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Model-Based Design and Optimization of Electric Vehicles

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Abstract. Model-Based Design (MBD) is a process that enables fast and cost-effective development of dynamic and complex systems, including control systems, signal processing, communications systems on the one hand and mechanical systems on the other hand. In Model-Based Design, a system model is at the center of the development process, from development requirements through design, implementation, and testing. At each stage of design, the model is a reflection of the state of knowledge about the designed system. The model is an executable specification that you continually refine throughout the development process. This is especially important for complex systems whose operation is difficult to predict. through simulations performed on the model, we can therefore determine whether the development of the system is going well. Simulation shows whether the model works correctly. The General Model-based Design method has been applied to the design of an electric car. In addition, this method has been used to optimize the vehicle towards minimizing energy consumption and, consequently, increasing the range of the vehicle, which is a critical functional parameter for currently developed electric vehicles. The application of optimization methods in a combination with the Model-Based Design creating additional possibilities of verification of other calculation methods (eg FEM) used in the design of the vehicle.

Keywords. Electric vehicle, Model-based design, Model-based optimization, Model-based design and optimization, Efficiency, Model, Inverse model

Introduction

Modeling, optimization and numerical simulation methods are commonly used in the design of transport means for solving partial design problems [1, 2, 3]. In the pursuit of improvement of designed vehicles, there is a need to use these methods not only for partial tasks but also for the task of overall vehicle design [4, 5]. This task is not easy, because due to the wide scope and multidisciplinary issues, a holistic approach to the optimization and modeling of the designed vehicle faces considerable problems. Such problems reveal the multidisciplinary nature of the issues solved and a high degree of complexity, which means that often different methods and tools are used to solve design partial problems and these problems are solved by completely different

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specialists through various organizational units. Reconciliation of all that requires considerable treatments - organizational, methodical, technical, software, etc.

There are known methods for solving such complex multidisciplinary problems. On the one hand, complex collaboration platforms are applied to complex aircraft optimization problems [6] and other multidisciplinary tasks [7]. On the other hand, relatively small tasks related to the design of mechatronics systems [4] use Model-Based Design (MBD) methods that are comparatively easy to use whereas such tools as MATLAB/Simulink are used to solve design problems of complex systems. In Model-Based Design, a system model is at the center of the development process, from requirements development through design, implementation, and testing. At each stage of design, the model is a reflection of the state of knowledge about the designed system. Thus, independently of the specific tools and methods used at particular stages of designing, the developed model has a superior role. Most often, it is not even attempted to integrate computer systems used at individual stages using CFD [8, 9], CAE, FEM, etc. methods.

In certain special cases of designing, for example, highly specialized vehicles, global vehicle optimization is required based on certain specific criteria. This is the case when designing electric vehicles, which, due to the unsatisfactory performance parameters associated with the range, are particularly optimized in terms of energy consumption. It is especially true when designing sports vehicles and also those used in energy-saving racing of electric vehicles [5, 11] (Fig.1). In a typical vehicle, such determination to maximize certain performance does not make much sense, since the satisfaction of a possible customer is not related to providing a certain level of one of the operational parameters but is associated with a set of features that is difficult to determine. In a sports car, however, it is obvious to provide much more specific features related to obtaining a result such as speed, acceleration, or energy consumption depending on the nature of the competition.

Figure 1. Examples of energy efficient electric vehicles designed for Shell Eco-marathon.

1. Model-Based Design and Optimization(MBDO) methodology

In specific cases when a strong desire to optimize a vehicle is required based on a set of strictly defined criteria, it is necessary to use the mathematical model to verify how the designed system behaviour when using different versions of parameters, but also using formal methods, unlike the regular MBD method (Fig. 2) also optimization with the use of this model is done.

