consideration of the power limits and can be parameterized by applying different consumption maps and power limits. The transmissions can be parameterized with different ratios as well. This is a brute force procedure and the total simulation time increases with higher amounts of possible solutions. In order to accelerate the identification of alternative solutions, a rule-based algorithm automatically defines various mechanical parameters for each topology, regarding the boundary conditions. This is an important part of the tool because there are many shaping possibilities for each single synthesis solution. From these topologies, of course, only a few are mechanically realizable and therefore the rule-based algorithm does not generate those that are not realizable. For the developer it would not be possible to decide whether a solution is realizable or not without investigating each topology. Even if he did, it would be hard to estimate the impact of different planetary gears orientations in the combination of complex topologies. The amount of possible solutions is very high and that is the reason why the tool is needed to reduce the complexity and the simulation time.

To run the simulation model, a general control is considering all possible driving modes for each topology class (serial, parallel and power-split), whereby the algorithm automatically identifies the topology class. The control calculates the torque demand at the wheels for each time step, which is needed to follow the current driving cycle. At the same time, for each topology from previously generated look-up tables, the control reads out with what kind of torque combination, provided by the various propulsion machines in the drivetrain, the optimal combination of all propulsion machines can be reached in order to increase the overall efficiency. Besides, the control considers the state of charge and all possible gear ratios at each time step. The general control of the power-split topologies is challenging as the planetary gears allow more degrees of freedom and therefore, it is also necessary to control the speed of the propulsion machines. Furthermore, there are clutches needed to enable different modes in which not all propulsion machines are propelling the vehicle because the planetary gear can otherwise not transmit any power.

As introduced in the state of the art, the simulation is a part of the validation and verification activity and can be described by the IPEK XiL framework and it is also displayed in the iPeM with an own layer for the development of the validation environment. In context of the topologies' validation in the early phase of the product generation development, only virtual models are used and lots of information has to be derived from previous product generations to have enough data for the rest-vehicle-system in the simulation. Compared to the final product, there is a certain risk in this kind of validation caused by the uncertainty concering the percentage of the carry-over share at the final product of generation n+1 will be, compared to the previous generation n, which are displayed in the different layers of the iPeM. The maneuvers and test cases for the evaluation of the topology, related in the simulation to the driving cycles and additional tests, as acceleration and high-speed tests e.g., have to be defined according to the input parameters.

The simulation model itself is verified against established hybrid topologies that are available on the vehicle market and it performs exactly enough to make a statement to the suitability of a topology for the defined input parameters.

After the simulation, there is the automatic evaluation of the simulation results. The rating considers the fulfilment of the customer needs in relation to the vehicle performance, costs and the fulfilment of legal requirements on CO_2 emissions, which is estimated from the fuel consumption of the simulation results. The developer gets a ranking of the topologies and can perform further investigation and development activities with the best-ranked ones. The last layer of the iPeM deals with the development of the production process for the new product generation. In this early phase of product development, it is not yet possible to give a statement about the final production process but in the evaluation of possible drivetrain topologies, there can already be considered whether the existing production can be used or not.

5 Summary and Outlook

Within this work, a proceeding for the automated topology synthesis, simulation and rating has been presented. The proceeding shall support the developer in the complex activities of modelling principle solutions and embodiment and in the activity of validation and verification, in order to develop more efficient hybrid electric vehicles' drivetrains. Therefore, it provides various input-parameters, which can be modified by the developer, depending on the vehicle and the use purpose for that the drivetrain is in development. By selecting the input-parameters, the boundary conditions for the synthesis process are set and the synthesis process with the following automated simulation model creation and the simulation can start. At the end of the tool chain there is the automated evaluation of all simulation results, considering the fuel consumption, performance and cost.

In the next steps the whole framework will be investigated regarding varying scenarios under the aspects of the plausibility of the fuel consumptions and cost models. A multicriterial optimization will be performed as well in order to investigate if this has an effect on the ranking of the topologies.

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