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MODEL BASED VALIDATION OF AUTOMOTIVE POWERTRAINS

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Abstract

The elementary design model “Contact & Channel Model C&CM” developed at the Institute of Product Development at the University of Karlsruhe connects the shape-oriented level of describing technical systems with the corresponding function-oriented level. In this paper the extension of the C&CM model with the mathematical-oriented level using Modelica simulation models is presented. The Modelica language is suited for multi-domain simulation of large, complex and heterogeneous physical systems. Both models are integrated in a CAD program to create a so called “Behavioural Mock Up BMU” which contains beside the geometrical and functional information all relevant mechanical, dynamic, kinematic and electric properties with sufficient simulation quality. The BMU modules are used in the vehicle development process during the validation phase in different simulation environments including test beds for powertrain components. The simple example of a spur gear unit shows the basic ideas of the newly developed concept, while the simulation of an automated gearbox illustrates the applicability of the BMU modules for complex systems. The method is finally applied for testing of powertrain components in the validation phase of the vehicle development process.

Keywords: vehicle development, validation, testing, element model

1 Introduction

In general the product development process includes many subconscious processes which are difficult to be determine and which requires an engineering team with a great deal of experience and expertise. The validation process follows the design process to ensure the functionality and durability of the product.

In the future vehicle development process the main design and testing tasks will be done using virtual product models supported by software based simulation tools. An important phase is the validation of prototype vehicle components on test beds at an early stage when a complete prototype vehicle for track testing is not available [1].

A key factor in this process is the capability to simulate the non-existing vehicle components on the test bed in a very realistic way. This requires an integrated validation environment to exchange simulation models, to get design information to parameterize the simulation models and to perform test runs to validate the models. The models can be grouped in non-realtime and realtime models. Non-realtime models can represent complex mechanical, hydraulical and electrical effects of the vehicle while realtime models can be used to interface to the real world for example to be used on engine or powertrain test beds, which are shown in figure 1.

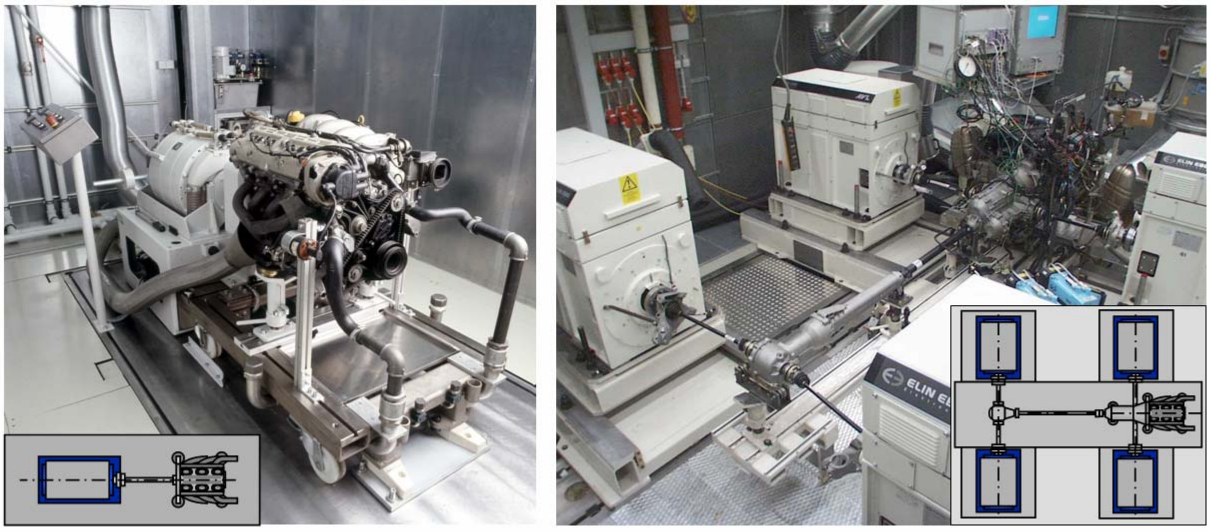

Figure 1. Test beds for engine (left) and powertrain (right)

Although the product validation process cannot be fully automated it is still possible to support the development engineer in this process. In order to be helpful to the engineer in his everyday work the support is to precisely describe the components of the vehicle in digital models [6]. The presented methodical approach in this paper consists of modular component prototypes which are extended with functional and mathematical properties to create so called "Behavioural Mock Up" (BMU) modules for the different parts of the vehicle, as defined in [9].