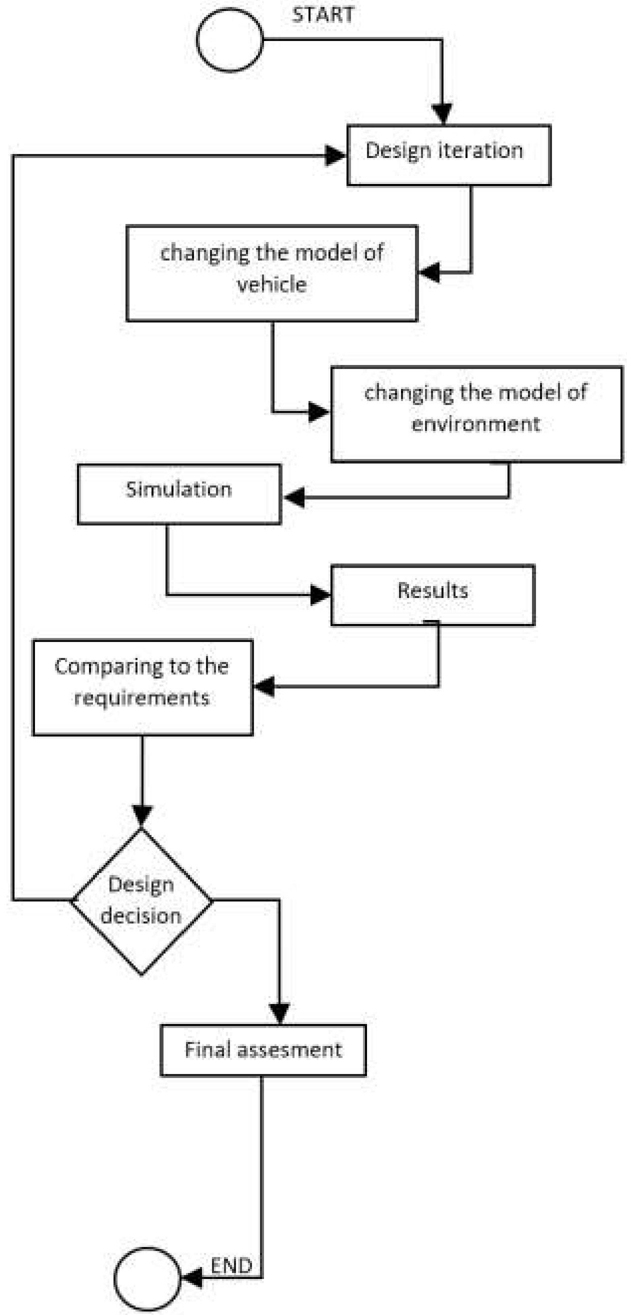

Figure 2. Model-Based Design (MBD) diagram.

