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Heterogeneous models to Support Interdisciplinary Engineering – Mapping Model Elements of SysML and CAD

Thomas Schumacher[a]*, David Inkermann[a]

Technische Universitaet Clausthal, Institut für Maschinenwesen, Robert-Koch-Straße 32, 38678 Clausthal-Zellerfeld, Germany

* Corresponding author. Tel.: +49 5323 72 3504; fax: +49 5323 72- 3501. *E-mail address:* schumacher@imw.tu-clausthal.de

Abstract

A successful development of mechatronic systems need both domain specific as domain independent engineering models and approaches. The interface between domain specific and domain independent engineering often represents a possible source for failures and inconsistencies. Within this paper, this interface will be addressed by introducing heterogeneous models based on linked SysML and CAD model elements. Therefore a mapping of SysML and CAD elements will be presented and refined for the development of heterogeneous models. Furthermore, a technical concept for linkage of SysML and CAD models to ensure model consistency will be illustrated and an exemplary heterogeneous model will be visualized. In addition, future research targets and fields will be listed.

Keywords: model-based systems engineering, heterogeneous modelling, SysML, CAD, interdisciplinary engineering

1. Introduction and Problem Description

The development of mechatronic systems require multiple views upon the system. On the one hand, domain specific views are needed to define and engineer domain specific solutions (typically distinguished between mechanics, electric/ electronics and software). On the other hand, domain integrating views are required to ensure an overall system understanding in particular in early design stages. Based on different system views, various product models are applied also referred to as domain models. Model-based Systems Engineering (MBSE) aims at establishing consistent system models based on views and viewpoints of the engineering domains involved by using domain independent languages for system modelling like SysML [1]. Major benefits of MBSE reported in the literature are better communication and sharing of information between different engineering departments as well as better traceability [2] between requirements and engineering solutions. However, the main challenge is that the mentioned benefits can get lost at the interface between domain specific and domain independent engineering. This leads to a loss of knowledge and higher efforts to ensure consistency of product models within the occurring iterations during the development process. At the same time missing approaches to map domain specific and domain independent product models are seen as a major barrier when implementing MBSE in industrial practice.

1.1. Need of Domain Specific and Domain Independent Models

Effective engineering of modern products requires a sound overall system understanding (insight of system and system environment) and collaboration between different engineering domains. Semi-formal modelling languages, like SysML or UML, present a domain crossing approach to model systems and include different views and viewpoints during the development. The proposed modelling procedures link system requirements, system behavior, and structure descriptions as well as system parameter to an overall system model [1,3], which will

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have various benefits during development, e.g. better communication and information sharing as well as improved consistency [2]. At the same time, it is not reasonable to apply SysML models for detailed domain specific engineering tasks. For example, SysML models are not appropriate to describe the geometrical and spatial structure and arrangements of system components needed for analysis and evaluation of potential disruptive effects, like temperature influences. These engineering tasks require domain specific modelling. Thus, both domain independent models, like SysML models, and domain specific models, like CAD models, are needed in a model-based development process. Furthermore, already in the early design stages, on the system level, important design decisions are made, which should be considered during the detailed design phases in the domain specific engineering. Therefore, an exchange of design information (system requirements, functions, interface descriptions, system elements) between domain independent and domain specific models, in both directions, is needed to ensure consistency [4]. This contribution focuses on the linkage of model elements used in SysML and those used in mechanical CAD models to generate heterogeneous models to support interdisciplinary engineering.

