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Requirement Oriented MBSE Approach for Next-Generation Electrified Rail Vehicles

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Abstract

This paper presents a methodology for the systematic, requirements-oriented development of new passenger rail vehicles using MBSE. The application example focuses on the implementation of drive systems with electric battery storage, with the objective of reducing CO_2 emissions on branch lines. The customer requirements, in particular with regard to range and track profile, are recorded in the SysML model. A bidirectional interface between CAD and SysML models, developed in Python, allows for the automatic determination of optimal parameters, for example in terms of capacity and weight distribution, for vehicle development. The CAD models are configured from the SysML model.

Keywords: Modelbased Systems Engineering (MBSE); Computer Aided Design (CAD); Railway Vehicle; Alternative Drives

1. Introduction

The reactivation of railway lines is crucial for reducing greenhouse gas emissions in the transportation sector, especially in rural regions. Innovative propulsion systems such as battery-hybrid and fuel cells can help with this; however, suitable vehicle concepts are currently lacking. This research project investigates how model-based systems engineering and modularization can accelerate the development of such vehicles. It pursues the following objectives:

1. *Interdisciplinary modeling*: Develop a methodology for systematically capturing and representing technical and non-technical requirements. A focus is placed on incorporating socially relevant information and integrating the needs of passengers, maintenance staff, and train drivers.

2. *Integration of modeling tools*: Seamless and consistent integration of development tools for automatic synchronization and plausibility checking of parameters. This enables comprehensive evaluation and optimization of ecological, economic, and social dimensions already in the early development phases.

3. *Modularization of vehicle architecture*: Dividing the vehicle into harmonized, reusable modules that can be flexibly adapted to different requirements. The modularization of certification documents also facilitates the approval process.

The project aims to advance the development of flexible, environmentally friendly rail vehicles that address urban and rural challenges.

2. State of the art

For the mobility transition and reduction of traffic-related emissions, railways are of utmost relevance. Railways are increasingly becoming the focus again in rural areas. A major aspect is the reactivation of disused lines and the revitalization of previously underutilized branch lines to reconnect rural areas more effectively to passenger rail transport, thereby creating a more comprehensive and accessible rail service

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Fig. 1 NGT-Taxi digital mock-up [31]

across the region [1]. Some vehicle concepts exist for this purpose, such as FlexSbus-LR (RWTH Aachen), Draisy (SNCF), Train Léger Innovant (SNCF), Revolution VLR (University of Warwick), and Coventry VLR (University of Warwick) [2][3][4]. All these vehicle concepts are smaller than the currently existing due to that they are adapted to the requirement of the focussed lines. For the success of all these vehicle concepts, it is crucial to keep development and modification costs low. Therefore, this initiative does not focus on vehicle development but rather on developing a methodology for requirement-driven modularization. A particular challenge is considering the numerous national and international regulatory frameworks for rail transport [5][6][7][8]. The NGT-TAXI (Fig. 1) is a vehicle concept for use on currently less profitable branch lines and reactivation routes and its integration into the system. The approach involves a small, lightweight, automated rail vehicle with alternative propulsion and a capacity of between 20 and 70 passengers [9][10][11].

Approaches to mastering the increased complexity can be found in Model-Based Systems Engineering (MBSE) [12][13]. Within this, three elements can be distinguished: language, tool, and method [14]. The Systems Modeling Language (SysML) has largely established itself as the standard language, providing a formal basis for modeling through its defined semantics and syntax [15]. Various software products are available as tools. Proprietary products have limited expandability through interfaces compared to open-source projects, which, while more adaptable, often have less industrial adoption and lack professional support. Currently, there is no unified approach regarding methods, which limits the reusability of models or model elements and collaboration within value networks. A research project at RWTH Aachen aims to store standard functions in libraries. Since these are modeled as blocks and due to specific, non-public stereotypes, they can only be used in the Cameo software [16][17]. In contrast, TU Clausthal is researching the fundamental comparison of the syntax of system models and shape models but without specific application reference [18][19].

Other approaches in the international research landscape focus on automated requirement testing at the interface between CAD and SysML, mainly investigating mountability [20]. At KIT, SysML is used for agile product development of mechatronic products. However, the methodology focuses more on project management than on the development of modular products [21]. Further approaches include using the Action Language for Foundational UML (Alf) to depict the behavior of mechatronic systems in SysML models, though its use has so far not extended beyond simple academic examples [21][23].

