A Domain Specific Systems Engineering Framework for modelling Electric Vehicle Architectures

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***Abstract*— The deployment of electric vehicles into smart grids introduces additional complexity due to a shift of the contemplable system border. An approach to handle complexity is Model-based Systems Engineering. However, in cross-domain systems engineering this approach is not comprehensible to all stakeholders. This work presents the transfer of the Domain Specific Systems Engineering approach from the energy-domain to the automotive-domain. The results are a Framework, a Domain Specific Language and a software toolbox. Altogether enable interdisciplinary modelling of electric vehicle architectures. The applicability of the framework, DSL and toolbox has been evaluated by modelling a case study. (*Abstract*)**

***Keywords*— *Electric Vehicle, Smart Grid, Model Based Systems Engineering; Domain Specific Language; Domain Specific Systems Engineering* (*key words*)**

I. Introduction

Smart Grids (SG) consist of geographically distributed, operational and managerial independent sub-systems. Further, the sub-systems are heterogenic and interdisciplinary. They constitute a network without a final state and with the ability to show emergent (unpredictable) behavior. Reflecting these characteristics, SGs follow the properties, which define a *System-of-Systems (SoS)* [1]. Besides the components of the electrical grid and the communication technology in SG, in future a bulk of the sub-systems will be *electric vehicles (EVs)*. The deployment of many EVs, may have an impact on SGs with respect to emergent behavior.

One aspect of a power net is to keep the equilibrium between production and consumption. However, due to the introduction of renewable energy sources, such as wind-turbines or photovoltaic systems, this equilibrium can be disturbed by changing weather conditions. The result might be an over- or under-production of electric energy. To keep the equilibrium, different strategies, such as load shifting, can be introduced [2]. In such a scenario EVs in a SG are used as flexible loads by introducing electricity rate-based charging. For example, in times when the energy supply reaches a peak, EVs are triggered to start charging by decreasing the electricity rate. Even if such an approach seems reasonable, it might lead to emergent behavior, such as the rebound effect presented in [3]. This is an unwanted influence, which needs to be considered through examining EVs on a holistic point of view as part of a SoS. Thus, an increasing number of stakeholders from technical and non-technical domains have a major share in the development of such systems. To meet these requirements, the development of EV architectures demands a modelling approach, which can deal with the rising interdisciplinarity and cross-domain properties of such systems. Moreover, as EVs are part of SGs, EV architectures should enable the integration into today's standards-based SG architectures, such as the *Smart Grid Architecture Model (SGAM)* [4]. This leads to a shift of the contemplable system border and introduces more complexity, which needs to be considered during the process of *Systems Engineering (SE)* of EVs.

Basically, in SE, complexity is handled through the transition of pure SE into a model-based approach, which is *Model-based Systems Engineering (MBSE)* [5]. But in cross-domain development, such as it is the case for EVs, MBSE is not comprehensible for all involved stakeholders. Thus, interdisciplinary development needs an approach, which brings together stakeholders from different domains. This can be achieved by using a framework that is able to address the concerns of all involved stakeholders on different viewpoints. For this reason, an ISO/IEC/IEEE 42010 [6] architecture description is needed. Further, it should support interdisciplinary systems engineering. Usually, this requirement can be fulfilled by the utilization of *General Purpose Language (GPL)*, such as the Unified Modelling Language (UML) [7] or the *Systems Modelling Language (SysML)* [8]. However, the usage of a GPL postulates that all involved stakeholders are familiar with it. Thus, a *Domain Specific Language (DSL)*, which inherits from a GPL and is tailored to the domain can be introduced. Such a DSL can support interdisciplinary modelling and communication, as it can be easier approached by the involved stakeholders.

Existing automotive frameworks, such as presented in [9], [10], [11] or [12], do offer a comprehensive definition for frameworks. Some of those also suggest the usage of a certain modelling language. But these frameworks offer space for

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further research. On the one hand, the frameworks are not compatible with the standards-based SGAM framework. On the other hand, no practical implementation of these frameworks exists. In contrast to that, the SGAM is implemented as practical solution within the SGAM Toolbox consisting of a DSL, a software tool and a process model [13]. A major advantage of the toolbox is, that it allows standard-based engineering of SGs through utilization of the *Domain Specific Systems Engineering (DSSE)* approach presented in [14]. This is an approach which allows interdisciplinary systems engineering. Such an approach does not yet exist within the automotive domain. Thus, the main contribution of this paper is on the one hand a transformation of the DSSE approach to the automotive domain with focus on remaining compatibility to SGAM. On the other hand, it also provides a domain specific framework together with a DSL and software toolbox. Further, the alignment with current modelling standards, such as the ISO/IEC/IEEE 42010 and the ISO/IEC/IEEE 15288 [15] enable consistent and structured modelling of electric vehicle architectures.