1.2. Research Objective

The objective of these contributions is the linkage and integration of different model elements into heterogeneous models. Heterogeneous models contain and capture different sub-models or model elements to support the engineering process with appropriate models [5]. Within this paper, available concepts for linkage of different models will be analyzed and the need for heterogeneous models will be derived. To evolve meaningful heterogeneous models two separate aspects need to be considered. First, the integration of different models (SysML and CAD) requires a mapping of model elements. Therefore a basic mapping between SysML and CAD will be presented and a concept for linkage of SysML and CAD elements will be illustrated. Second, appropriate domain specific and domain independent model elements needed to be selected and refined for integration in heterogeneous models. This contribution will focus on system structure modelling, especially system elements and their relations. The following research questions will be addressed within this paper:

- Which SysML and CAD model elements need to be integrated into a heterogeneous model in order to support the system structure modelling?
- How can a heterogeneous model, as an integrated presentation of different model elements, be visualized?

The paper is organized as follows: Section 2 introduces model structuring strategies and the use of heterogeneous models. Furthermore established concepts for linkage and visualization of different models will be analyzed. Within section 3 a concept for linkage SysML and CAD model elements and a basic model element mapping will be presented. Additionally, model elements for structure models will be identified and refined in order to integrate them into heterogeneous models. Section 4 will visualize an exemplary heterogeneous model and explain potential benefits. This contribution closes with a summary and an outlook on future research fields.

2. State of the Art

The following chapter will introduce strategies to structure models within interdisciplinary engineering. Additionally available concepts for linkage and visualization of different model elements are presented and the concept of heterogeneous models is introduced.

2.1. Model Structuring Strategies

During a model-based development process, various SysML models from different model types are generated. With proceeding development, the level of abstraction decreases and the applied models represent the system in more detail. It needs to be considered, that these models utilize engineering decisions and information based on earlier created models. These dependencies demonstrate that between different models relations exist. Hence, for effective development, it is important to apply structuring strategies.

Two different kinds of model structuring strategies are frequently used. Structuring of the models based on the level of abstraction and structuring by different system views. Figure 1 presents these two structuring strategies and shows a typical engineering path. The structuring of models based on the level of abstraction is applied within the architecture definition process. Here, the allocation of functions to realizing system elements is important and arranged on different levels of abstraction [6]. Model structuring based on different system views and viewpoints is established [3,7] and used to define and analyze the system behavior. Here, it is described how the system is expected to operate by definition and interoperation between functional blocks, input and output definitions. In the model-based development requirements, behavior, structure (logical and technical) and parameters are considered as different viewpoints. A viewpoint can be understood as a collection of provisions and constraints from a specific stakeholder perspective for the creation of a view. A view is usually a visualization of the system and shows the system from a specific perspective. In the case of model-based systems engineering, a view is typically a model or diagram of the system.

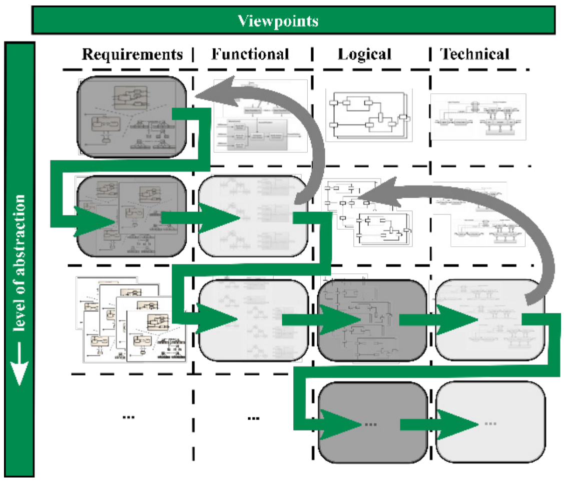

Fig. 1. Typical engineering systematics including iterations, based on [8].

An ideal engineering path starts on an abstract system level and with proceeding engineering the level of abstraction decreases. For every level, requirements will be identified and functional, logical as well as technical system descriptions will be developed. The technical description is simultaneous input for new requirements on the following level of abstraction. Based on the specific engineering task typical engineering paths often differ from these systematics by a more flexible movement, including iterations, within the matrix, see figure 1. The mentioned structuring strategies (level of abstraction and individual system view) define when and in which order models should be applied within the development process, this increases the effectiveness and makes the engineering results more predictable. The concept of heterogeneous modelling will use these structuring strategies to create meaningful heterogeneous models for specific engineering activities.