An analysis of the state of the art has revealed a continued lack of methodology for consistent system modeling of variant-determining requirements and modularization-relevant design parameters, as well as their automated exchange at the SysML to 3D-CAD interface. In the DFG Collaborative Research Center 562 "Robot Systems for Handling and Assembly," the authors laid the foundations for interdisciplinary requirement management for modular and reconfigurable products. Using parallel robots as an example, they developed a methodology to capture and evaluate requirements from different knowledge domains (mechanics, control, cost) based on industrial applications. Various interconnected partial models (requirements, function, architecture) were created in SysML. The network of relationships could be evaluated using algorithms to automatically identify previously undiscovered conflicts, which allowed them to be specifically resolved and a plausible requirement catalog for a specific application created. If the application case of the robot system changed, the model could be used to identify parameters for reconfiguration (e.g., arrangement of drives) [24][25].

In the EU project ELVA, the developed methods were transferred to the requirement management of electric vehicles. Besides technical requirements, it was necessary to anticipate new legal and safety-relevant requirements to enable sensible battery integration in passenger cars. A particular focus was on considering uncertainties in requirement elicitation due to the new technology and deriving a robust safety concept. Furthermore, it was examined how natural language terminologies could improve the creation and automatic evaluation of requirement models [26][27][28].

Additionally, methods for objectifying decisions in the development of region-specific vehicle concepts were further developed. For this, requirements for a vehicle type were systematically captured from all relevant target regions and linked with the vehicle architecture. Automatic analysis identified requirements that could be globally harmonized and those that needed to be diversified regionally, e.g. depending on climate or route profile [29][30][31].

At a rail vehicle manufacturer, approaches to requirement-driven modularization were implemented by establishing a lean, digital development process for cable harness development. Adaptable modules for different customer requirements, such as in pneumatic braking systems, were also created in this context [32][33].

The most recent work deals with establishing a digital process for developing rail vehicles with alternative drives. Consistent data exchange from the SysML model to the CAD model and then to augmented (AR) and virtual reality (VR) applications is intended. At the same time, altered data in VR should be fed back into the CAD and eventually into the SysML model. The basic feasibility was demonstrated on individual assemblies of a battery electric multiple unit (BEMU) [34][35][36].

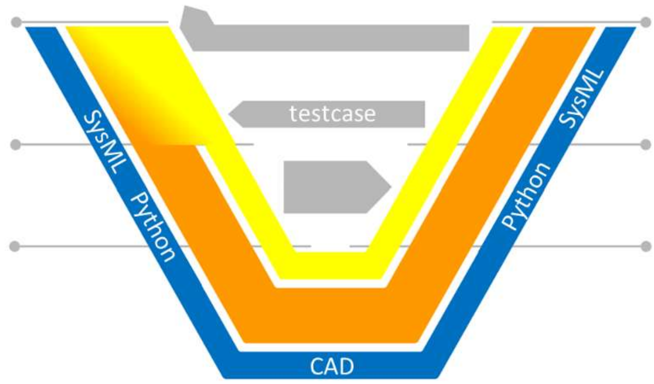

Fig. 2 Use of models in the V-model to achieve the objectives of the feasibility study.

3. Concept of the Feasibility Study

In the following, the modeling of the application example is explained. The modelling approach is based on the V-model (see Fig. 2), with SysML representing the upper, more abstract layer, CAD the concrete technical design, and Python combining both models. This necessitates the clarification of the task to be solved. Subsequently, the requisite specifications for the models and their system architecture are delineated. In order to develop an interface between SysML and CAD, it is first necessary to create appropriate models.

The system under consideration is a rail vehicle that is operated using electric power. The vehicle is equipped with battery packs, which are mounted individually on the roof. Each battery pack is characterised by a specific capacity, physical dimensions and weight. The batteries can be mounted on the train's roof using C-rails in a modular fashion. The mounting time scales with the number of bolts. The weight, axle loads and range of the vehicle are dependent upon the number of installed packs and their positioning. The number of battery packs is constrained by the available space on the roof and the weight distributed to the axles. The range is determined by the total capacity and the overall weight of the vehicle. Furthermore, it is essential to consider the minimum battery lifespan, as batteries inevitably lose capacity over time, which consequently reduces the vehicle's range. The objective of the interface is to identify the optimal parameters that enable the rail vehicle to achieve the greatest possible range while ensuring that the axle loads remain within the prescribed limits.

