Measuring the Evolution of Meta-models, Models and Design Requirements to Facilitate Architectural Updates in Large Software Systems

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To my son Filip
Your smiles and laughs came just in time to inspire me to finish
up what I started long before you were born.

Abstract

Background: In order to reduce complexity of the system and its development cost, the architecture of large software systems is often developed following the MDE (Model-Driven Engineering) approach. Developing architectures according to MDE relies on three main artifacts in the development process: domain-specific meta-models, architectural models and system design requirements. The architecture of the system is defined in the architectural models which are developed using modeling tools. The syntax of the models is defined in domain-specific meta-models, while their semantics is usually provided in a form of system design requirements in the supporting specifications.

Objective: The main objective of this thesis is to develop methods and tools for managing architectural updates in the development of large software systems. Our goal is to automatically assess the impact of using new architectural features on the development projects (e.g., in terms of model complexity and required updates of the modeling tools) in order to assist system designers in planning their use in the models. The assessment is based on measuring the evolution of domain-specific meta-models, architectural models and system design requirements related to relevant architectural features.

Method: We performed a series of case studies focusing on the domain-specific meta-model, architectural models and system design requirements from the automotive domain. On the one hand, the case studies helped us to understand relevant industrial contexts for our research problems and develop our methods using constructive research methodology. On the other hand, the case studies helped us to empirically validate the results of our methods.

Results: We developed three new methods and software tools for automated impact assessment. The first method and the tool (*QTool*) show the complexity increase in the architectural models after adding a set of new features to the system. The second method (*MeFIA*) and the tool (*ARCA*) assess the impact of using these features in the system on the used modeling tools. Finally, the third method and the tool (*SREA*) identify a subset of design requirements that are affected by the use of the new features.

Conclusion: We showed in practice that our methods and tools enable faster use of new architectural features in the development projects. More concretely, we showed that quantitative analysis of evolution of domain-specific meta-models, architectural models and system design requirements related to new architectural features can be a valuable indicator of which features shall be used in the system and what is their impact on the development projects.

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List of Publications

Included publications

This doctorate thesis is based on the following publications:

[A] D. Durisic, M. Nilsson, M. Staron and J. Hansson, "Measuring the Impact of Changes to the Complexity and Coupling Properties of Automotive Software Systems", *Journal of Systems and Software (JSS), vol. 86, no. 5, pp. 275-1293, 2013*

[B] D. Durisic, M. Staron, M. Tichy, J. Hansson, "Addressing the Need for Strict Meta-Modeling in Practice - A Case Study of AUTOSAR", *Proceedings of the 4th International Conference on Model-Driven Engineering and Software Development (MODELSWARD), pp. 317-322, 2016*

[C] D. Durisic, M. Staron, M. Tichy, J. Hansson, "Assessing the Impact of Meta-Model Evolution - A Measure and Its Automotive Application", *Journal of Software and Systems Modeling (SoSyM), pp. 1-27, 2017*

[D] M. Jimenez, D. Durisic, M. Staron, "Measuring the Evolution of Meta-Models - A Case Study of Modelica and UML Meta-Models", *Proceedings of the 5th International Conference on Model-Driven Engineering and Software Development (MODELSWARD), 2017*

[E] D. Durisic, M. Staron, M. Tichy, "Identifying Optimal Sets of Standardized Architectural Features - A Method and its Automotive Application", *Proceedings of the 11th International Conference on Quality of Software Architectures (QoSA), pp. 103-112, 2015*

[F] D. Durisic, M. Staron, M. Tichy, J. Hansson, "ARCA - Automated Analysis of AUTOSAR Meta-Model Changes", *Proceedings of the 7th International Workshop on Modeling in Software Engineering (MiSE), pp. 30-35, 2015*

[G] C. Motta, D. Durisic, M. Staron, "Should We Adopt a New Version of a Standard? - A Method and its Evaluation on AUTOSAR", *Proceedings of the 17th International Conference on Product-Focused Software Process Improvement (PROFES), pp. 127-143, 2016*

[H] D. Durisic, C. Motta, M. Staron, M. Tichy, "Co-Evolution of Meta-Modeling Syntax and Semantics in Architectural Domain-Specific Modeling Environments - A Case Study of AUTOSAR", *Proceedings of the 20th International Conference on Model Driven Engineering Languages and Systems (MODELS), 2017*

Additionally, case study background of the thesis described in Chapter 2 is based on the the first five sections of the following book chapter:

- D. Durisic, "AUTOSAR", *Chapter in Automotive Software Architectures book, Springer, 2017*

Other publications

The following publications are published but not appended to this thesis due to their content overlap or smaller relevance to the research questions:

- D. Durisic, M. Staron and M. Nilsson, "Measuring the Size of Changes in Automotive Software Systems and their Impact on Product Quality", *Proceedings of the 12th International Conference on Product Focused Software Development and Process Improvement (PROFES), pp. 10-13, 2011*

- D. Durisic, M. Staron, M. Tichy, J. Hansson, "Evolution of Long-Term Industrial Meta-Models - An Automotive Case Study of AUTOSAR", *Proceedings of the 40th EUROMICRO Conference on Software Engineering and Advanced Applications (SEAA), pp. 141-148, 2014*

- D. Durisic, M. Staron, M. Tichy, J. Hansson, "Quantifying Long-Term Evolution of Industrial Meta-Models - A Case Study", *Proceedings of the International Conference on Software Process and Product Measurement (MENSURA), pp. 104-113, 2014*

Contents

Chapter 1

Introduction

Model-Driven Engineering (MDE) [22] is a widely used methodology in the development of large software systems. The main benefits of MDE are the facts that it raises the level of abstraction [3] and employs tools to enable automation in the development process [2]. Raising the level of abstraction contributes to the reduced complexity of the system and increased understandability of the interplay between the system's components. Therefore, MDE is especially useful in the development of large systems that consist of many complex parts which have to communicate with each other [10]. Automation contributes to the increased development speed.

Automotive software system is a good example of a large software system where MDE facilitates the development process. One reason for this lies in the highly increased size and complexity of automotive systems in the past decade. Today, one premium car consists of more than 150 computers (referred to as ECUs - Electronic Control Units) responsible for executing more than 1 gigabyte of on board binary code, compared to only 50 ECUs and 10 megabytes of binary code ten years ago [18]. This trend of increasing complexity of the automotive software systems is expected to continue [26] driven by the new functionalities that are expected from modern cars, e.g., autonomous drive and car-to-car communication.

Another reason for using MDE in the automotive domain is the highly distributed development of software for different ECUs, which is usually developed by different suppliers. Therefore, using formalized models for exchanging information between different actors in the development process, and modeling tools for reading and editing the models in the automated way contributes to the increased development speed. An alternative approach would be manual work with the non-formalized artifacts of the system description which would, given the complexity and size of the system, be hardly feasible.