2.2. Understanding and Application of Heterogeneous Models

Heterogeneous models enable the integration of different sub-models or model elements into one model presentation [5]. With regards to this paper, a heterogeneous model integrates model elements from domain specific and domain independent models into an overall system presentation. For example, functions, system elements, and their relations as well as spatial partitioning and requirements can be combined. Jansen presents a mechatronic leg as a heterogeneous model [9]. This model contains three-dimensional objects as well as two-dimensional substitute models including their relations. Additional information about the context of the system is included in the model, like assembly space restrictions. By integrating model elements of different levels of abstraction, meaningful models can be created for specific engineering activities, like the definition of system integration strategy. Based on the specific use case, heterogeneous models can present engineering results in different views and levels of abstraction (see chapter 2.1) in a flexible way [9]. For instance, heterogeneous models support the allocation of functions to the realizing engineering domains (functional partitioning) or the spatial positioning of system elements based on defined functional relations (spatial partitioning) [9]. For the generation of a heterogeneous model not only the model presentation is important also the model representation (data structure) has to be considered. Therefore, in section 3.2, a technical concept for linkage of the representation of SysML and CAD model elements is introduced.

2.3. Established Concepts for Linkage of Different Models

One objective of this paper is to define a mapping concept to integrate model elements from SysML and CAD as well as to ensure information exchange between these models consistently. Therefore, in the first step existing concepts for linking and visualization of different kinds of models were analyzed. The main criteria for this analysis are:

1. Linkage of different models (linkage of models with different levels of abstraction or viewpoint)
2. Integration of SysML-diagrams (use of SysML diagrams for comprehensive system description)
3. Kind of visualization (presentation of linked models in a meaningful manner)
4. Visualization of integrated models (integrated presentation of different model elements)

For this analysis, established concepts in industry and research were selected by literature and internet investigation, searching for linkage of models and interdisciplinary development approach: Siemens mechatronic concept designer, Dassault Systèmes 3DExperience, Intercax Syndeia and FAS4M project.

Siemens Mechatronic Concept Designer

The mechatronic concept designer by Siemens is typically applied at mechanical engineering and facilities, especially the interdisciplinary machinery development. Originating from the customer requirements and functional models design solutions can be developed. Additionally, the mechatronic concept designer supports the evaluation of different design alternatives based on simulations [10]. The overall target is to ensure the machinery release process based on early system simulation and validation. Therefore, simultaneous engineering of different domains is supported by linking requirements to system elements and mapping of domain specific solutions to the functional system structure. For visualization, the mechatronic concept designer is using CAD-models extended by control software, like a PLC.

Dassault Systèmes 3DExperience

3DExperience is an available software platform to support model-based development processes using the established RFLP approach [11]. The software links requirements with functional and logical architecture to avoid inconsistencies (e.g. function deployment based on stakeholder requirements). Physical system design is supported but without linkage to the functional or logical architecture. Requirements, functional and logical architecture can be presented in SysML-diagrams and the physical realization uses CAD-models.

Intercax Syndeia

The Syndeia software platform enables cross-domain system development, by creating a digital thread through the complete system life cycle. Syndeia creates interfaces between various software tools to enable information exchange between different engineering tools. This enables for example an automated generation of block definition diagrams (SysML) out of CAD model tree [12]. Following the idea of the digital thread, Syndeia is focussing on the visualization of intra model connections (relations between different engineering tools).