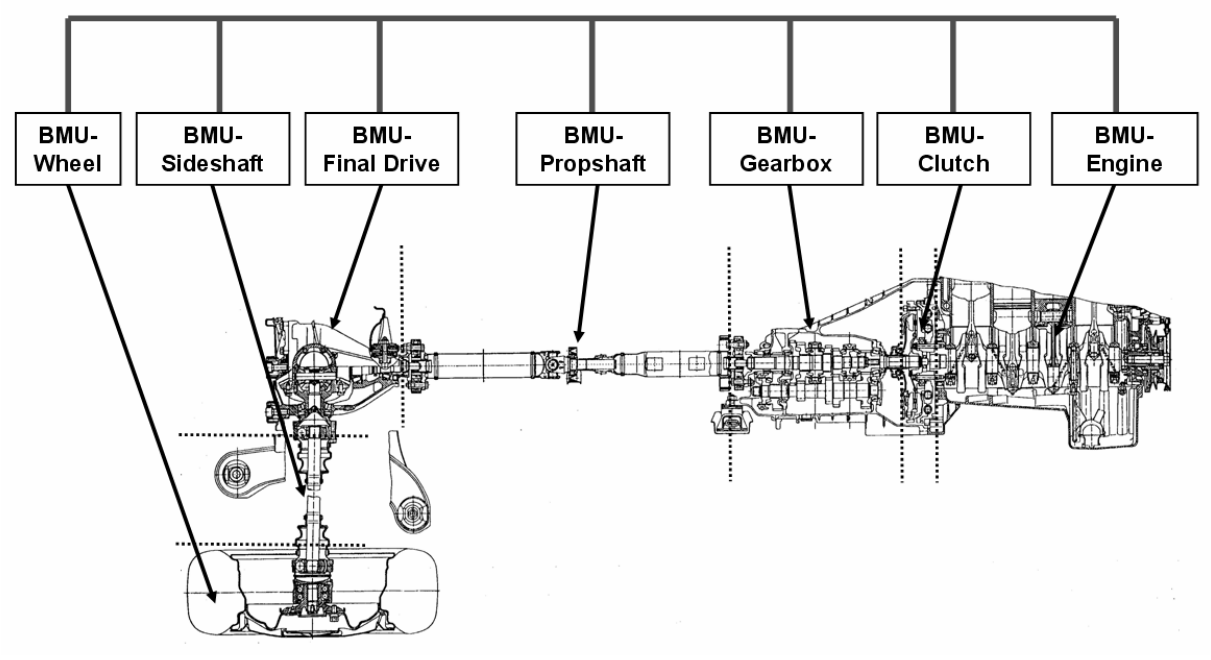

Figure 2. BMU modules of the vehicle powertrain (rear-wheel drive)

For example the BMU modules of the powertrain for a rear-wheel driven passenger car are shown in figure 2. The BMU modules contain beside the geometrical information all relevant mechanical, dynamic, kinematic and electric properties with sufficient simulation quality. The interfaces of the modules are clearly defined and allow an easy exchange of modules. The parameter dependencies inside and between the modules allow the prediction of the consequences from design changes without the necessity to build new and expensive prototypes.

2 Objectives

2.1 The Contact and Channel Model C&CM

At the Institute of Product Development at the University of Karlsruhe the elementary thinking model "Contact and Channel Model" (C&CM) has been used successfully in research and product development for several years [3], [4], [5]. It connects the abstract level of functions with the concrete level of the shape of technical machine elements and systems. Working Surface Pairs (WSP) and Channel and Support Structures (CSS) are basic elements of this design model and they define the interface between these two abstraction levels [2].

Working Surface Pairs are the surface of a technical system via which system parameter such as material, energy and information are transmitted. Channel and Support Structures always connect two Working Surface Pairs and can therefore be regarded as a linkage. Channel and Support Structures conduct system parameter such as material, energy and information from one Working Surface Pair to the next. Apart from that they can also save these system parameter for giving them to one of the two Working Surface Pairs some time later. To realize any function in a technical system at least two Working Surface Pairs and one Channel and Support Structure are necessary.

The function of a technical system is exclusively determined by the properties of the Working Surface Pairs and the Channel and Support Structures of this system. Objective of this paper is to demonstrate the usability of the C&CM together with mathematical modelling to define BMU modules in the product validation process.

2.2 Mathematical Model

The description of the real physical system using a mathematical description is now widely used to quickly determine and optimize product properties without building costly physical prototypes. Such an approach can often drastically reduce development time, while increasing the quality of the designed product [7].

When modeling a system it is essential to use the appropriate laws of nature that govern the behaviour of the different parts of the system. These laws are often expressed as mathematical equations. There are basically four main kinds of equations:

- Differential equations
- Algebraic equations
- Partial differential equations
- Difference equations

Different kinds of mathematical models can be characterized by different properties reflecting the behaviour of the systems that are modeled. One important aspect is whether the model incorporates dynamic time-dependent properties or is static. Another dividing line is between models that evolve continously over time, and those that change at discrete points in time. Some phenomena are conveniently described by probability distributions leading to stochastic models, whereas deterministic models allow the behaviour to be represented without uncertainty.

The principle of conservation of energy is one of the most fundamental laws of nature. It can be formulated as follows:

- The amount of energy in a closed system can be neither created nor destroyed.

A consequence of this principle for a closed system is the following:

- When energy flows together at a certain point, without storage at that point, the sum of all flows into that point is zero.

Energy is always transported using some carrier, which for example in translational or rotational mechanical systems is linear or angular momentum. Different physical domains will usally have different flow quantities, since they normally use different carriers. The concept of potential is a measure of the level of energy. The choice of a potential quantity for a particular domain must always be such that at a connection point all potential variables of connected components are equal, as shown in table 1.

Table 1. Energy carriers with associated potential and flow quantities

Domain Type	**Potential**	**Flow**	**Carrier**
Electrical	Voltage	Electric current	Charge
Translational 1D	Position	Force	Linear momentum
Rotational 1D	Angle	Torque	Angular momentum
Mechanical 3D	Position and Rotation angle (3D)	Force and Torque (3D)	Linear and angular momentum (3D)
Magnetic	Magnetic potential	Magnetic flux rate	Magnetic flux
Hydraulic flow	Pressure	Volume flow rate	Volume
Heat	Temperature	Heat flow rate	Heat
Chemical	Chemical potential	Particle flow rate	Particles

3 Methods

3.1 Object-oriented model language Modelica

Modelica is a freely available, object-oriented modeling language that allows specification of mathematical models of complex systems for the purpose of computer simulation of dynamic systems where behaviour evolves as a function of time [8]. The most important features are:

- Modelica is based on equations instead of assignment statements. This permits acausal modeling that gives better reuse of models since equations do not specify a certain data flow direction.