Other examples of large software systems can be found in the avionics domain, where the software for military jets today has up to 50 million lines of code, and the software for the newest passenger planes almost 100 million lines of code (comparable to some luxury cars) [18]. Similar to the automotive software systems, other large software systems are usually also composed of functionally diverse components which are developed by unrelated teams. This additionally increases the complexity of the development process.

In the area of software architectural design, the methodology of MDE is built around three main artifacts in the development process: domain-specific meta-models, architectural models and system design requirements. The architecture of the system is defined in the architectural models, which are developed in one or more architectural modeling tools. In order to be able to exchange the models between modeling tools used by different actors in the development process, the tools are based on a common domain-specific meta-model that defines syntax for the models, thus assuring the tooling interoperability. Finally, the semantics of the models is usually defined in the natural language specifications, which may consist of a number of design requirements explaining the use of one or more modeling elements.

Despite being used in industry for many years, employing MDE in practice brings a number of challenges related to the evolution of the MDE artifacts and their impact on each other. Some of these challenges are well covered in the existing literature, such as the coupled evolution of models and meta-models related to the automated model updates according to the new meta-model versions [28]. Certain challenges, however, received less attention, such as the impact of meta-model evolution on the compliant modeling tools and the complexity of the models. This is important for planning updates of the tools in order to support new modeling features in the meta-model, and prioritizing testing areas in the system upon using these features in the models. Therefore, the existence of such methods for automated impact assessment has a potential to increase the speed innovation in the development projects.

The main goal of this thesis is to develop methods and tools for managing architectural updates, that require updates of the modeling language, in the development of large software systems. This management includes the assessment of impact of using a new architectural feature in the models (e.g., new communication protocol) on the modeling tools used in the development process, in terms of updating effort, and existing models, in terms of increased complexity. The tooling impact assessment is particularly important if software is developed in a distributed environment, like in the automotive domain, where architectural models are exchanged between multiple actors in the development process. This is because each actor may use different modeling tools, and all of them should be considered in the assessment.

In order to achieve our goal, we performed a series of case studies of meta-models, architectural models and design requirements. For example, we examined the architectural models from Volvo Cars and the domain-specific meta-model and the standardized requirements from the AUTOSAR standard [6], a reference architecture and methodology used in the automotive domain. We used these case studies as part of the constructive research methodology to develop, evaluate and validate our methods for analyzing the evolution of these three MDE artifacts. For example, we performed one case study to understand the organization of domain-specific meta-models in order to define a method for measuring meta-model evolution, and another case-study to evaluate and validate the method using one or more industrial meta-models.

The main results of this thesis are three methods for automated impact assessment of using new architectural features in large software systems on the development projects, each based on one or two software measures. This is based on our hypothesis that simple measures of change in the domain-specific

meta-models, architectural models and design requirements can produce accurate early indicators of which architectural features shall be used in the system, and estimate their impact on the development projects.

The first method, realized in the *QTool*, shows the complexity increase in the architectural models after adding a set of new features to the system. The method is based on the two measures of model complexity and coupling. The second method, named *MeFIA* and realized in the *ARCA* tool, assesses the impact of supporting different features on the used modeling tools. The method is based on the measure of meta-model change (NoC) and it can also show concrete meta-model changes caused by a particular feature and relevant to a particular actor in the development process. Finally, the third method, realized in the *SREA* tool, identifies the subset of design requirements, that provide semantics to the modeling elements, affected by the analyzed feature. The method can also identify the most unstable requirement specifications based on the measures of requirements change and maturity index (RMI).

We can see that each of the three methods analyzes the evolution of one of the three MDE artifacts, i.e., domain-specific meta-models, architectural models and system design requirements. The methods can also perform impact assessment of this evolution on the development projects, i.e., the first method in terms of complexity increase in the models upon using the new architectural features, the second method in terms of updating efforts of the used modeling tools to support the new features, and the third method in terms of time required to understand how to use the new features in the models. Therefore, the methods complement each other and should be used together by the system designers in order to decide which new features shall be used in projects, and accurately estimate their impact on the development projects.

For example, the *ARCA* tool can be used first to assess the feasibility of supporting one feature in the modeling tools in the project time-frame. If it is considered feasible, the *ARCA* and *SREA* tools can then be used for planning the required updates in the tools and understanding the relevant requirements specifications, respectively, related to this feature. Finally, the *QTool* can be used to indicate which parts of the system are mostly affected by the use of this features for prioritizing testing areas or revising the system's architecture.

In order to validate our methods in practice, we applied them in the automotive domain on the AUTOSAR artifacts. The choice of the automotive domain is justified as automotive software systems represent large systems which are developed, including the architectural design, fully according to MDE. The choice of AUTOSAR is justified due to its long industrial use (more than 10 years) by the majority of car manufacturers, and its large size. For example, the newest release of the AUTOSAR meta-model exceeds 10000 meta-classes and 35000 meta-model changes in comparison to the previous release, and more than 20000 requirements in the AUTOSAR specifications our of which at least 2000 are changed in every release.

We first found that, using the *QTool*, it is possible to verify that certain quality attributes of the AUTOSAR models have not deteriorated and to identify new testing areas in the system. We then found that the *ARCA* tool can provide a preliminary indicator of effort needed to update AUTOSAR-based modeling tools in order to support new AUTOSAR features. Finally, we found that, using the *SREA* tool, we can support system designers to faster under-

stand how to use the new features in the architectural models. We used these findings to validate our hypotheses described above.

This rest of Chapter 1 is structured as follows: Sections 1.1 and 1.2 provide theoretical background related to modeling/meta-modeling and software measurement, respectively, and how it is used in this thesis. These two areas of software engineering are particularly important as our methods are based on software measures applied on different modeling artifacts. Section 1.3 defines our research questions and describes the contribution of our studies. Section 1.4 describes the methodology we employed to obtain the results. Finally, Section 1.5 summarizes our conclusions and describes possible future work.

Chapter 2 describes automotive modeling environment and the role of the AUTOSAR standard, as our main unit of analysis, in it. Chapters 3-10 present the individual papers included in this thesis. Each paper is independent and represents one study that addressed one or several research questions.

1.1   Modeling and meta-modeling

In this section, we first explain the theory behind modeling and meta-modeling following the MDE approach in Section 1.1.1. We then describe how meta-modeling is used in different domains, such as automotive, in Section 1.1.2. After that, we show the use of meta-modeling in the architectural design of one system and clarify the term "architectural feature" in Section 1.1.3. These three sections define the terms related to modeling and meta-modeling (indicated in bold) which are used in the rest of the thesis. Finally, we explain the use of modeling and meta-modeling in this thesis in Section 1.1.4.