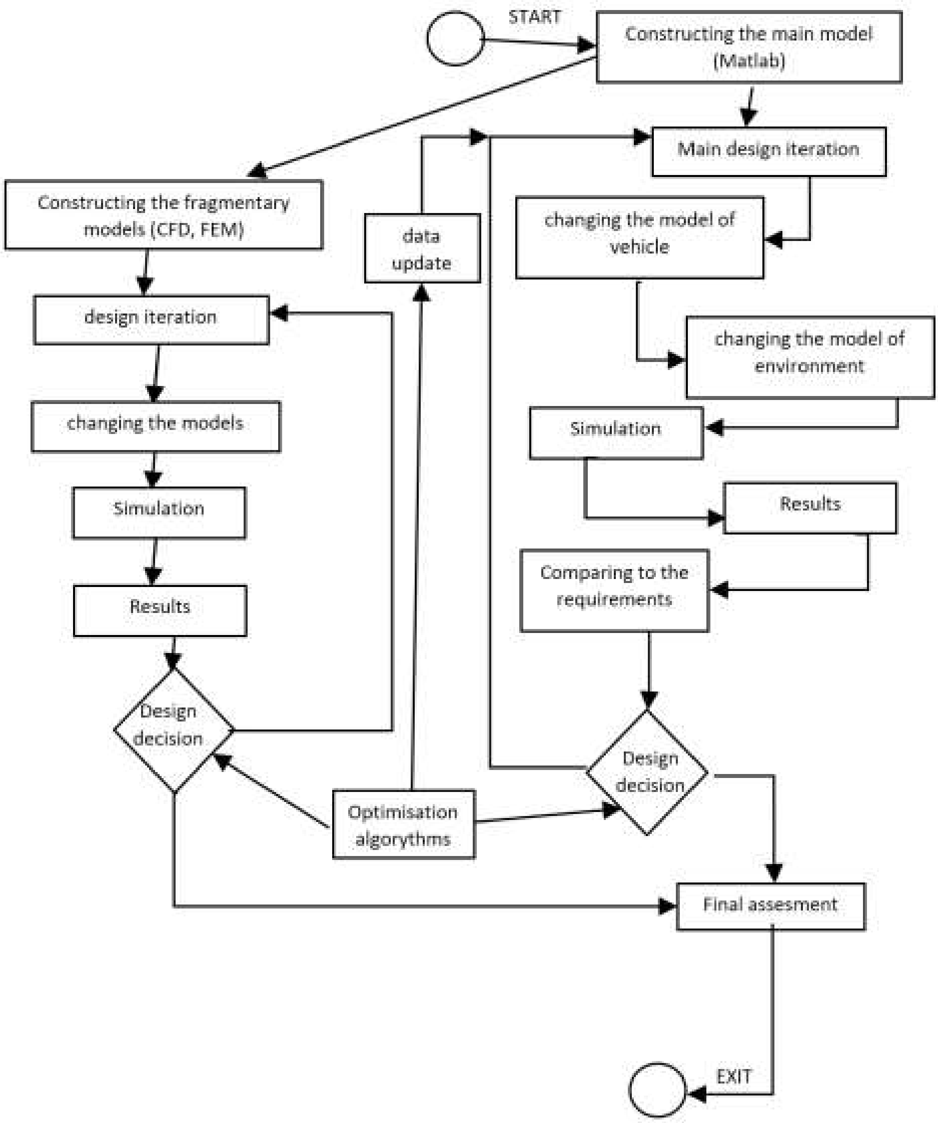

Figure 3. Model-Based Design and Optimization (MBDO) diagram.

In the classic case of the MBD method, the model is an executable specification that you continually refine throughout the development process. This is especially important for a complex system where it is difficult to predict. through simulations performed on the model, we can therefore determine if the system goes well. In the case of using the proposed MBDO metod (Fig. 3), the model is used to determine the system parameters, which are analyzed by the optimization algorithm and are used to search for the optimal solution. Consequently there is a need to perform fast iterative calculations with the use of this model. In the case of the impact on a global solution of many different parameters of the structure determined in a classical way by different methods and software tools, integration of these different systems is required in the first place and ensurance of their cooperation, which may be a problem due to the specificity of each software.

The system optimization model developed in the MATLAB/Simulink environment in which the basic optimization task is carried out plays a key role in the proposed MBDO development method. The optimization algorithm performs calculations using a mathematical system model. Calculation of the current system parameters is possible only when the model itself does not include complex multidisciplinary issues [12, 13], in other words, the model can be developed using a homogeneous MATLAB environment. If within the model it is necessary to make calculations using CFD or FEM methods, then it is necessary to use other tools. This happens when complex issues of shaping the external form of the vehicle and the impact of this form at the same time on the aerodynamic parameters of the vehicle as well as the load capacity and dynamic parameters of the vehicle. The basic difference between the MBD method used so far and the MBDO method proposed is the integration in the calculation phase of complex computational methods implemented with the use of separate specialized programs.

The application from the conceptual phase to subsequent development phases requires the adoption of certain assumptions for the use of the MBDO method:

- In subsequent phases, different degrees of model simplification and different methods for calculating are applied.
- In advanced stages of development, further elements of the model are integrated using external specialized software.
- The test results on a real object or prototype can be used either for tuning the numeric model itself or for verification of parameters defined so far with a low degree of certainty. Optimization methods [13] and the inverse model [14] of the system can be used extensively for this purpose

2. Use cases of MBD and MBDO tasks

So far, the proposed methods have been applied in:

- defining the concept as well as detailed racing parameters of vehicles competing in the Shell Eco-marathon [15] (SEM) competition at the design stage
- defining driving strategies during the SEM race in Rotterdam and London [4, 5, 16]
- verification of critical parameters of the aerodynamic characteristics of the racing vehicle [14].

Using the indicated methods, MuSHELLka racing vehicle was designed and built in the Prototype Battery Electric category, Bytel - UrbanConcept, Battery Electric category and HydroGENIUS – UrbanConcept, Fuel Cell Hydrogen category. In the design phase a number of restrictions were encountered that disrupted the use of the above-mentioned methods resulting from the fact of considerable financial constraints, technological limitations in the manufacturing of a large number of the components as well as high fluctuation of the project staff. All these limitations resulted from the student character of the project. The greatest achievements of using this method in this stage was to prove unambiguously and prioritize the various parameters of the vehicle and to accurately determine their impact on the final efect - result. Such knowledge, even with significant limitations, allowed for the optimal use of modest project resources.