In the initial phase, a list of requirements is formulated. The requirements are derived from a process of clarification regarding the task at hand and include all information necessary for the creation of a model. The values are estimated based on real rail vehicles in order to achieve results that are as realistic as possible. Such values include typical data points such as mass, dimensions, and the size of components, which are primarily utilized for the modeling of the CAD model. In addition, the list includes requirements that must be met, such as maximum axle loads and the configuration of the travel route, which directly influence the consumption and, consequently, the vehicle's range. Accordingly, an illustrative route is selected for the computations in this study. For purposes of clarity, the requisite specifications are allocated to the corresponding components. Based on the aforementioned requirements list, a requirements diagram is constructed with the Eclipse Papyrus software, with the objective of integrating the written requirements into the SysML model. The requirements pertaining to the rail vehicle are itemized. These include the length of the usable roof surface that is necessary for the CAD model, the weight of the vehicle without the battery systems, and the allowable axle loads that are utilized for subsequent calculations.

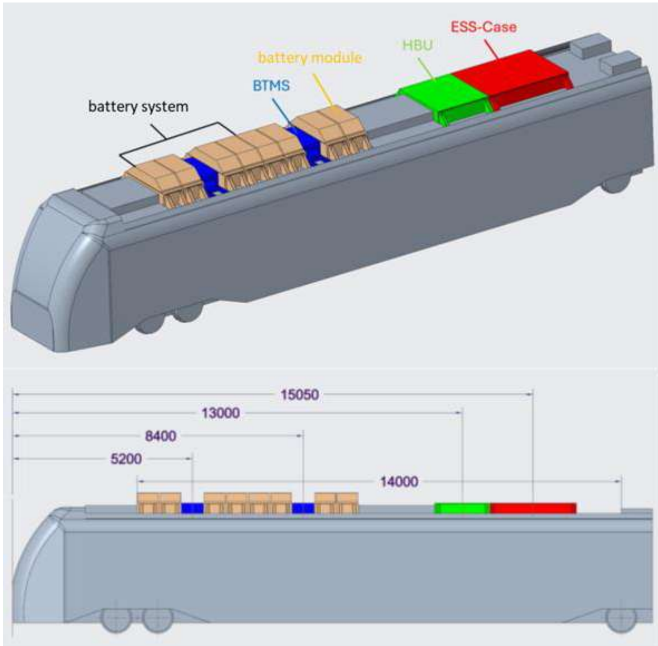

Fig. 3 CAD-model of the train roof and roof equipment.

The values from the requirements list are used as the basis for the CAD model in Fig. 3. The dimensions are taken from real-life examples, and the model only shows rough contours to indicate the space. Since the focus is on the battery system, this work does not include comprehensive modelling of the train. The model consists of five different elements. The basic frame is formed by the vehicle dummy. C-rails are mounted on the roof, where various components can be attached. On a real rail vehicle, certain areas are predefined for structural reasons and cannot be changed, so the available space on the train's roof is indicated with components that cannot be relocated, such as the air conditioning system. Additional equipment like auxiliary converters (HBU) and ESS case are to be installed on the rear mounting area, while the front area is reserved for the battery systems. Each battery system comprises a Battery Thermal Management System (BTMS) and up to four battery packs. One to two battery systems, equivalent to eight battery packs, can fit on the available mounting space. Fig. 3 illustrates the positioning of individual components on the roof using parameters, originating from the foremost edge of the vehicle as a reference. The parameters are listed in a family table, where they can be adjusted. Since the models are created as allocated volumes for space reservation, the individual masses must be manually set for each part in the CAD program. The masses and the overall center of gravity of the entire vehicle are also stored in the family table to simplify data exchange. The number of battery packs can be varied to optimize the weight and range of the rail vehicle. It is assumed that only identical battery systems are installed. For example, with six battery packs, two battery systems each with one BTMS and three battery packs are used. Different variants result from this and are listed in the CAD program in a family table. The table can be saved and edited as an Excel spreadsheet, resulting in a .xlsx file. Python libraries like pandas enable reading, editing, and saving such files. To overwrite the values in the CAD program with new ones, the updated .xlsx file must be manually imported via the family table and saved in the folder with the CAD files. This allows data from the table to be used for further calculations and overwritten to update the CAD model accordingly. The position and number of battery packs influence the center of gravity and axle loads. Additionally, the total battery capacity and thus the vehicle's range change.