- Modelica has multidomain modeling capability, meaning that model components corresponding to physical objects from several different domains can be described and connected, as shown in table 1.

- Modelica has a strong software component model, with constructs for creating and connecting components. Thus the language is ideally suited as a description language for complex physical systems.

- Components have well-defined interfaces, called connectors, for communication and coupling between a component and the outside world. A component is modeled independentely of the environment where it is used, which is essential for its reusability. No means of communication between a component and the rest of the system, apart from going via a connector is allowed.
- A pictorial representation of components and connectors is available as connection diagram.

The currently at the Institute of Product Development at the University of Karlsruhe developed methodical approach for model based product validation combines the strength of the Contact and Channel Model with the Modelica simulation language.

The basic idea is to describe the shape and the functional properties using the Contact and Channel Model within a CAD software model, which is at the same time a framework to integrate the mathematical description of the physical properties of the system using Modelica into a “Behavioural Mock Up”, as shown in figure 3.

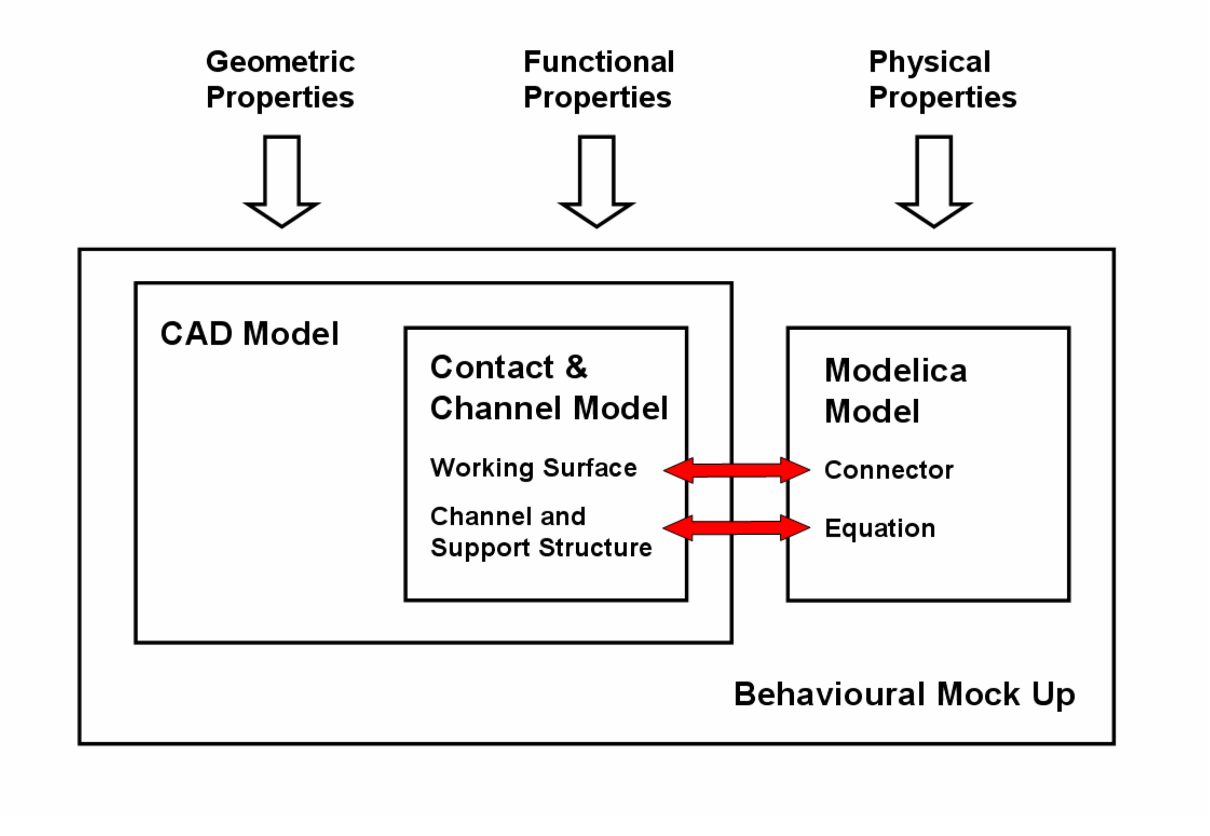

Figure 3. Integration of CAD, C&CM and Modelica into a BMU

It must be noticed, that the Working Surface in the C&CM is extended by physical properties using the “Connector” in Modelica, while the physical properties of the Channel and Support Structure in the C&CM is described by “Equations” in Modelica.

3.2 Application example: Simulation of a Spur Gear Unit

Figure 4 shows a simple technical system: two gearwheels of a spur gear unit. Between the tooth flanks of the two gearwheels the Working Surface Pair WSP_1 is formed. The WSP_1 transmits force from gearwheel 1 to gearwheel 2. It is formed because of the functional contact of the Working Surfaces WS_1 and WS_2 of both gearwheels. At the flank of the fitting key the force is transmitted into the key, here is the second WSP to fulfill the function of gearwheel 2. Both WSP are connected by the Channel and Support Structure CSS of the body of the gearwheel [5].