II. Related Work

Architectural Frameworks represent a common ground for the development of architectures in any domain. To gain wide acceptance, the description of such frameworks should be aligned with common standards, such as the ISO/IEC/IEEE 42010. This ensures a consistent and structured description, when it comes to modelling complex systems or even more, SoS [7].

A. Automotive Systems Engineering

The Automotive Architecture Framework (AAF) presented in [9] delineates a very early concept of how to structure the relevant information in a model. It defines mandatory viewpoints, such as functional, technical, information, driver/vehicle operations and value net. Those frame the information that is indispensable. In addition to the mandatory viewpoints, optional viewpoints, such as Safety, Security, Quality or Noise-Vibration-Harshness (NVH) are suggested.

The Architectural Design Framework (ADF) presented in [10] is aligned with the ISO/IEC/IEEE 15288 and thus, supports the system design process. It defines four different viewpoints, which frame the operational, functional, constructional and requirements perspective of a vehicle. ADF uses SysML as main modelling language.

The Architecture Framework for Automotive Systems presented in [11] delivers a set of fully defined viewpoint descriptions. The Requirements, Functional, Implementation and Information Viewpoint, have been condensed from the previously mentioned AAF and ADF. The Feature and Deployment Viewpoint have been extracted from Architecture Description Languages.

The Volvo Cars Architecture Framework [12] builds upon the ISO/IEC/IEEE 42010 standard. Based on interviews with an OEM, 5 viewpoints, additionally to those from AAF, ADF and AFAS, have been identified. These are the Continuous Integration/Deployment, the Ecosystem/Transparency, the System-of-Systems, the Autonomous Car and the Modes Management Viewpoint.

All presented frameworks provide to a certain extend a comprehensive architecture description. Nevertheless, there are still open issues that need to be addressed. First, no practical implementation of those frameworks exists. Furthermore, the utilization is not supported by a clearly defined modelling process. Finally, the utilization of GPLs is not suitable for interoperable systems engineering. Such languages postulate that all involved stakeholders are familiar with it. For these reasons, it is difficult to utilize these frameworks for modelling EV architectures.

B. Domain Specific Systems Engineering

DSSE represents a holistic approach for standard-based engineering of complex systems. It has first been published in [14]. The main idea behind DSSE is that it builds upon existing standards to allow interdisciplinary development of complex systems. The main element of DSSE is a standards-based architecture framework. To enable interdisciplinary development, a DSL, which is based on a standardized GPL, such as SysML, should be part of the framework [8]. Moreover, the DSL should also provide a possibility for structuring all information regarding a system in models. Through this, the standards-based framework together with the DSL supports cross-domain development and enables a frictionless handover of information between all involved stakeholders [16].

The DSSE approach has first been applied successfully in the domain of energy transport systems. A major change of the current energy grid towards complex SGs rises new challenges in the development of such complex systems. On the one hand, it is characterized by e.g. the highly dynamic behavior of the participants, such as renewable energy resources or connecting and disconnecting EVs. On the other hand, additional stakeholders of technical and non-technical domains get involved into the development. For these reasons, the European Commission's Standardization Mandate M/490 developed the Smart Grid Architecture Model (SGAM) [4]. SGAM, as depicted in Fig. 1, provides a set of Interoperability Layers in a cube like model.

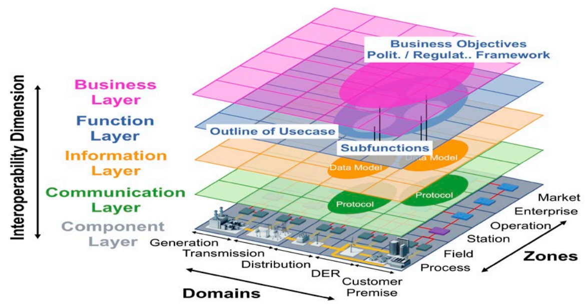

Fig. 1. Smart Grid Architecture Model [4].