1.1.1   Theory of modeling and meta-modeling

Modeling plays an important role in the development of large software systems because it reduces their complexity by raising the level of abstraction. This abstraction is achieved by specifying what the system does rather than how it does this [3]. Models and meta-models are the two most important concepts involved in any modeling environment. Based on the definitions of Bézivin et al. [9], a **model** represents a simplified representation of a software system that has been created for a specific purpose, whilst a **meta-model** represents the model of the language this system model is expressed in.

The prefix "meta" is of Greek origin meaning "after" or "beyond", and in general it indicates that certain concept lies above the original concept; for example, the meta-model represents "a model of the model" and the meta-meta-model represents "a model of the meta-model". Applying this logic several times creates a **meta-modeling hierarchy**, which is also referred to as the meta-pyramid [19]. The meta-modeling hierarchy of MOF [30] standardized by the Object Management Group (OMG) [33] is considered a *de facto* standard in meta-modeling and it consists of the following layers:

1. The **M3 layer**: MOF meta-meta-model that defines modeling concepts

2. The **M2 layer**: meta-model that defines language specifications

3. The **M1 layer**: model that defines application meta-data

4. The **M0 layer**: objects that define application data

The Meta-Object Facility (MOF) [30] resides at the top of the hierarchy. This is a meta-meta-model that defines the general modeling concepts used by meta-models on the *M2* layer. A frequently used meta-model on the *M2* layer is UML (Unified Modeling Language). The actual UML models reside on the *M1* layer and their actual execution at run-time resides on the *M0* layer. An example of the meta-modeling hierarchy is depicted in Figure 1.1.
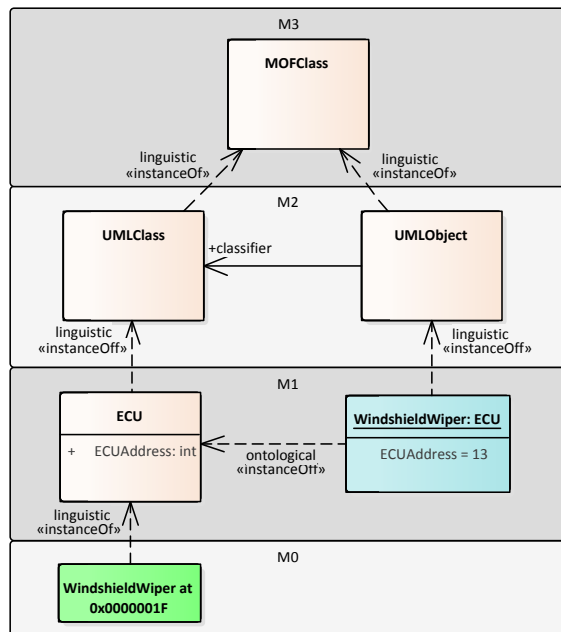
Figure 1.1: Example of the meta-modeling hierarchy

The layers of MOF are connected by the **instantiation** mechanism, i.e., elements of each layer represent instances of the elements of the layer above, except for the top layer *M3* whose elements are considered to be instances of themselves. For example, *ECU* on the *M1* layer is an instance of *UMLClass* on the *M2* layer. This type of instantiation is referred to as **linguistic instantiation**, and it is used to provide the instantiating elements with general language types (e.g., classes, objects, attributes). In addition to the linguistic instantiation, **ontological instantiation** is used to provide the instantiating elements with semantic classifiers (e.g., *WindshieldWiper* is an *ECU*).

In both case, the instantiating element defines the characteristics of the instance element, and the instance element defines the specific details of these characteristics. The *instanceOf* relationship, however, is not transitive, e.g., the *M1* model element will only receive characteristics from the *M2* meta-model elements and not from the *M3* meta-meta-model elements [5].

According to the **strict meta-modeling** principle [4], all model elements on one layer of a meta-modeling hierarchy are instances of the meta-model elements of the layer above, except for the top layer. No relationships other than *instanceOf* are allowed to cross the layer boundaries, and no *instanceOf*

relationships are allowed within one layer. If these conditions are not met, we refer to the meta-modeling as loose. An example of **loose meta-modeling** can be seen in Figure 1.1 where the *instanceOf* relationship between the *WindshieldWiper* and *ECU* resides entirely on the *M1* layer.

1.1.2   Domain-specific modeling and meta-modeling

Meta-modelling plays an important role in the development of description languages suitable for modeling systems in specific domains [37], e.g., automotive, telecommunications and avionics. A **domain-specific model** represents an abstract representation of the system of a particular domain, while a **domain-specific meta-model** defines the syntax and the semantics of the domain-specific models instantiating this meta-model [31].

Four important concepts of domain-specific meta-models can be distinguished: abstract syntax, concrete syntax, static semantics (well-formedness) and dynamic semantics (or just semantics). The **abstract syntax** describes the structural essence of the meta-model, e.g., elements and their relations independent of the representation of the actual models. An example can be seen in Figure 1.1 in the definition of the *ECU* element and its potential relation to other elements, e.g., *Signal*s and *Bus*es. The **concrete syntax** specifies the representation of the model instances, e.g., *WindshieldWiper*, in the models. These representations include graphical notations and XML, as a commonly used format for exchanging models between different modeling tools. There can be more than one concrete syntax for one abstract syntax, and vice versa.

The **static semantics** impose a set of constraints on the abstract syntax. For example, each *ECU* needs to have an *ECUAddress*. This can be achieved by specifying different constraints, e.g., in the form of multiplicities of the attributes and relationships or using OCL (Object Constraint Language) [32]. Finally, the **dynamic semantics** provides meaning to the syntax notation of the meta-model and it can be formal or informal (e.g., natural language specifications). For example, "An ECU represents one micro-controller in the system." informally describes the semantics of the *ECU* element. One domain-specific meta-modeling environment usually specifies all four concepts [24], i.e., the meta-model itself specifies the abstract syntax and the static semantics, while the concrete syntax (e.g., XML) for the models and their dynamic semantics may be specified in the supporting natural language specifications.

Domain-specific meta-models are often linguistically instantiated from a general-purpose meta-model such as MOF or UML. In case of UML-based domain-specific meta-models, UML **profiles** with the defined **stereotypes** and **tag definitions** can also be used for customizing the abstract syntax and the static semantics of the UML meta-model for a specific domain.