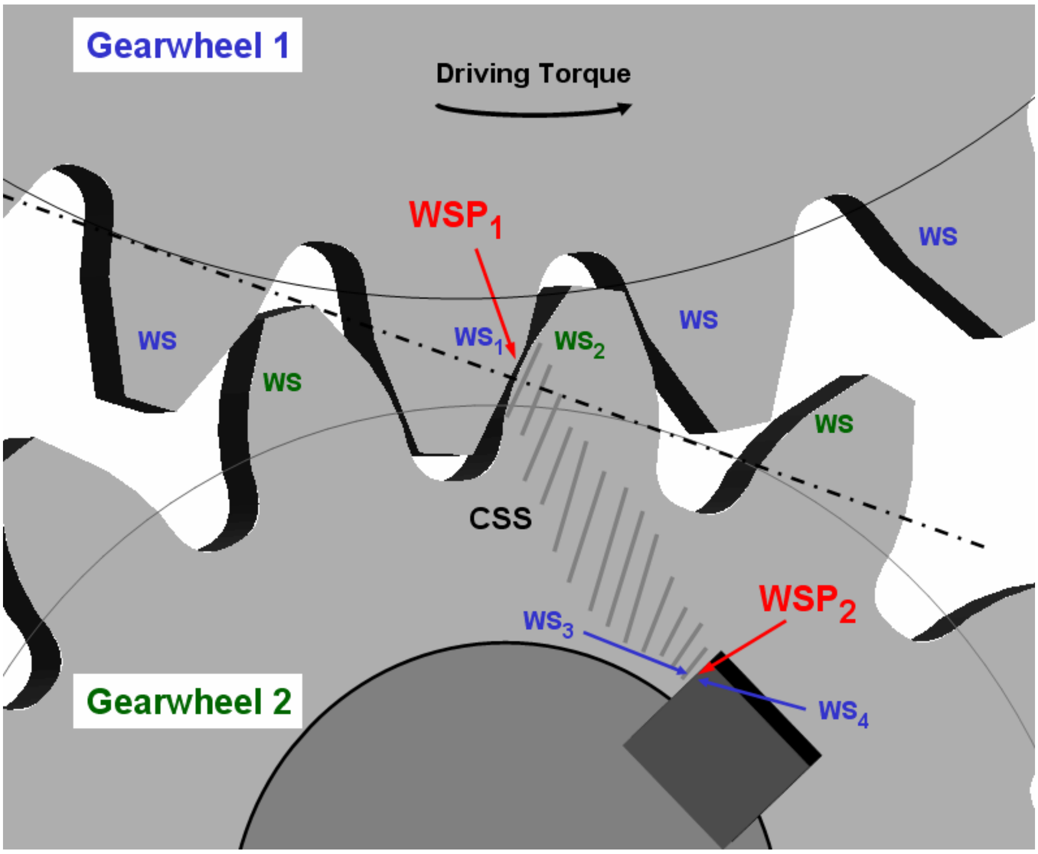

Figure 4. WSP and CSS at the example of a spur gear unit

In a classical modeling approach the dynamic behaviour of the spur gear unit is described using a spring element “c” and a damping element “d” between gearwheel 1 and gearwheel 2 as shown in figure 5, while the connections to the center of the gearwheels are considered to be infinite stiff. The spring and damping elements have to account for all physical effects in the body and teeth of the gearwheels and in the functional contact between Working Surfaces WS_1 and WS_2.

Using the Contact and Channel Model it is now possible to describe the dynamic effects in a much more suitable way. As shown in figure 6, the actual energy transfer in WSP_1 is desribed in terms of the flow variable *Force* and the potential variable *Position*. In this simple mechanical model we neglect the thermal heat transfer in WSP_1. Using the principle of conservation of energy we can now state that the amount of energy between Working Surfaces WS_1 and WS_2 has to be constant. As consequence it follows, when we assume that both WS_1 and WS_2 have the same *Position*, that the acting *Force* is the same on both WS_1 and WS_2.