The Domains-axis has been derived as an adoption of the National Institute of Standards and Technology (NIST) domain model [17]. The Zones-axis represents the different functions in a smart grid. They have been conveyed from the automation pyramid. The third axis, the Interoperability Layers, are based on the GWAC Interoperability Stack [18]. Each layer represents the SG from a different perspective [4]:

- The *Business Layer* provides the business and regulatory perspective of a SG.
- The *Function Layer* describes functions, services and their relations from the perspective of the architecture.
- The *Information Layer* describes the exchanged information objects and the subjacent data models.

- The *Communication Layer* provides protocols and mechanisms necessary for the information exchange.
- The *Component Layer* describes all physical components, which are participating in the SG.

Further, the SGAM-Toolbox, which enables modelling under consideration of the SGAM, has been developed [13]. It is the successful result of the research with respect to the development of the DSSE approach presented in [14]. The toolbox is embedded in Enterprise Architect (EA), a repository based modelling application by Sparx Systems, and allows the standards-based development of SG architectures. The main components of the toolbox are:

- *EA Model Driven Generation Technology (MDG)*, containing the model kinds for each viewpoint and the DSL definition.
- *Reference Data,* representing a grid in the SGAM model kinds.
- *Model Template,* as fully modelled example to support the task of modelling.

In the automotive domain no similar approach exists. For this reason, the transfer of the already successfully implemented DSSE approach from the energy domain introduces interdisciplinary and standards-based systems engineering of EVs in the automotive domain.

III. Research Approach and Case Study

A successful transformation of DSSE to the automotive domain demands a structured research approach. The *Agile Design Science Research Methodology (ADSRM)* fosters creative research by simultaneous development of both, the problem- and the solution space [19]. This is from importance when the initial requirements are very uncertain. The iterative nature of this approach allows the evolvement of the requirements and the solution in each iteration.

First, the main input for each iteration is an appropriate case study. In the context of this work, an EV braking-system has been chosen, as modelling the whole EV would go beyond the scope of this work. Further, an EV braking-system can be divided into a friction brake system and a regenerative brake system. The work presented in [20] and [21] delivered the decomposition of the sub-systems into the main system components, which have been chosen to be relevant for the commenced research. Based on the case study the stakeholder needs can be extracted. Further, the analysis of those deliver a first set of requirements for the development of the main artefacts. In the context of this work, the main artefacts are:

- *Automotive Reference Architecture Model (ARAM) Framework:* Cornerstone of the developed artefacts.
- *Domain Specific Language:* Supports standards-based, interdisciplinary modelling.
- *Toolbox:* Enables software-based modelling
- *Process Model:* Supports consistent modelling

Second, the artefacts need to be evaluated. Therefore, a first model of the case study is created by using the developed artefacts. The experiences and findings made during modelling, together with an evaluation of the final model by domain experts, serve as input for the next implementation loop. The main advantage of this approach is, that it delivers the appropriate artefacts together with a first, already evaluated architecture model of the case study.

IV. Implementation and Artefacts

As outlined before, the DSSE approach relies on the utilization of a domain specific framework, a DSL and a corresponding process model. These artefacts should be embedded in a software tool to enable the utilization of the developed artefacts. The following chapter delineates the implementation of the framework and DSL, the corresponding process model and the software toolbox.

A. Automotive Reference Architecture Model Framework

The Automotive Reference Architecture Model (ARAM) Framework, which is delineated in Fig. 2, is the first result of the evaluation of the previously mentioned automotive frameworks as well as on the implemented concepts of the energy domain. It is aligned with the ISO/IEC/IEEE 42010 standard for architecture descriptions. It suggests looking at the EV from the perspective of five different viewpoints.

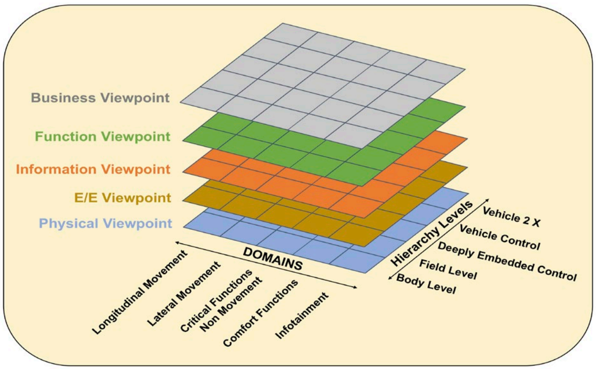

Fig. 2. The 3-dimensional ARAM Framework.