Functional Architectures of Systems for Mechanical Engineers (FAS4M)

The FAS4M project considers the systematic development and modelling of mechatronic systems (function and structure relationship) from the mechanical domain perspective. Part of the project results is an additional SysML-profile for mechanical engineering (MechML) and technical interfaces (API) between chosen CAD and SysML tools. Thereby exchange of model information between CAD models and SysML diagrams, like block definition diagrams, was realized. Interesting use cases are the integration of design sketches into SysML diagrams or generation of SysML blocks out of CAD model tree [13]. For visualization FAS4M uses the SysML editor and the CAD tool. Next to the typical dimensional and spatial descriptions the CAD tool can also present charts including SysML model elements, like requirements or functional descriptions. The target is to visualize the allocation of requirements and functions to the design.

Analysis result

Depending on the individual use case, the presented concepts enable the consistent use of models even between different abstraction levels and modelling languages in a defined tool environment (first criteria). The integration of SysML diagrams is included in 3DExperience, Syndeia, and FAS4M, the Siemens concept designer is more focused on the 3D modelling (second criteria). For the kind of visualization (third criteria) mostly independent SysML and CAD models are used. The main conclusion is that no concept considers an integrated presentation of model elements from different models (fourth criteria). Therefore, in the following section, the generation of heterogeneous models is proposed.

3. Linkage of Model Elements between SysML and CAD

This chapter will identify needed model elements for system structure modelling. Afterward, these elements will be used to present a mapping between SysML and CAD models elements based on a defined mapping concept, and finally, these elements will be refined to integrate them into heterogeneous models.

3.1. Identification of Required Model Elements

This paper focuses on structure modelling therefore needed model elements will be identified. To describe a system structure at least the following model elements are needed: *system elements, relations between system elements and to their environment, system element characteristics* and *interface description*. Especially the relations between system elements are important to describe the system behavior. The following table presents relations types (following called linkage types) and their allocation to the respective engineering domain.

Table 1. Linkage types and domain allocation, based on [14]

Linkages types	Domain		
material transfer	ME		
spatial relation or physical connection	ME	E/E	
transfer of loads, forces or torques	ME		
translational or rotational movement	ME		
vibrations and acoustics	ME	E/E	
magnetic field	ME		
thermal relation	ME	E/E	
electric or electromagnetic field	ME	E/E	
electrical earth		E/E	
electrical power		E/E	
information or control signals		E/E	software

Taking the linkage type *information or control signals* as an example, it becomes clear that domain specific interfaces are described, like transfer of control signals as part of the E/E domain and the processing and interpretation of signals as part of the software domain [14]. Moreover, this linkage-type can be used to describe cross-domain interfaces. These cross-domain interfaces are of great relevance for heterogeneous models since they indicate required mappings of model elements from different domains. Additionally, it has to be notice that based on the needed level of abstraction different model elements have to be used. Looking at the linkage type *material transfer*, the definition of which kind of material needs to be exchanged between different system elements should be determined in the early development stages. In this stage, typically abstract models, like SysML models, are used to define basic architectures or design solutions. By proceeding the development process models become more concrete and with design definition the development will be handed over to the domain specific engineering, which uses domain specific engineering models and procedures. However, the different models have to be consistent. To ensure a continuous information exchange and prevention of model inconsistencies an information exchange approach between domain independent and domain specific models is required. Section 3.2 proposed a concept for mapping of SysML and CAD model elements.

3.2. Technical Concept for Linkage of SysML and CAD Models Elements

The following concept for the mapping of model elements from SysML and CAD models is based on existing standardized data structure and exchange formats to enable a tool independent solution. The established export format for SysML models is the XMI (XML Metadata Interchange) format, which was specified by the Object Management Group. The exchange of CAD models typically follows the STEP format as an international standard. Within STEP, there are various application protocols (AP) available, which customize the data structure for specific use cases. The exchange of CAD models usually is based on AP 242 (managed model based 3D engineering). A key element of the technical concept, see Figure 2, is the definition of STEP AP 233 (Systems Engineering data representation) as the central data exchange format. Therefore, this concept revives the original STEP AP 233 idea to be an exchange standard for systems engineering data like requirements, behavior and structure descriptions, physical elements, configuration, and project management information [15].