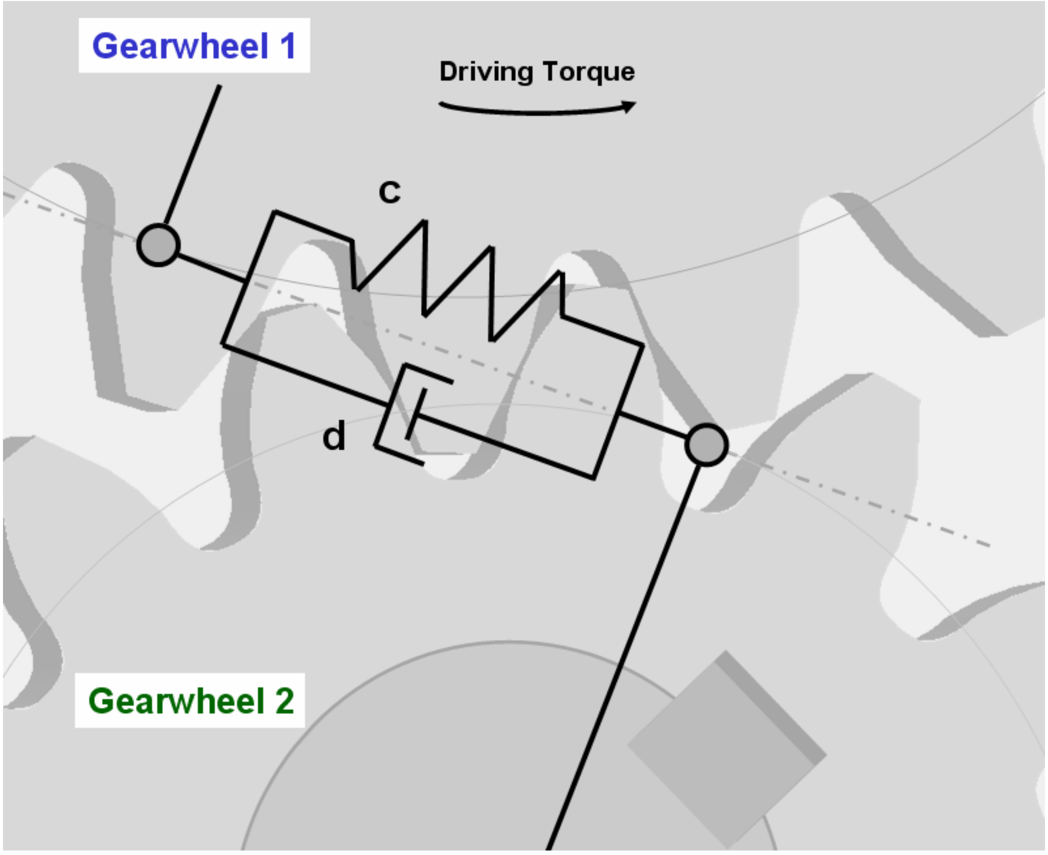

Figure 5. Dynamic model of the spur gear unit using classical approach

For the Channel and Support Structure CSS we have now different model options to choose from. In the simplest case we assume an infinite stiff behaviour of the gearwheels 1 and 2, which leads to a rigid body model of the spur gear unit, where the driven torque is the driving torque multiplied by the gear ratio. A more accurate model can now account for elastic effects in the CSS and is taken for example from numerical simulation data using finite element solver.

Based on a functional consideration we must assure that the fitting key on gearwheel 2 has no slack in circumferential direction, this means that WS_3 and WS_4 have the same *Position*, thus follows that the acting *Force* is the same on both WS_3 and WS_4.

To describe the Working Surfaces WS_1 to WS_4 we define the following connector type in the Modelica language:

```
connector Flange
  Position      s;   // Potential variable for WSP 1 and 2
  flow  Force   f;   // Flow variable for WSP 1 and 2
end Flange;
```

It has to be noticed that Modelica uses a language syntax very close to the programming language “C” to define variables, equations, connections and models.