The *Business Viewpoint* governs the business view and is an extraction from the SGAM-Toolbox. It delineates the economic- and regulatory-related structures. The *Function Viewpoint* governs the function view and looks at the EV from the perspective of requirements and vehicle functions. The *Physical Viewpoint* provides the physical view and thus, looks at the EV from the perspective of the physical components and the relations between them. The *Electrics/Electronics (E/E) Viewpoint* frames the concerns regarding the E/E architecture. The *Information Viewpoint* provides the information view with respect to the exchanged data objects.

Further, another property of the ARAM framework is that it allows the decomposition based on different aspects of the system. As outlined in Section II, the concept of a two-dimensional matrix on each viewpoint has been successfully utilized in the SGAM-framework. Thus, a matrix spanning over *Hierarchy Levels* and *Domains*, is introduced in the ARAM framework as well.

The hierarchy levels represent groups of components of an EV. Whereas, the Body Level are components that do not process any kind of energy or information. The Sens/Act Level represents actuators and sensors. On the Deeply Embedded Control Level ECUs, which contribute to main vehicle functions, are placed. The Vehicle Control Level represents ECUs, which contribute to direct control of the vehicle. All components, which are communicating with e.g. the SG, or are sensing the environment, are placed at the

Vehicle to X Level. Besides the alignment with SGAM, this also allows an easier integration of ARAM into SGAM based SG architectures.

The domains have been extracted from the decomposition of the case study on the Physical Viewpoint with respect to three different domain candidates. First, the decomposition along the Business Units of an automotive supplier leads to the violation of Conway's Law [22]. Second, the decomposition along a chain of effects might lead to unwanted complexity of the modelling itself. Third, the decomposition along main vehicle functions resulted into the most appropriate result. The violation of Conway's Law will arise at an earlier stage of modelling, e.g. on the Business Viewpoint. Further, modelling does not follow any kind of chain of effects, which keeps the modelling process at a lower level of complexity.

B. *Domain Specific Language*

The implemented DSL has been developed as an extension of the standardized language SysML. This supports the handover of the whole model or even single elements to engineers, who will do the detailed design.

First, a metamodel of the language has been developed. This contains the main DSL elements to be used to model each viewpoint. Second, based on this metamodel, the DSL has been implemented as profile as extension of SysML elements, containing the detailed definitions of the new stereotypes and relations. To support the interdisciplinary development, the SysML notation of the new stereotypes is replaced by more descriptive icons. Further, relations are colored and named according to their domain specific meaning. However, the implemented DSL also allows experienced users to switch from the DSL appearance to the SysML appearance. This introduces more flexibility into the automotive DSL. An extraction of the DSL is delineated in Fig. 3.

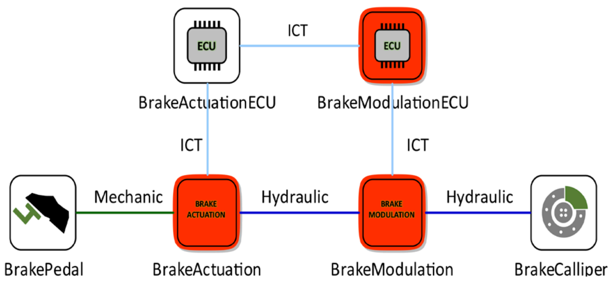

Fig. 3. Example showing the DSL used for modelling the physical view.

Further, the DSL contains definitions of new model kinds. They are inherited from UML/SysML model kinds and serve as starting point for modelling on each viewpoint.

The *ARAM Business Diagram* is the main model kind of the business view and allows modeling of all business-related aspects. The *ARAM Functional Diagram* is the main model kind of the function View and mainly frames the functionality of the EV. The *ARAM Physical Diagram* is the main model kind of the physical view and is mainly used for modelling the physical architecture. The *ARAM E/E Diagram* is the main model kind of the E/E view and allows the definition of interfaces, communication protocols and electrical relations. The *ARAM Information Diagram* is the main model kind of the information view. It allows modelling of information flow relations and the exchanged data objects. Further, also predefined UML/SysML model kinds can be used for modelling.

C. *Toolbox*

The utilization of the DSL under consideration of the defined ARAM Framework is enabled by the ARAM Toolbox. Like the SGAM-Toolbox, the ARAM-Toolbox has been implemented as an MDG technology in the modelling software Enterprise Architect. The toolbox definition contains specific profiles defining stereotypes, relations and model kinds. Further, to enable the usage within EA, toolbox profiles are included. Those govern the possible stereotypes and relations, which can be used for modelling within the viewpoint related model kind.

D. *Process Model*

Modelling using a framework needs the support of a standardized process. This ensures consistency through the whole task of modelling. The process, delineated in Fig. 4, is therefore aligned with the ISO/IEC/IEEE 15288.