One domain-specific modeling environment may contain an arbitrary number of layers; in practice, there can be more than the four layers defined by MOF. These layers need to co-evolve in order to support the addition of new modeling and meta-modeling features [14]. For example, in order to express new modeling features on the *M1* layer, the *M2* layer need to evolve in order to describe how to model these new features. Similarly, evolution of the *M2* layer may require evolution of existing models of the *M1* layer in order to maintain conformity between the *M1* and *M2* layers.

System modelers of one domain-specific modeling environment usually rely on **software modeling tools** (CASE - Computer Aided Software Engineering tools) to create and update models and generate code based on them. Since the development of large software systems often involves multiple **actors** (**design roles**) potentially using different modeling tools in the development process, a smooth exchange of models between these roles can be somewhat challenging. Nevertheless, a smooth exchange can be enabled by defining and gaining consensus from all roles for a domain-specific meta-model, which is then fundamental to the development of all tools used in a specific modeling environment. This is based on the assumption that if two modeling tools adopt the same model structure defined by the meta-model, they can exchange software models that comply with this meta-model [2].

Since the modeling tools are based on a commonly-accepted domain-specific meta-model, its evolution may significantly impact all the tools in a specific modeling environment. Such tools tend to be developed based on their own meta-models (e.g., to support graphical representations) so the evolution of the domain-specific meta-models directly impacts the importers and exporters of the compliant models, as well as the meta-models used by these tools.

1.1.3 Architectural modeling and architectural features

Software architecture represents a set of design decisions made about a system (not all design decisions are architectural, though). A model that captures some or all of these design decisions can be regarded as the **architectural model** [41]. An architectural model defines a number of architectural components responsible for the execution of different system functionalities.

Based on these definitions, the possibility of utilizing the architectural components and their interactions in a specific way to achieve certain semantics can be considered as an **architectural feature**. For example, the possibility of modeling communication between two ECUs of specific ECU addresses. The architectural models and their features are expressed using a general modeling language, which has both the linguistic and ontological instantiations. For example, in order to model the concrete ECUs and their addresses, a domain-specific meta-model must define the "*ECU*" class with "*ECUAddtess*" attribute, as shown in Figure 1.1.

1.1.4 Modeling and meta-modeling in this thesis

As already explained, in this thesis we focus on analyzing the evolution of three main artifacts used in domain-specific meta-modeling environments: meta-models, models, and design requirements. Meta-models define abstract syntax and static semantics for the models which ontologically instantiate them using a concrete syntax, while design requirements provide informal dynamic semantics to the models. Table 1.1 show the focus of our studies and studied artifacts in different papers:

As we can see, the majority of our studies focus on the analysis of the AUTOSAR meta-modeling environment, except the one described in Paper D that analyzes UML and Modelica meta-models. AUTOSAR meta-model is used as a basis for the architectural design of automotive software systems and

Table 1.1: Study focus and studied artifacts

Focus	Artifact	Paper
Analyzing domain-specific meta-modeling environments with respect to MOF	AUTOSAR meta-model	B
Analyzing the evolution of models	AUTOSAR models	A
Analyzing the evolution of meta-models	AUTOSAR meta-model	C, E, F, H
Analyzing the evolution of meta-models	UML and Modelica meta-models	D
Analyzing the evolution of system design requirements	AUTOSAR design requirements	G, H

the development of AUTOSAR modeling tools (CASE tools), i.e., it defines architectural models and their features. It is defined as a linguistic instance of UML. AUTOSAR models represent ontological instances of the AUTOSAR meta-model and linguistic instances of UML. As explained in Paper B, both the AUTOSAR meta-model and the AUTOSAR models reside on the *M2* layer of the MOF hierarchy, despite the fact that AUTOSAR defines five meta-modeling layers (see Chapter 2).

Due to the fact that AUTOSAR artifacts represent the most important units of analysis in this theses, we dedicated Chapter 2 to the detailed definition of the AUTOSAR standard and its role in the development of automotive software architectures. In this chapter, one can also find detailed description of the AUTOSAR meta-model and examples of the AUTOSAR models in XML and textual AUTOSAR design requirements.

Together with the analysis of the AUTOSAR meta-model, as a domain-specific meta-model used for defining architectural models, we analyzed two additional meta-models of a different kind. The first one is the meta-model of Modelica [34], which is used for defining the behavioral models of complex systems containing, e.g., mechanical, electrical and electronic components. The second one is the meta-model of UML [42], which represents a general-purpose meta-model used for modeling a number of aspects, such as architecture (e.g., using UML class diagrams) and behavior (e.g., using UML sequence or state machine diagrams), of a wide variety of software systems. It represents a direct linguistic instance of the MOF meta-model, and it can also be used as a meta-meta-model for defining further domain-specific meta-models.

1.2   Software measurement

In this section, we first explain the theory behind software measurement in Section 1.2.1. We then describe how to perform the measurement process in Section 1.2.2. These two sections define the terms related to software measurement (indicated in bold) which are used in the rest of the thesis. Finally, we explain the use of software measurement in this thesis in Section 1.2.3.

1.2.1 Measurement theory

Measurement in software engineering plays an essential role not only to assessing a variety of quality attributes of the software system, such as reliability, maintainability and efficiency [40], but also to estimating the implementation cost and effort to support different features in the system. According to the measurement theory [15], **measurement** is a process in which numbers (or symbols) from the mathematical world are assigned to different entities from the empirical world to describe the entities according to defined rules. A **measure** (also referred to as **metric** [16]) represents a variable to which a value is assigned as a result of the measurement [38].

The measurement theory describes how to construct measures and formalize their mapping from the empirical to the mathematical world, i.e., empirical relations between entities are mapped to mathematical relations so that they can be analyzed. For example, if two software systems (A and B) are related by the empirical relation "more complex than", we can define a measure of their complexity (c), where measurement results are related by the mathematical relation ">". The mapping between the empirical and mathematical relations, therefore, is defined as:

$$c(A) > c(B) => A \; more \; complex \; than \; B \tag{1.1}$$

Measurement results can be represented on different scales and different relations between the results are possible depending on the scale [15]:

- *Nominal scale* - only a relation of equivalence possible (A = B)

- *Ordinal scale* - a nominal relation + greater/smaller than (A > B)

- *Interval scale* - an ordinal relation + difference computation (A − B)

- *Ratio scale* - an interval relation + ratio computation (A / B)

- *Absolute scale* - like ratio, but for measurements with a predefined minimum value (e.g., zero) which are mostly used for counting entities

In order to structure software measures according to their objectives, **Goal Question Metric** (GQM) approach proposed by Basili et al. [8] can be used. GQM defines the measurement as a mechanism that helps to answer a variety of questions about the software process and products. It defines the measurement model on three levels: Conceptual (goals), Operational (questions) and Quantitative (metrics), as shown in Figure 1.2:
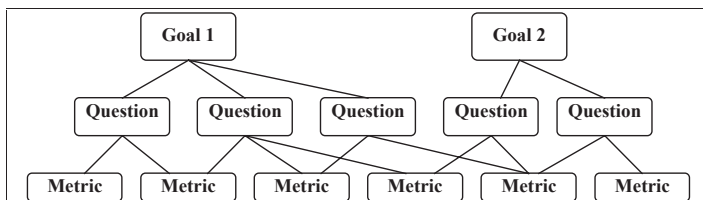
Figure 1.2: The Goal Question Metric (GQM) levels [8]

The **goal** is defined for one object (e.g., a product or process) with respect to its quality attributes for a specific purpose (e.g., an evaluation) and from a specific perspective (e.g., that of a system designer). A set of **questions** for one goal is used to specify how the goal will be assessed by characterizing the object to be measured. Finally, the **metrics** represent the quantitative data associated with every question that enable the question to be answered.