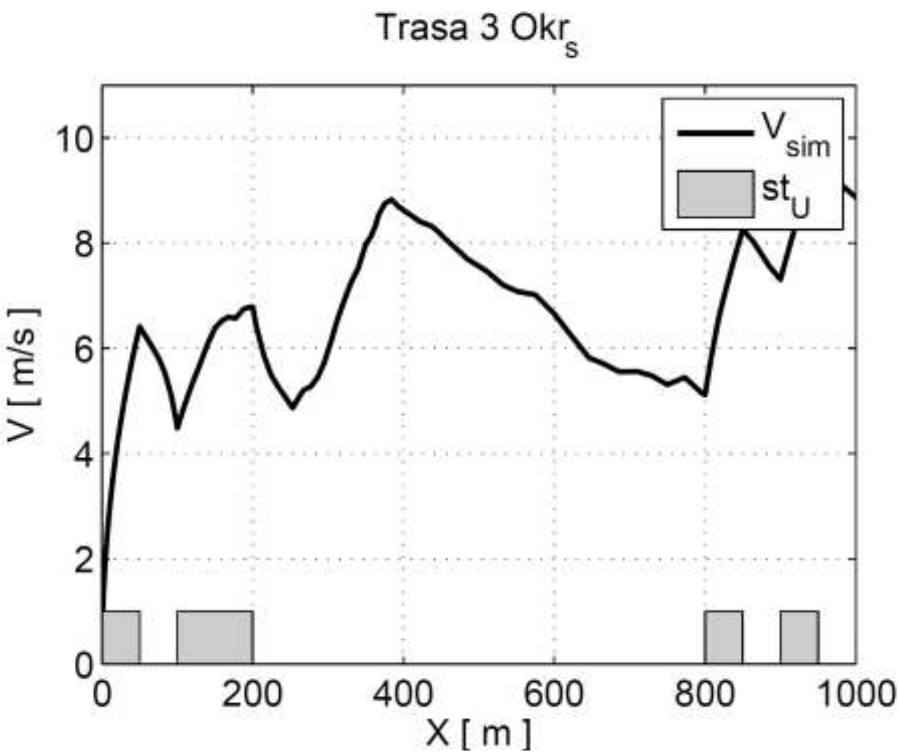

Figure 4. Drive control strategy according to simulation with resulting velocity profile.

The next elaborated task of developing a detailed strategy (Fig. 4) for the races was carried out carefully, based on the exact numerical model of the designed object and the results of the calculations were verified based on real data coming from measurements in the competition (Fig. 5, 6). Tuning of the models was carried out based on the research on the test track. These tests allowed the exact determination of the expected result, which was carried out with great accuracy during the race. Ultimately, this research led to the 2nd place in Shell Eco-marathon in 2016 in London.

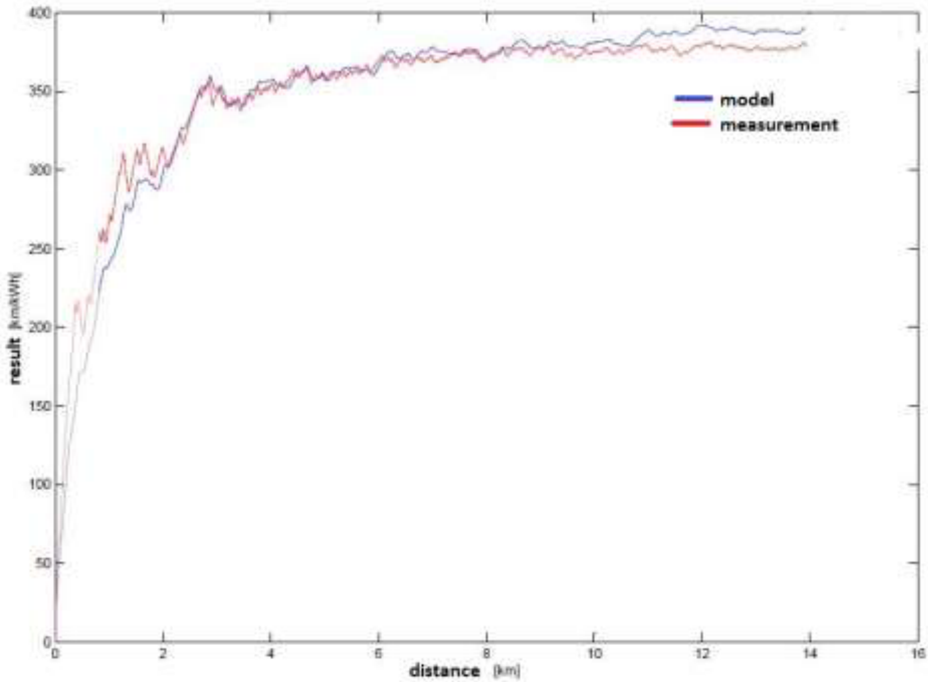

Figure 5. Final result prediction chart – comparison between numerical simulation and measurements.