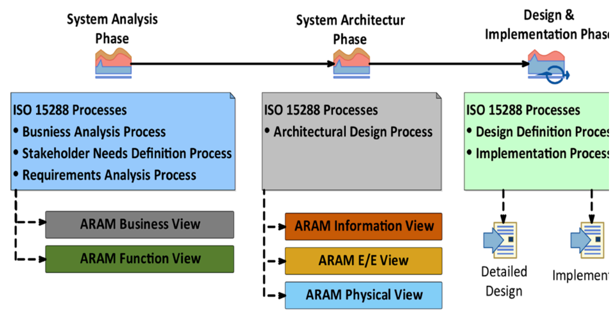

Fig. 4. ARAM Process model showing the single steps of modelling.

The main task of the *System Analysis Phase* is to gain a major understanding of the system regarding its context, business interests as well as requirements and functional architecture. It delivers the Business and Function View of the EV. The goal of the **System Architecture Phase** is the realization of a possible architectural solution from a physical point of view. Therefore, physical components are retrieved from the System Analysis Phase. Further, those components are used to model physical, E/E and information view.

Whereas, the physical view serves as input for the E/E view and the information view. The **System Design Phase** is not part of this research, but for the sake of completeness it is delineated in the process. It should deliver the detailed design and the implementation.

V. Evaluation

The evaluation of the ARAM framework and the toolbox follows a two-step strategy. First, the case study presented in Section III is modelled under consideration of the process model. Second, an evaluation with domain experts is undertaken.

A. *Modelling the Case Study*

The starting point of modelling is the *Business View (BV)*, through the utilization of Business Actors (BAs), who are involved in Business Use Cases (BUCs), which allows them to achieve their intended Business Goals (BGs). Further, BUCs are realized through High Level Use Cases (HLUCs). Regarding the case study two main Business Actors (BAs), the OEM and the automotive supplier (AS), are involved. The OEM and the AS peruse different BGs, which are *Integrate*

EV Braking System and *Gain Profit through selling EV Braking System*, respectively. Further on, the AS can be further subdivided into two BAs, who are responsible for developing an EV braking system. These new BAs are for example a company's business units, such as *Powertrain Systems* in case of the regenerative brake system and *Chassis Control* in case of the friction brake system. Each of these BAs is involved in a different BUC, which is the provision of their braking system. Following the concept of BUC realization via HLUCs, both BAs are involved in the same HLUC *Reduce Speed of the EV*.

Based on the findings in the BV the *Function View (FV)* is modelled. The HLUC is refined by Primary Use Cases (PUCs), like e.g. *Charge Battery*. Further, the analysis of the PUCs allows the extraction of the involved *Logical Actors (LAs)*. In case of the mentioned PUC, LAs are *E-Machine*, *Battery Management System* and *Inverter*. To gain full traceability, a transformation of the BV into the FV is done. This is achieved by tracing the BAs on the LAs.

The FV serves as input for the *Physical View (PV)*. Through a transformation, LAs are traced on *Physical Components (PCs)*. In case of the *Battery Management System* PCs are *BMS-ECU* and *High Voltage Battery*. The relations between the PCs are further modelled in the ARAM Physical Diagram. For example, the High Voltage Battery has an ICT-relation to the BMS-ECU and an electrical-relation to the Inverter.

ICT- and electric-relations are further refined in the E/E view. For example, the ICT-relation between the High Voltage Battery and the BMS-ECU uses the CAN protocol for transmitting data. The electrical-relation between these is characterized by 400V relation.

Finally, the information view is modelled. Therefore, information object flows with corresponding data objects are defined between components with an ICT-relation. In case of High Voltage Battery and the BMS-ECU, this could be an information object containing the *State of Charge*.

Fig. 5 exemplarily shows the physical view of the presented case study. The final model has been presented to and discussed with domain experts.

B. Findings of the Evaluation

The evaluation revealed, that the concepts of the artefacts allows to model the underlying case study. However, the result of the evaluation with the domain experts showed, that it needs further research. For this reason, the introduction of further sub-systems into the case study has been suggested. The introduction of sub-systems like the electrical system and the thermal system demands the extension of the DSL by additional stereotypes. Moreover, modelling these subsystems revealed, that also the matrix needs the inclusion of an additional column and row, to satisfy the new case study.