1.2.2   Measurement process

The *ISO/IEC 15939* standard for the **measurement process** in software engineering [39] defines the process as a set of activities that are required to specify: (i) what **information need** is required for the measurement, (ii) how the measures are made and measurement results are analyzed, and (iii) how the results are validated. Additionally, the measurement process specifies how to build the measurement products, although this area is beyond the scope of this thesis. A simplified measurement process is shown in Figure 1.3:
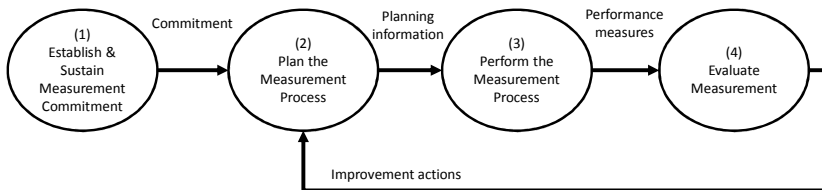
Figure 1.3: Measurement process activities [39]

Activity (1) defines the **scope of the measurement** and who will execute it. Activity (2) elaborates on the **measurement plan**, such as what is to be measured (i.e., which entities and their quality attributes), what information is needed (i.e., the reason for the measurement), which measures will be used and on what scale, and the criteria for evaluating the measurement results. Activity (3) describes the **data collection** and **data analysys**. Finally, activity (4) describes the **evaluation** of the measures and the measurement process based on the defined criteria of activity (3). This process is defined as iterative in order to improve both the measures and measurement process based on the results of the evaluation.

One important segment of the planning activity (3) is to ensure the **definition of the measures** in order to avoid different interpretations of how the measurement has been done (see the measurement errors of different implementations of the commonly known lines of code measure [36]). The measures will be defined based on the **conceptual model** (also referred to as the **data model**), which is used to describe the entities in the empirical world [20] to ensure that the metrics can satisfy the required information need.

Software measures are usually defined using either set theory or algebra expressions. In order to prevent a definition of a measure using one of these two approaches from becoming too complex, however, alternative approaches can be taken, e.g., using pseudo-code snippets. For example, the complexity (c) of one software component (x) that can be used as an indicator of the number of faults in it's code, can be defined using algebra as follows:

$$c(x) = \sum_{i=1}^{n} r_i(x) * \sum_{i=1}^{n} t_i(x);$$

$$r_i(x) = \begin{cases} 1, & \text{if x receives } sig_i \\ 0, & \text{otherwise} \end{cases} ; t_i(x) = \begin{cases} 1, & \text{if x transmits } sig_i \\ 0, & \text{otherwise} \end{cases}$$

where n represents the total number of signals and sig_i the signal with serial-number i. Using set theory, this same result can be achieved by defining two sets $Sin(x)$ and $Sout(x)$:

- $Sin(x) = \{sin_1(x), sin_2(x), ..., sin_\alpha(x)\}$ - a set of signals received by software component x.

- $Sout(x) = \{sout_1(x), sout_2(x), ..., sout_\beta(x)\}$ - a set signals transmitted by software component x.

The complexity would then be calculated as follows:

$$C(x) = |Sin(x)| * |Sout(x)|$$

Finally for the purpose of completeness, the simplified corresponding pseudo-code could look like this:

```
int Complexity(Component x)
{
    int Sin = 0;
    int Sout = 0;

    foreach (Signal in ReceivedSignals(x))
        Sin = Sin + 1;

    foreach (Signal in TransmittedSignals(x))
        Sout = Sout + 1;

    return Sin * Sout;
}
```

An important part of the measurement process is to validate the defined software measures. Two different types of validation can be performed [11]: a theoretical validation to answer "*Are we measuring the right attribute?*" and an empirical validation to answer "*Is the measure useful?*".

The **theoretical validation** ensures that a measure does not violate the properties of the measured entity [23]. This can be achieved by assessing whether the measure satisfies certain theoretical criteria. For example, there must be at least two entities for which the measure yields a different result, measuring the same entity twice yields the same results or measuring two entities can yield the same result. Additionally, Briand et al. [12] classify the measures according to five attributes (size, length, complexity, coupling and cohesion) and define a set of properties required to measure each attribute. These properties can be used to group measures according to different properties and validate that they indeed measure an intended attribute.

The **empirical validation** ensures that the measurement results reflect the entities of the real world [23]. This can be achieved by discussing the results with experts who work with the measured entity in order to ensure

that they are consistent with their expectations (e.g., code complexity should decrease after re-factoring). Statistical analysis can also be used to validate the relationship between two attributes of the measured entity using their historical values. This is useful in situations where the value of one attribute can be predicted by measuring the value of another attribute. An example of this is the use of a correlation analysis based on historical data to empirically validate the link between code complexity and the number of faults.

1.2.3   Software measurement in this thesis

The results presented in this thesis rely heavily on the use of software measures and measurement results as all papers, except from Paper B, define and/or use one or more software measures. The meta-models, architectural models and system design requirements represent the scope of the measurements, and our main information need was to assess their evolution with respect to a number of properties, including changes, size, complexity and coupling. Since available, off-the-shelf measures do not use the specific modeling characteristics of the automotive domain, we defined our own set of measures for this purpose. A summary of the most important measures used in our studies is shown in Table 1.2.