To provide a more detailed illustration of the interconnections between the various components, a block definition diagram is constructed using the Eclipse Papyrus software. The central element is the rail vehicle, which comprises an ESS case, the HBU, the drive, and one to two battery systems. All irrelevant components are collated and categorised under the heading of "Other Components." For example, a composite association exists between the rail vehicle and the battery system, implying that the rail vehicle includes one to two battery systems. In consequence, the rail vehicle is comprised of the derived attributes *TotalMassRailVehicle*, *TotalEnergyRailVehicle*, and *TotalEnergyConsumptionRailVehicle*, which are constituted by the attributes of the subordinate blocks. The range attribute is calculated via the interface. The battery system block contains the attributes *TotalMassBatterySystem* and *TotalEnergyBatterySystem*. This block, in turn, contains one to four battery packs and one BTMS, which are connected through composite associations and have their own attributes. The requisite attributes for calculation are ascribed to each block, with the most significant being the mass of the constituent parts and the energy consumption or capacity of the battery packs.

The generation of the SysML model automatically produces a .uml file that can be accessed and modified. The file is stored directly within the SysML project folder. The file is based on XML and can be read with the Python programming language. The structure is divided into three levels: *packagedElement* (class), *ownedAttributes* (attributes), and *defaultValue* (values). At each level, objects may be created, each of which is marked with a start and end frequency. By identifying the nomenclature of the elements and attributes, the requisite parameters can be located within the file, thereby facilitating calculations and the modification of specific values within the .uml file. In order to incorporate changes into the SysML model, it is necessary to overwrite the existing file and restart the SysML modeling tool. A use case diagram is constructed for the purpose of modeling the travel route. The train operator has the option to accelerate, decelerate, maintain a constant speed, or remain stationary. Each of these actions has an impact on the vehicle's overall consumption. In order to facilitate the calculation of consumption, it is necessary to simplify the model by not considering the incline of the travel route. This results in a model in which consumption is dependent on four sources. In any given use case, the train is assumed to have a baseline consumption level that is required to power systems such as air conditioning or lighting. In the case of constant travel, a rolling resistance acts on the rail vehicle. Similarly, an acceleration resistance is present during acceleration, while in deceleration, energy can be recovered. However, this latter phenomenon is not considered in the calculations presented here. The exact calculations are performed within the designated Python interface.

4. Implementation of the Interface

This section provides an overview of the methodology employed in the implementation of the interface between the SysML and CAD models, which was developed in Python 3.9.13. The following section will provide an overview of the program's structure and functionality, with a examination of the key libraries that have been imported. The ElementTree module is employed for XML file handling and namespace registration, while Pandas is utilized for Excel file import. Additionally, the Regular Expressions (RE) module is leveraged for the extraction of numerical data from variant names. Two principal classes, "Variant" and "Part," define objects with properties unique to variants and components. These properties can be modified as required throughout the program.

The program workflow is structured through the implementation of a series of functions. The `register_namespace` function serves to register SysML-specific names, thereby enabling the creation of new .uml files for Papyrus. Subsequently, the `read_uml` function reads a .uml file as XML, thereby confirming successful loading to the user. The "definepartslist" function is responsible for defining a comprehensive list of all components. The "defineparts" function is then employed to match component names across the model and parts list, thereby creating new "Part" objects and reading their attributes in the event of a match. The `readxlsx` function is responsible for loading the .xlsx file, which contains data pertaining to the installation variants. Subsequently, the `definevariants` function generates `Variant` objects based on the data extracted from the Excel file, recording pertinent properties such as mass and center of gravity. The `replacemass` function guarantees that the mass data from the CAD file is given precedence, thereby maintaining consistency across the model. Subsequently, the finduml_value function searches for elements and attributes within the UML document and updates them in accordance with the results of this search. The function designated as "save new UML" is responsible for the saving of all modifications to a new file with the .uml extension. The `checkaxleload` function performs the calculation of axle loads, filtering out any variants that do not comply with the relevant specifications (This is normally 20 tonnes on existing lines, but can also be as little as 10 tonnes on reactivated lines.). Meanwhile, the `checktotalmass` function serves to verify the consistency of the total mass between the computed values and those provided in the Excel file. The `tractionandrequest` function performs the calculation of the energy requirements and operational range of each variant, incorporating the effects of battery aging over time. It therfore calculates required traction and range for remaining variants, initially defining the route with acceleration [%], constant travel [%], minimum distance [km], and vehicle efficiency [%]. General consumption from other components is read from a miscellaneous components object in the parts class. A for-loop calculates air, rolling, impact, running, and acceleration resistance. Resultant total resistance equates to needed traction. Installed battery packs provide available energy *EBatt* in watt-hours (Wh). Each route segment's energy need is computed, formulating available energy on the one and required energy on the other side. Ultimately, the permissible variants are enumerated, thereby enabling the user to select one for further utilization. The `saferesult` function saves the selected variant's data back into the .uml file, thus finalizing the updated file and rendering it ready for use in Eclipse.