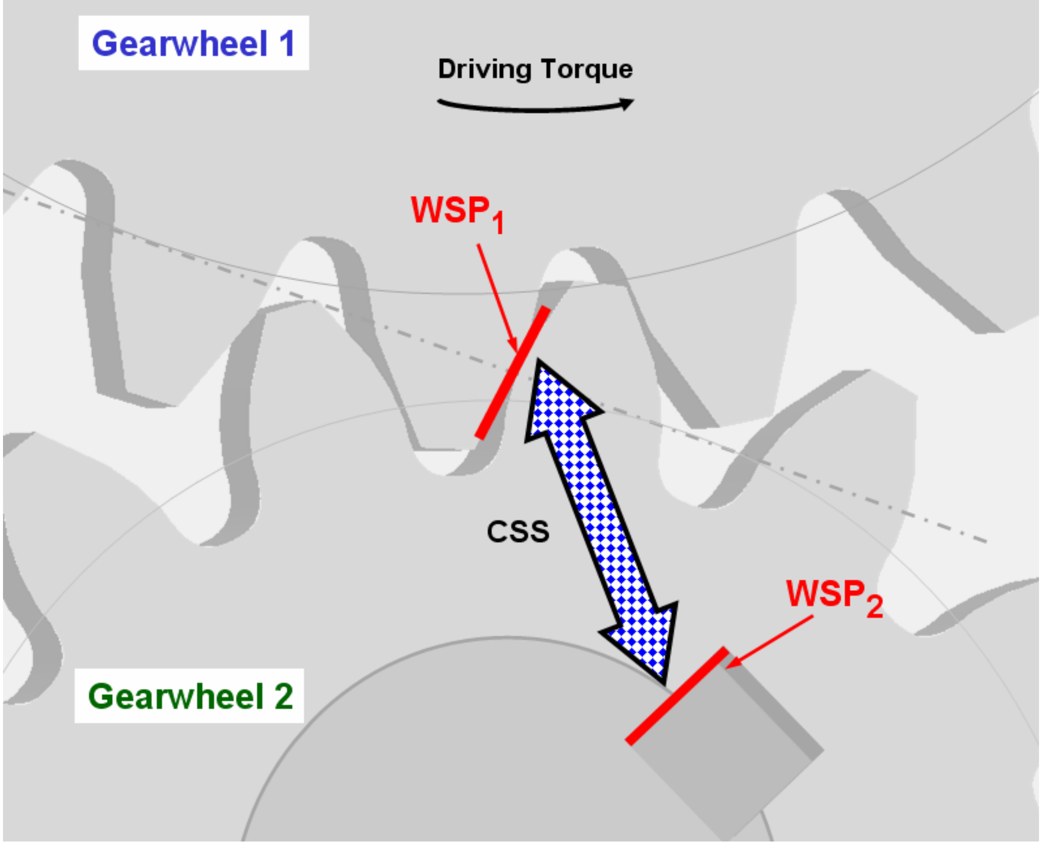

Figure 6. Dynamic model of the spur gear unit using Contact and Channel Model

We can now write the following model description for the dynamic behaviour of a gearwheel inside the spur gear unit using a simple linear spring model, where the internal force in the CSS is a linear function of the relative displacement between the position in Working Surface 1 and 2:

```
model Gearwheel
   Flange    flange_a; // Working surface 1
   Flange    flange_b; // Working surface 2
   Force     f;        // Internal force in CSS
   parameter c;        // Spring constant in CSS
equation
   f = c *(flange_b.s - flange_a.s);
  flange_b.f =  f;
  flange_a.f = -f;
end Gearwheel;
```

To complete the overall model for the spur gear unit we can now combine two instances of the gearwheel model and add two external forces on the driving and driven side:

```
model Spur_Gear_Unit
  Gearwheel  gearwheel_1;
  Gearwheel  gearwheel_2;
  Force      force_driving; // External force on gearwheel 1
  Force      force_driven;  // External force on gearwheel 2
equation
  connect (force_driving, gearwheel_1.flange_a);
  connect (gearwheel_1.flange_b, gearwheel_2.flange_a);
  connect (gearwheel_2.flange_b, force_driven);
end Spur_Gear_Unit;
```

3.3 Application example: Simulation of an Automated Gearbox

Figure 7 shows a more sophisticated example which is an automated gearbox for passenger cars. Goal of this example is to illustrate the usage of the C&CM to define the framework for the mathematical description of the physical system.

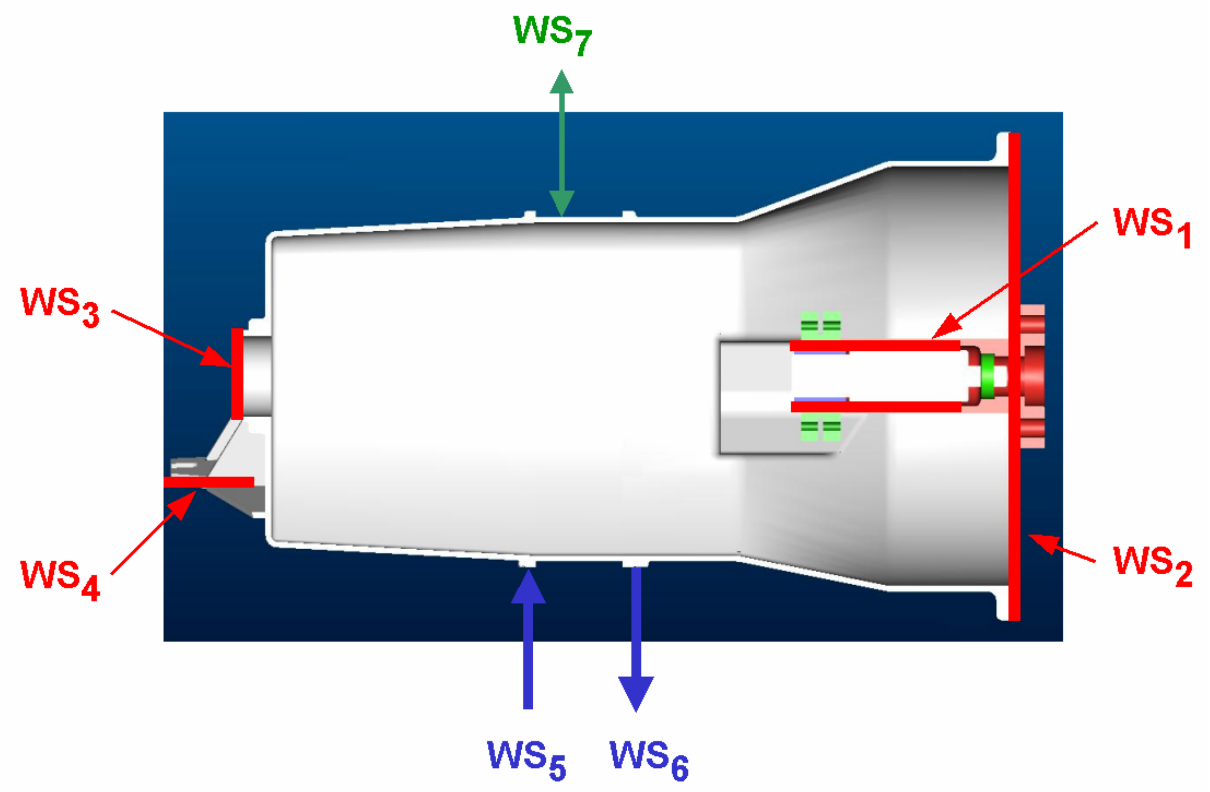

Figure 7. CAD model of the Automated Gearbox

For a better understanding the internal parts of the gearbox like hydraulic converter, clutches and gearwheels have been suppressed in the CAD drawing.

In the first step in the CAD model the following Working Surfaces have been marked as shown in table 2. The information interface in WS_7 exchanges digital signals and data with other components of the vehicle and influences the dynamic behaviour of the gearbox, e.g. getting an external gearshift request.