Table 1.2: The most important measures used in the studies of this thesis

Measure name	Measure goal	Defined	Used
Complexity measure	Monitoring the complexity evolution of the automotive software systems.	Paper A	Paper A
Package coupling measure	Monitoring the coupling evolution of the automotive software systems.	Paper A	Paper A
Number of (meta-model) changes measure (NoC)	Estimating the effort/cost of adopting a new meta-model version or a subset of the new features it supports.	Paper C	Papers C, D, E, F, H
Number of changed requirements	Monitoring the evolution of system requirements.	Paper G	Papers G, H
Requirements maturity index (RMI)	Monitoring the stability of requirements changes in relation to the past releases.	Paper G	Paper G

Some studies also include additional more detailed measures. For example, in addition to the results of the NoC measure, Papers D and F show the results of the *Number of added/modified/removed elements* (elements can be classes, attributes and connectors) and the *Number of elements* measures. Another example can be found in Paper H where, in addition to the results of the *Number of changed requirements* measure, the results of the *Number of added/modified/removed requirements* measure are used.

The majority pf our measures are developed following the GQM approach based on the appropriate data models. Clearly defining both the goals and

questions for each study enabled us to re-use the logic behind certain measures used for measuring one entity, in order to address similar questions and goals about another entity. For example, the goal of our *Number of changed elements* measure in Paper F was to monitor the evolution of domain-specific meta-models. Similarly, to the goal our *Number of changed requirements* measure in Paper G was to monitor the evolution of requirement specifications.

Some of our measurement results are presented on the ratio scale (e.g., model *Complexity* and *Package coupling* measures) whilst others are shown on the absolute scale (e.g., *NoC* and the *Number of changed requirements*). The majority of measures are defined using either algebra or pseudo-code snippets. For example, we defined the *Complexity* and *Coupling* measure of the architectural models used in Paper A using algebra and the *NoC* measure for domain-specific meta-models used in Paper C using pseudo-code snippets. However, some measure are defined in words, e.g., the *Number of changed requirements* and *RMI* measures used in Paper G.

The process of data collection was fully automated as we developed software tools to measure the properties of architectural meta-models, models and requirements based on the appropriate data model. All the presented measures are evaluated by calculating them on industrial project data, e.g., from Volvo Cars and the AUTOSAR consortium. The *Complexity* and *Coupling* measures for monitoring the evolution of architectural models were calculated on a number of software components and ECUs from the two evolving models at Volvo Cars. The *NoC* measure was calculated on a number of AUTOSAR meta-model releases and the new features they support, and a set of releases of Modelica and UML meta-model. Finally, the *Number of changed requirements* and *RMI* measure were calculated on a number of AUTOSAR requirement specification from a set of chosen AUTOSAR releases.

The empirical validation of the measures, except for the *RMI measure*, was done using one of the following two approaches: The first approach was to match the measurement results with the expectations from the experts in the field and/or available documentation. The second approach was to use statistical methods, such as correlation analysis, in order to analyze the relationship between the measurement results and the attributes of the measured entity.

The *Complexity* and *Coupling* measures for monitoring the evolution of the architectural models were also validated theoretically based on the properties of complexity and coupling measures defined by Briand et al. [12].

1.3   Research questions and contributions

The goal of this thesis was to develop methods and tools for managing architectural updates in the MDE development of large software systems. These architectural updates are usually manifested in a form of new architectural features used in the development projects. In order to achieve our goal, we focused our studies on the automotive domain, considering automotive software system as a good example of a large software system developed following the MDE approach. Therefore, we defined the following main research question:

RQ: How to automatically assess the impact of using new architectural features in the system on automotive software development projects?

Using new architectural features in the system, that require updates of the modeling language, causes the evolution of domain-specific meta-models, architectural models and system design requirements. The evolution of these three MDE artifacts, however, has significant impact on the development projects. The evolution of meta-models requires updates of the used modeling tools and possibly existing models. The evolution of architectural models usually requires verification and validation of the entire system. The evolution of design requirements requires detailed inspection of the requirement specifications for the correct use of new features in the models. Therefore in order to be able to assess the impact of using new architectural features on the development projects, we needed to analyze the evolution of architectural meta-models, models and design requirements, each representing one direction in our study.

In order to address our main research question, we divided it into fourteen smaller research questions, each addressed in one of our eight studies/papers. These smaller research questions, including a short description of our contributions in each paper, are presented in Table 1.3.

Table 1.3: Research questions and contributions

No.	Research question	Contribution/finding	Paper
RQ1	How can the complexity increase of architectural models and their components be monitored during the evolution of large software systems?	Two measures are needed to monitor the complexity evolution of automotive architectural models when new architectural features are added to the system - the measures of architectural complexity and coupling. *QTool* can be used for combined analysis of results of these two measures.	Paper A
RQ2	What are the consequences of UML based loose meta-modeling in the automotive domain?	The main consequence is that not all semantics can be conveyed between meta-modeling layers by means of modeling, e.g., which defined stereotypes are applicable to classes and which to associations. In practice, this is solved by the modeling tools by providing means to specify additional semantics.	Paper B
RQ3	What are the drawbacks of approaches for assuring strictness of the AUTOSAR meta-model?	The main problem with approaches assuring strictness is the lack of tool support and their relatively short and narrow use in industry.	Paper B

No.	Research question	Contribution/Finding	Paper
RQ4	What are the practical meta-modeling concerns of the automotive modeling practitioners?	One of the major practical concern of the automotive modeling practitioners is the impact of evolution of domain-specific meta-models on other artifacts in the development process.	Paper B
RQ5	How can the evolution of domain-specific meta-models be measured in order to accurately reflect the impact of meta-model changes on the modeling tools used by different actors in the development process?	A simple measure of meta-model change (NoC) can be used as a preliminary indicator of impact of new domain-specific meta-model versions on the used modeling tools.	Paper C
RQ6	What types of changes can be distinguished between different versions of the AUTOSAR meta-model?	Data model that captures all relevant meta-model changes for analyzing the evolution of the AUTOSAR meta-model.	Paper C
RQ7	How can the evolution of the AUTOSAR meta-model be quantified?	The NoC measure based on our data model for quantifying the evolution of the AUTOSAR meta-model.	Paper C
RQ8	How accurately can quantitative analysis of the AUTOSAR meta-model changes be used for predicting its impact on the AUTOSAR tools?	Statistically significant positive Spearman's correlation of 0.69 between the results of NoC and the actual effort needed to update the AUTOSAR based modeling tools.	Paper C
RQ9	What is the level of applicability of the measures of domain specific meta-model evolution and the underlying data-model defined in (Durisic et al., 2014) for monitoring the evolution of Modelica/UML meta-models?	The NoC measure and the underlying data-model are applicable for measuring the evolution of two additional meta-models of Modelica and UML.	Paper D
RQ10	How to assess the impact of different architectural features on the used domain-specific meta-models?	The $MeFIA$ method can be used for assessing the impact of new architectural features on domain-specific meta-models.	Paper E