The example route presented here does not include specific travel segment times; however, it does define the percentage composition of the journey, which is 20% acceleration, 70% constant speed, and 10% resting. The percentage times implied by the aforementioned composition imply that the maximum range for each permissible variant can be computed. It should be noted that battery efficiency decreases with lifespan; capacity drops to 80% after ten years, which must be factored into calculations by multiplying the available energy (EBatt) by 0.8. Additionally, energy consumption in kWh/km helps assess variants effectively. Calculated distances versus requirement minimums prompt user feedback on compliance.

5. Conclusion and outlook

The model-based approach offers numerous advantages. It fosters collaboration between disparate departments, encourages an agile work methodology, and can result in significant future cost savings. The objective of this study was to investigate the potential for an interface between a SysML model and a CAD system. The electric rail vehicle was selected as the application example. The vehicle was then modelled in a variety of diagrams using the Eclipse Papyrus software, and subsequently created as a CAD model in Creo. The objective was to identify the optimal variant for this model by integrating the two models into an interface. The CAD model represents the actual state, whereas the SysML model represents the desired state for comparison. The objective was to identify the optimal actual state and incorporate it as the desired state into the SysML model.

The .uml file generated from the Eclipse Papyrus software can be read using a library and appropriate namespace definitions. A family table was created manually for the CAD model and exported to an Excel file, thus facilitating access to the parameters. Subsequently, the parameters from the models were aligned with one another. For the sake of clarity, a mapping was created on which the classes "Parts" and "Variants" were established. The number of battery packs in each variant is variable, resulting in a corresponding range of values for the properties of the variants. Subsequently, the variants are evaluated with regard to their axle loads and range. The target values for axle loads and range are derived from the SysML model, whereas the actual values are obtained from the CAD model or calculated within the interface.

The presented work demonstrates the feasibility of establishing an interface between CAD and SysML. The data may be read, processed, and subsequently saved. The newly generated data can be utilized in the SysML model. The data exchange between the interface and the SysML model is automatic, with the exception of the necessity to restart Eclipse Papyrus. Nevertheless, manual procedures are required between the interface and the CAD model. At present, parameters can only be exported or imported via an Excel file. It is imperative that a method be devised to circumvent the necessity for a manual step in the future. Providing direct access to the family table in the CAD system would eliminate this intermediate step and facilitate the saving of parameters in the CAD model. At present, the only available option is to export parameters from the CAD system. The importation of parameters would facilitate not only the variation and optimization of the number of battery packs, but also the variation and optimization of their position. Furthermore, a considerable number of parameters are currently hardcoded, including the list of components. The necessity for greater variability demands the development of a method capable of automatically recognizing the structural characteristics of the models and subsequently creating the requisite objects.

The potential for expanding the SysML model through interface development is a promising avenue for further research. The developed interface illustrates the viability of data exchange, which remains highly customized to the given application example. To extend the applicability of an interface, it is necessary to further automate the process of data exchange. In the case of more complex models, the interface should serve solely as a platform for data exchange, without any involvement in parameter calculations. It is recommended that parameter calculations be conducted within the models themselves, through the restructuring of both the CAD and SysML models to facilitate direct access to the calculated parameters. This can be achieved in the CAD model through comprehensive parameterization, whereas in the SysML model, implementation is feasible through the use of an Action Language for Foundational UML. This entails a textual representation of the elements present within a UML model. It is an imperative and object-oriented language, comparable to C or Java, which permits the assignment of particular instructions in the form of code to abstract UML elements. In light of these possibilities, it is recommended that the focus of the interface be on the automated recognition of the model structure and mapping.

In conclusion, it can be stated that the approach demonstrated has the potential to facilitate the development of products with a diverse range of variants in a customer-centric manner, while simultaneously considering the aspects of standardization and cost-effectiveness. This approach may prove particularly beneficial in the context of the development of compact, autonomous rail vehicles, with the objective of achieving a cost-effective production and operation. Subsequent research endeavors will be directed towards further developing this approach for the aforementioned application scenario.

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