Table 2. Working Surfaces in Automated Gearbox

Working Surface	**Domain**	**Description**
WS_1	Rotational 1D	Input shaft
WS_2	Translational 1D	Mounting flange to engine body
WS_3	Rotational 1D	Output shaft
WS_4	Translational 1D	Mounting flange to vehicle body
WS_5	Heat	Input oil cooler
WS_6	Heat	Output oil cooling
WS_7	Information	CAN-Communication to engine and vehicle control unit

In the second step the information about the Working Surfaces is exported from the CAD model into the Modelica environment. If desired some geometric information from the CAD data is linked to model parameters in Modelica, for example the size of the input shaft or the size of the piping to and from the oil cooler.

In the third step the appropriate mathematical equations are stated in Modelica language to describe the dynamic behaviour of the gearbox with respect to the mechanical and thermal domains and also for the information interface. All necessary geometric parameters in the mathematical model are linked to the CAD model. In the simplest case an ideal gearbox model sets a certain constant gear ratio requested from extern and neglects the translational interfaces WS_2 and WS_4 and thermal interfaces WS_5 and WS_6:

```
model AutomatedGearbox
  Flange    flange_a; // Working surface 1
  Flange    flange_b; // Working surface 3
  CANratio  ratio;    // Working surface 7
equation
  flange_a.phi = ratio * flange_b.phi;
  0 = ratio * flange_a.tau + flange_b.tau;
end AutomatedGearbox;
```

Now the steps one to three are repeated for all BMU modules in the vehicle like engine, driveline, chassis and auxiliary devices.

In the forth step the complete vehicle is virtually assembled as shown in figure 8. The Working Surfaces of the different components are now merged to Working Surface Pairs (WSP), thus enabling Modelica to generate automatically the necessary connection equations. The CAD model in this example includes the geometric description of the powertrain, while the Modelica model incorporates the physical functionality including the software functionality of the different electronic control units (ECU) in the vehicle. The arrows indicate the linkage of geometric parameters between the CAD model and the Modelica model. The parameters in the Modelica model are automatically updated upon change of the geometry in the CAD model.

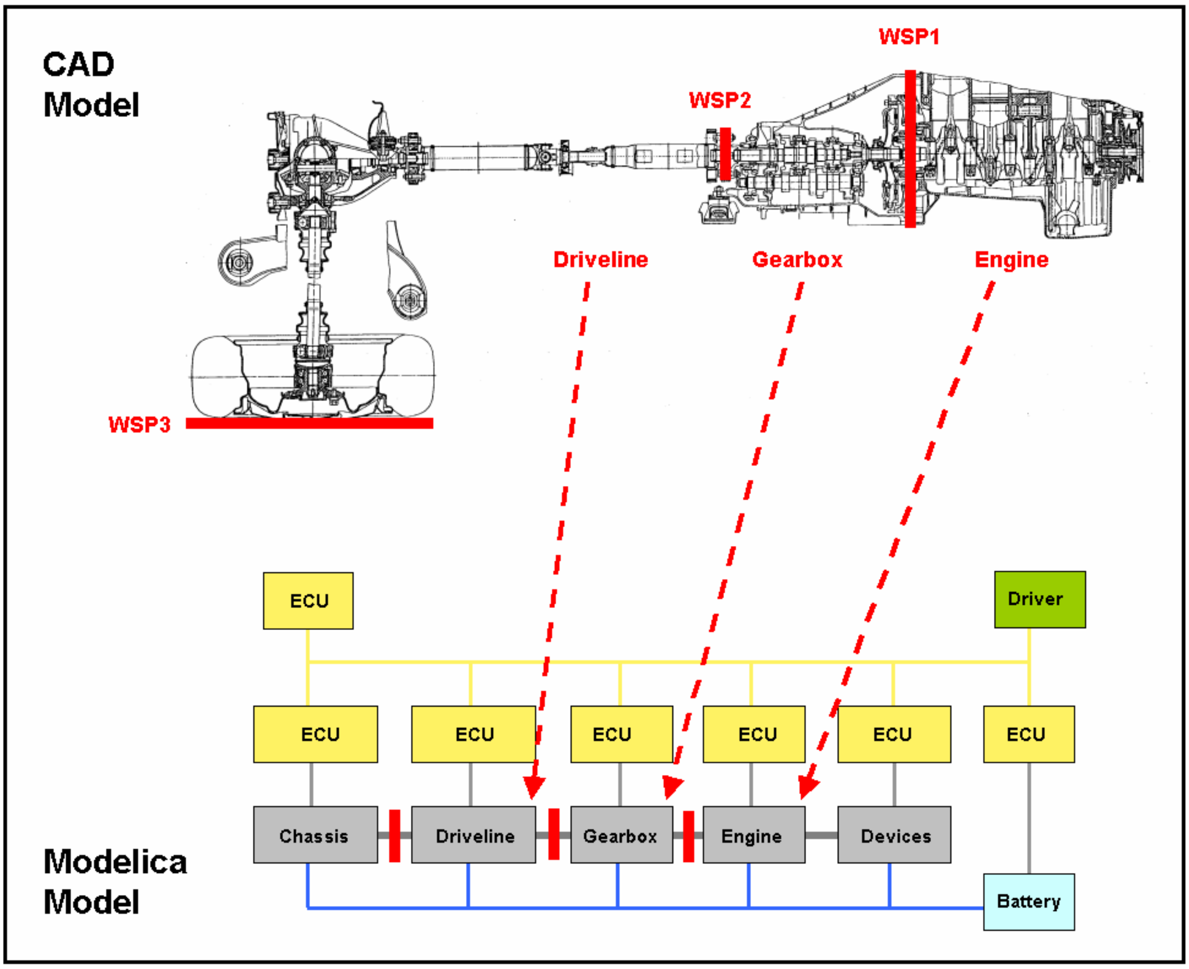

Figure 8. BMU modules of the vehicle powertrain

4 Results

In the course of this research project a new approach to integrate the concrete level of the shape of a technical system with the abstract level of its functionality has been developed and extended with a framework for the mathematical description of the physical properties of the system. This concept supports very well the definition and implementation of BMU to be used in the validation process of the product development process.