No.	Research question	Contribution/Finding	Paper
RQ11	How to identify the optimum set of features to be adopted based on the assessed impact?	The *MeFIA* method can be used for identifying optimal sets of new architectural features to be used in the development projects.	Paper E
RQ12	How to support modeling practitioners in analyzing changes between different versions of domain-specific meta-model related to different architectural features?	The *ARCA* tool realizing the *MeFIA* method can be used to support automotive modeling practitioners in deciding which new AUTOSAR features to use in the development projects.	Paper F
RQ13	How can we assure efficient adoption of new releases of standards in the development of large software systems by analyzing the evolution of standardized requirements?	The *SREA* tool can be used to support organizations in understanding which parts of the system will be mostly affected by the changes in the system design requirements.	Paper G
RQ14	How strong is the relation between the evolution of meta-modeling syntax and meta-modeling semantics?	Statistically significant positive Spearman's correlation of 0.63 between the results of the *NoC* measure (for meta-modeling syntax) and the *Number of changed requirements* (for meta-modeling semantics).	Paper H

The relation between our studies and research questions and how answers to our smaller research questions contribute to our main research question and general goal of this thesis are presented in Figure 1.4:

We divided our research area into three lanes, each lane dedicated to the analysis of evolution of one of the three main MDE artifacts - models, meta-models and design requirements (indicated as yellow, blue and green lanes in Figure 1.4, respectively). We first examined the evolution of architectural models in the yellow lane by investigating how to monitor the complexity increase of the automotive architectural models after certain architectural changes have been made. As the answer to RQ1, we found that two measures are needed for this purpose - the complexity and the coupling measure defined in Paper A. We also showed in the same paper the practical use of these two measures on a case of two evolving automotive architectural models. We did this by developing a method and the *QTool* implementing this method which can calculate the measures and perform combined analysis of the measurement results.

We then examined the evolution of meta-models in the blue lane. In Paper B, we analyzed the relevance of theoretical meta-modeling concepts in practice, i.e., strict vs. loose meta-modeling, in order to position our studies with respect to meta-modeling theory. We identified three consequences of loose meta-modeling related to the organization of meta-modeling layers, as the answer
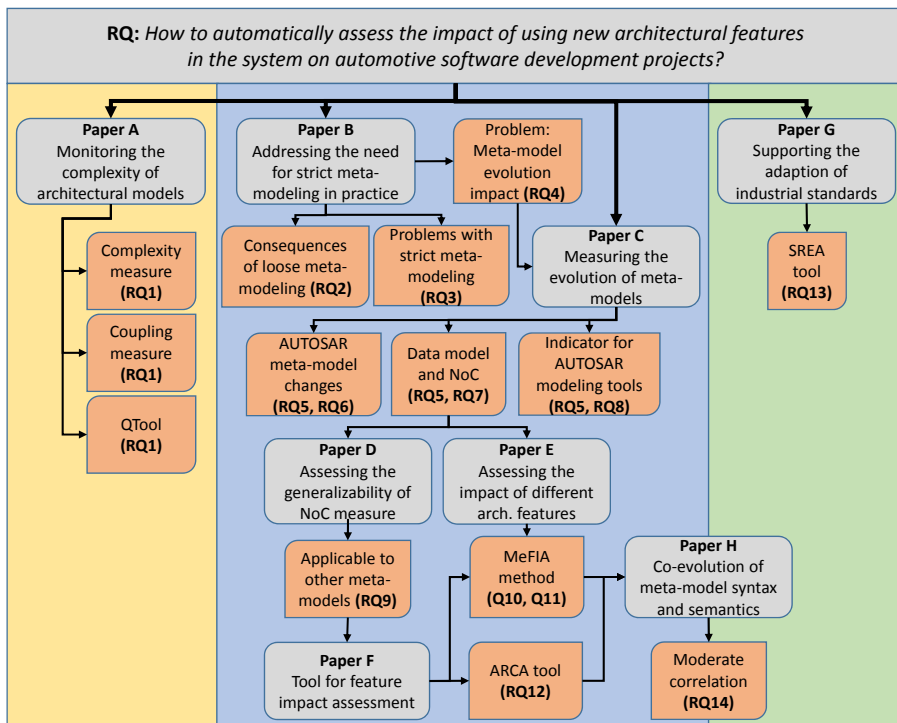
Figure 1.4: StudyDesign

to RQ2. We also identified the main problem of lacking tool support for the use of strict meta-modeling in practice, as the answer to RQ3. Finally as the answer to RQ4, we found that the evolution of domain-specific meta-models and their impact on the development projects is one of the major problems of the (meta-) modeling practitioners. This information served as a valuable input for our study described in Paper C which defined a measure of meta-model evolution (NoC) that can be used for preliminary impact assessment of new meta-model versions on the used modeling tools.

As the answer to RQ5 and more concrete RQ6, RQ7, and RQ8 defined in Paper C, we first identified meta-model changes that should be considered in the analysis of the AUTOSAR meta-model evolution (RQ5, RQ6). Considering these changes, we then defined a data model for the measurement and the NoC (Number of Changes) measure based on this data-model in order to quantify the evolution of architectural domain-specific meta-models (RQ5, RQ7). Finally, we validated the NoC measure by finding moderate to strong positive Spearman's correlation of 0.69 between its results and the actual effort needed to update AUTOSAR modeling tools according to the meta-model changes (RQ5, RQ8).

On the one hand, we used the NoC measure (and the underlying data model) in Paper D in order to assess its applicability to a wider range of meta-models. As the answer to RQ9, we found that our data model is able to capture relevant changes for monitoring the evolution of UML and Modelica meta-models. We also managed to calculate the NoC measure between different

releases of UML and Modelica. On the other hand, we used the *NoC* measure in Paper E to construct the *MeFIA* method that is able to assess the impact of a particular architectural feature on the used domain-specific meta-model. This is done by calculating meta-model changes related to this feature only, which represents the answer to RQ10. The *MeFIA* method is also able to identify optimal set of features to be adopted in the development projects based on their meta-model impact, which represents the answer to RQ11.

In order to enable industrial use of the *MeFIA* method in the automotive domain, we implemented the *ARCA* tool described in Paper F. The *ARCA* tool is able to automatically perform steps of the *MeFIA* method for a set of AUTOSAR features. Therefore, it provides the answer to RQ12 as it supports automotive engineers in analyzing the impact of different AUTOSAR features.

Finally, we examined the evolution of system design requirements in the green lane. We focused on the standardized requirements that provide semantics for the meta-modeling elements, as presented in Paper G. As the outcome of this study and the answer to RQ13, we constructed a method and the *SREA* tool implementing this method that can identify a subset of design requirements that are affected by the introduction of new architectural features.