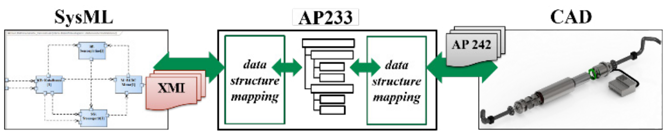

Fig. 2. Linkage concept for SysML and CAD model elements, based on [16].

To ensure an exchange without inconsistencies, it is important to harmonize the data structures (representation) between XMI, STEP AP 242 and STEP AP 233. Table 2 presents the mapping of model elements for each data structure based on the addressed use case system structure modelling. Within section 3.1 the following model elements were defined: *system elements, relations, system element characteristics, interface description*. For these model elements appropriate SysML and CAD elements as well as XMI, AP 233 and AP 242 elements were identified.

Table 2. Mapping of SysML and CAD model elements

Element	SysML	XMI	AP233	AP242	CAD
system element	block	uml:class	system	volume_ unit	ob- ject
relation	connector	uml:asso- ciation	inferface_ connection	direction	line
element charac- teristic	property	uml: property	system_ view_ definition	real_repre- sentation_ item	para- meter
interface	port/port definition	uml:port	interface_ connector	-	-

Table 2 demonstrates that linkage between SysML and CAD based on the presented concept can be realized. In future work also model elements for functional and behavior-related characteristics shall be linked.
The generation of heterogeneous models out of a linked model representation enables a flexible application of various model views (e.g. specific user or technology views) for different engineering tasks.

3.3. Linkage and Refinement of Model Elements to Evolve Heterogeneous Models

By analyzing the presented model element mapping within section 3.2, it needs to be determined, that it is rather a top-level mapping. For application within heterogeneous models the required model elements need to be refined. For example, a *system element* (SysML: block) needs to be classified into different block stereotypes, to present the different engineering domains. That means, there should be at least differentiation between mechanical, electrical, and software blocks [17]. A similar limitation is valid for the description of the system element *relation*. Therefore is differentiation in various linkage types is required, see table 1. A further limitation is that not all SysML elements can be meaningfully mapped to CAD elements, see Table 2, element: *interface*. This limitation is not necessarily an issue, because it is not meant to link all SysML elements with CAD elements. For each engineering activity, an appropriate selection and mapping of model elements are required.

Expressive heterogeneous models require detailed engineering information based on refinement of generic model elements and integration of domain specific model elements, like spatial and geometric characteristics of objects and shapes out of the mechanical domain. Table 3 presents the refinement of the element *relation* into different types and shows which SysML elements (block stereotypes and system boundary) can be linked by each type.

Table 3. Application of linkage types on SysML elements, based on [14]

Linkage Types	Linkage between SysML elements	
Material Transfer	MEBlock	MEBlock
	MEBlock	Boundary
Spatial Relation or Physical Connection	MEBlock	MEBlock
	MEBlock	EEBlock
	EEBlock	EEBlock
	MEBlock	Boundary
	EEBlock	Boundary
Transfer of Loads, Forces or Torques	MEBlock	MEBlock
	MEBlock	Boundary
Translational or Rotational Movement	-	-
Vibrations and Acoustics	MEBlock	EEBlock
	MEBlock	MEBlock
Magnetic Field	MEBlock	MEBlock
	MEBlock	EEBlock
	MEBlock	Boundary
Thermal Relation	MEBlock	MEBlock
	MEBlock	EEBlock
	MEBlock	Boundary
	EEBlock	Boundary
Electric or Electromagnetic Field	MEBlock	EEBlock
	EEBlock	EEBlock
	EEBlock	Boundary
Electrical Earth	EEBlock	EEBlock
	EEBlock	Boundary
Electrical Power	EEBlock	EEBlock
	EEBlock	Boundary
Information or Control Signals	EEBlock	EEBlock
	SoftwareBlock	SoftwareBlock
	EEBlock	Boundary
	SoftwareBlock	Boundary

The refinement of blocks into different block stereotypes and relations into different linkage types shall present the level of detail, which is needed to generate appropriate heterogeneous models. It can be concluded that a customized SysML-profile is needed to generate heterogeneous models for mechatronic systems.