As shown in figure 9 the BMU modules of the different vehicle parts are used in different simulation environments during the validation process, which is between the design and the production process. In Offline Simulation all parts of the vehicle including the human driver have to be simulated using mathematical models. For Hardware-in-the-Loop testing only the electronic control units (ECU) of the vehicle are used as a real prototype, all other components are simulated. At the engine test bed only the engine with ECU is set up using real parts, all other components are simulated and so on. Finally the complete real protoype vehicle is tested on a real track during the last phase of the validation process. It is obvious that BMU with clearly defined Workings Surface Pairs and Channel Support Structures allow a seamless integration of real and simulated vehicle components in different testing configurations.

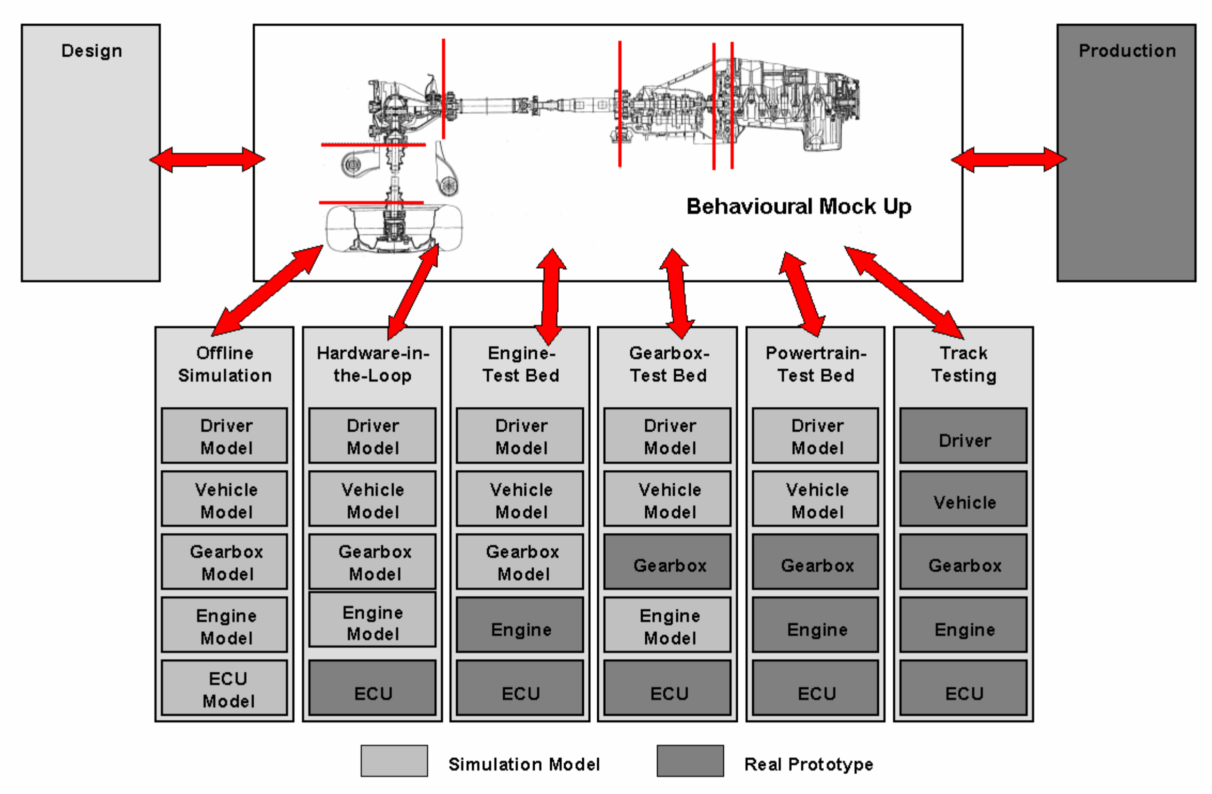

Figure 9. Usage of BMU in vehicle development

5 Conclusion

In the future the comprehensive utilisation of simulation technology in the verification process based on virtual prototypes like a BMU will improve the reliability, quality and productivity of the vehicle development processes in the automotive industry. The main benefit of the presented approach is a deeper integration of the geometrical description of the physical system with the functional and the mathematical description of its behaviour. This will help the development engineers to gain a better and faster insight into the various effects of the physical system.

Another benefit is the object-oriented design of the descriptive simulation language Modelica, which allows the building and extensive reuse of model libraries. This enables the engineering teams from different areas to share and exchange models of the physical systems for their specific use in the validation phase.

The main task of future research and development will be how to implement the Contact & Channel Model inside commercial CAD software programs and how to link it to the Modelica simulation environment to get an integrated BMU software environment. The challenge during this work will be to develop an intuitive user-interface so that the software implementation will fully exploit the strength of the combined C&CM and Modelica models in a natural and easy fashion.

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