VI. Conclusion and Future Work

The utilization of existing automotive architecture frameworks (e.g. [9], [10], [11], [12]) is hardly possible, as no practical implementation in common architecture modelling tools exists. Moreover, the integration into state of the art SG architectures is only partly considered or even not included. Further, some of them suggest the usage of GPLs as modelling language. As a utilization of GPLs postulates an overall understanding of these language by all involved stakeholders, this paper chooses a domain oriented approach. Therefore, the concepts of a domain specific architecture framework are presented together with a DSL, a process model and a software toolbox for model-based domain specific systems engineering of EVs. The development mainly is based on the successful transfer of the DSSE concepts [14] implemented in the energy domain [13].

Therefore, a framework, which is based on the evaluation of automotive frameworks as well as on the concepts realized

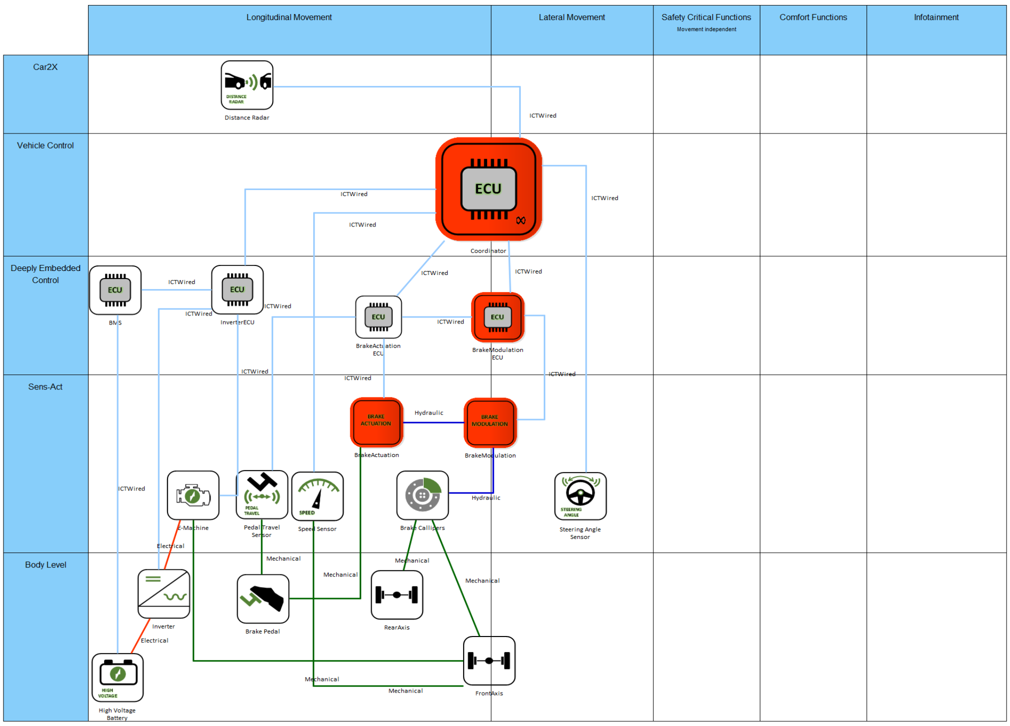

Fig. 5. Excerpt of EA showing the toolbox and a fraction of a ARAM Physical Diagram

by the SGAM framework has been defined. Moreover, a DSL together with domain specific model kinds has been implemented to allow interdisciplinary modelling based on a standards-based process model.

The underlying case study of an EV braking system has successfully been modelled under consideration of the developed artefacts. Even if the case study was only a part of an EV, and the artefacts are a first version of the DSSE approach in the automotive domain, it could be shown, that the transferred concepts are applicable also in the automotive domain. However, the model evaluation carried out with domain experts revealed, that there are still open issues for further research. Through extending the case study, changes in the framework, the DSL and the process model need to be considered. Further, the differentiation on different levels of abstraction needs further research. To allow more flexibility and to provide user interface-based guidance through the whole process of modelling, the concepts need to be implemented as an extension to a common modelling software.

Further, an additional framework for systems engineering, the Software Platform Embedded Systems (SPES) Modelling Framework [23], gained a lot of attention in the field of model-based systems engineering of embedded systems in different application domains. The framework allows the development of architecture models based on different viewpoints and various levels of abstractions. Therefore, mapping the ARAM framework to the SPES framework is on the future research agenda. Moreover, the DSL and the process model should also be aligned with SPES.

Finally, the ARAM DSSE approach provides a first concept for interdisciplinary development of EV systems architectures and opens various possibilities for further research in this field.

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