4. Integration of Different Model Elements into Heterogeneous Model

Leveraging on the need of heterogeneous models within this section an exemplary mock-up of a heterogeneous model is presented. Figure 3 shows a heterogeneous model that integrates CAD and SysML model elements. On the one hand, this model contains geometrical and spatial system information and on the other hand functional descriptions and interface description at the system boundary. This mock-up presents the roll-

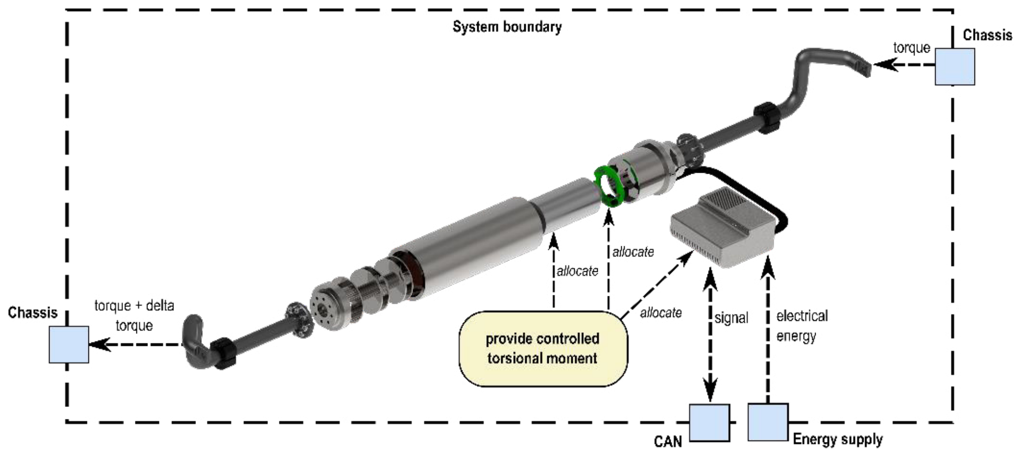

Fig. 3. Heterogeneous model.

stabilizer, which is an electro-mechanical subsystem of a vehicle. The roll-stabilizer is mounted twice in the chassis, with the target to increase the comfort by driving through rough roads and corners.

The presented heterogeneous model support different activities within the development process. First, this model can assist within the architecture definition process by visualizing the allocation of activities (system functions) to the realizing system elements. Second, it can foster early integration planning of the roll-stabilizer due to the description of linkage types to the car chassis. A third use case could be a better spatial description of system elements in the early design stages. SysML models typically do not consider spatial characteristics of system elements, but there are disturbances, like temperature influences, within the design process that require an early spatial description of the system. For example, the spatial arrangement of sensors within the system is a crucial engineering decision, which could have a major influence on the overall system design. Heterogeneous models can support by evaluating internal or external disturbances and their consideration in the system design.

5. Summary and Outlook

During the development of mechatronic systems various domain-specific and domain independent models are used. To handle these various models, strategies for model structuring were introduced. This paper considers the integration of different model elements into heterogeneous models. Therefore, in a first step existing concepts to link different models were analyzed, a mapping concept between CAD and SysML model elements was illustrated and the need of heterogeneous models was derived. The development of heterogeneous models requires a linkage of different model elements and refinement of the generic SysML-profile. Based on an application example an exemplary heterogeneous model was visualized and potential engineering benefits explained. The target of future work is the definition of a specific SysML-profile to enable meaningful integration of CAD and SysML elements into heterogeneous models. Based on the exemplary use case, evaluation of disruptive effects within the system design, the practical use, and benefits of heterogeneous models in different interdisciplinary engineering tasks will be researched.

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