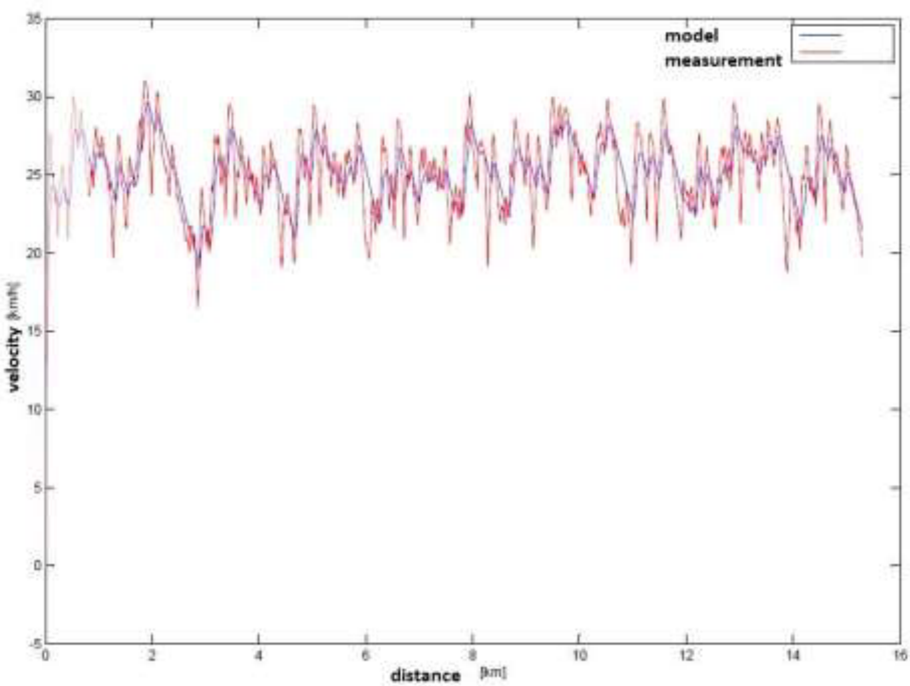

Figure 6. Comparison of velocity profile during race and as a result from numerical simulation.

An advantageous possibility appearing in later stages of product development using the MBDO method is the ability to verify the relevant parameters of the designed object. Such a need occurred during the development of the Prototype Battery Electric vehicle in relation to the aerodynamic characteristics of the vehicle. At the design stage, these characteristics were determined based on CFD methods. Since there were doubts about obtained the values, it was decided to verify these calculations [17]. It was planned to perform experimental verification based on the performance tests in the wind tunnel [18], but due to the time and costs it was not possible. Therefore, it was decided to use a directly developed numerical model in the MATLAB environment and the results of rides on the track. On the basis of the reverse model and the use of optimization methods, the aerodynamic characteristics of the tested vehicle have been calculated. The results of the calculations differed from those obtained by calculating with CFD methods. Therefore, at a later stage, further tests were carried out using the wind tunnel. Full compliance of the results obtained in the wind tunnel test (Fig. 7) and obtained with the use of MBDO methods and the inverse model as well as measurements of test drive parameters were confirmed [14].

Figure 7. Verification of aerodynamical characteristic in wind tunnel.

3. Conclusions

Improving the design methods gives you the opportunity to design more and more specialized products. The activities carried out by the team of employees and students related to the preparation of highly specialized electric race vehicles are a testing ground for testing new solutions also in the improvement of design methods. As part of efforts to optimize vehicles, improved MBD methods have been proposed that focus on MBDO optimization activities and can be integrated into the product development process in the development phases, in particular in the early stages of projection. The proposed method gives such opportunities when applying the existing design resources and in particular using of the same software supporting design as in the previous activities. This method was refined and applied during the design of vehicles that achieved outstanding results in the competition. In further works, it is necessary to automate these project activities even more, especially by ensuring cooperation with the systems used for FEM and CFD calculations, which is particularly important in these implemented applications. In the context of the development and shaping complex composite structures mainly with complex shapes es, there has been a need for automation and integration into the MBDO methods of generative modeling in CAD and KBE systems. This will enable the immediate and automatic change of the complex shapes of the geometric model used in the calculations of FEM and CFD.

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