Having the *SREA* and *ARCA* tools in place, we were also able to perform an additional study described in Paper H with the goal to investigate the relationship between the evolutions of meta-modeling syntax and meta-modeling semantics. As the outcome of this study and the answer to RQ14, we found a moderate positive Spearman's correlation of 0.63 between the evolutions of these two artifacts. This confirms the importance of analyzing the evolution of system design requirements together with the evolution of meta-models, and requires more effort from the meta-modeling practitioners in describing the syntactical changes in the meta-models.

Summarizing the results from all three lanes results in three new methods and tools (*QTool*, *ARCA* and *SREA*), one from each lane, that can be used for monitoring the evolution of architectural meta-models, models and system design requirements. The combined use of these methods and tools for assessing the impact of new architectural features on the development projects represents the answer to our main research question.

1.3.1   Industrial contribution

All results presented in this thesis are directly implemented at Volvo Cars by means of incorporating the *QTool*, *ARCA* and *SREA* tools into the company's change management process.

The *QTool* implements the complexity and coupling measures presented in Paper A and it is primarily used by the system architectural testers at Volvo Cars. The tool is used during the evolution of automotive architectural models in order to analyze the impact of added functionality on the complexity and coupling properties of different architectural components (e.g., sub-systems, ECUs and domains). If the results are unsatisfactory, some components need to be re-designed to reduce coupling and increase cohesion, e.g., by re-allocating functionality onto different ECUs. The results of the *QTool* are also used to indicate which parts of the system require more testing.

The *ARCA* tool implements both the *MeFIA* method and the measures

defined in Papers C, E, F and H (Paper F describes the *ARCA* tool itself) for monitoring of the evolution of the AUTOSAR meta-model. The tool is primarily used in one of the following three scenarios:

1. **To decide which AUTOSAR meta-model release shall be used**

   The analysis is primarily done by the AUTOSAR team at Volvo Cars with support from other teams (e.g., system architects and designers). The analysis includes impact assessment of adapting a new AUTOSAR release on the modeling tools used by different actors (design roles) in the development process. The aim of this analysis is to indicate if a new AUTOSAR release is feasible to be adopted in the development process.

2. **To decide which new AUTOSAR features shall be used**

   The analysis is primarily done by the AUTOSAR team at Volvo Cars with support from other teams (e.g., system architects and designers). The analysis includes impact assessment of adapting each new AUTOSAR feature on the modeling tools used by different design roles in the development process. The aim of this analysis is to indicate if a new AUTOSAR feature is feasible to be adopted in the development process.

3. **To influence standardization of the AUTOSAR meta-model**

   This analysis is done by the AUTOSAR team at Volvo Cars. The aim of the analysis is to continuously inspect changes in the AUTOSAR meta-model during the development of one AUTOSAR release, in order to be able to influence their standardization. For example, if an accepted change in the AUTOSAR meta-model removes one meta-element that is used at Volvo Cars, the change should be re-discussed in the AUTOSAR consortium involving representatives from Volvo Cars.

The *SREA* tool implements both the measures and the method defined in Papers G and H related to monitoring of the evolution of system design requirements and their specification. The tool is primarily used in one of the following two scenarios:

1. **To facilitate analysis of differences between requirements specifications from different AUTOSAR releases**

   The analysis is primarily done by the AUTOSAR team at Volvo Cars with support from other teams (e.g., system architects and designers). The aim of the analysis is to reduce time for analyzing differences between requirement specifications from different AUTOSAR releases.

2. **To facilitate analysis of differences between requirements specifications related to specific AUTOSAR features**

   The analysis is primarily done by the AUTOSAR team at Volvo Cars with support from other teams (e.g., system architects and designers). The aim of the analysis is to reduce time for analyzing differences between requirement specifications related to a specific new AUTOSAR feature. This analysis is meant to complement the analysis performed by the *ARCA* tool explained in the second bullet. For example, *SREA*

tool can list all introduced, removed and/or modified requirements related to a set of new modeling elements introduced to the AUTOSAR meta-model by the analyzed feature.

In addition to their use at Volvo Cars, there are three additional types of industrial application of these three tools:

1. They can be used without modifications by other car manufacturers and their software/tool suppliers in the similar scenarios as explained above, as long as they follow the AUTOSAR standard in the development.

2. The *ARCA* tool can be used by the AUTOSAR consortium to generate AUTOSAR meta-model change documentation, and the *SREA* tool can be used to generate change documentation of the AUTOSAR requirements specifications, related to different AUTOSAR features. Together, *ARCA* and *SREA* can also be used to indicate which meta-model elements (syntax) require further explanations in the specifications (semantics) related to their use in the AUTOSAR models.

3. Finally, all three tools can be used, with certain modifications, by the companies from other domains who work according to the principles of MDE. On the one side, they would need to re-implement the meta-model, model and requirements importers in the *ARCA*, *QTool*, and *SREA* tools, respectively, depending on the format they use for these artifacts. On the other hand, they would need to configure the tools in order to analyze relevant types of changes, e.g., meta-model packages and tagged values in case of *ARCA* and taxonomy of changes in case of *SREA*.

1.3.2   Individual contribution

In Papers A, B, C, E, F and H, the PhD candidate was the main contributor in planning and execution of the studies, and writing of the publications. In Paper D and G, the PhD candidate was the main contributor in planning of the studies, and participated in writing of the publications. The execution of the studies was performed by the first author of the papers, i.e., Maxime Jimenez and Corrado Motta, respectively.

The PhD student was the main contributor in writing of the "AUTOSAR" book chapter in the "Automotive Software Architectures" book.

The PhD student was the main contributor in the implementation of the *QTool* and *ARCA* tool, while Corrado Motta was the main contributor in the implementation of the *SREA* tool.

1.3.3   Related publications

As indicated in the list of publication under "Other publications", three of our publications related to the work presented in this thesis are not included in this thesis. In this subsection, we briefly describe their contribution and explain why they are not included in the thesis.

1. **"Measuring the Size of Changes in Automotive Software Systems and their Impact on Product Quality"** written by *D. Durisic,*

M. Staron and M. Nilsson and published in the *Proceedings of the 12th International Conference on Product Focused Software Development and Process Improvement (PROFES), pp. 10-13, 2011.*

This publication is entirely contained in Paper A that represents its extension by providing empirical validation, detailed explanation of the proposed method, and detailed description of the research methodology, related work and generalization of the presented results.

2. "**Evolution of Long-Term Industrial Meta-Models - An Automotive Case Study of AUTOSAR**", written by *D. Durisic, M. Staron, M. Tichy, J. Hansson* and published in *Proceedings of the 40th EUROMICRO Conference on Software Engineering and Advanced Applications (SEAA), pp. 141-148, 2014.*

   The paper presents the study which defines and uses seven software measures for analyzing and visualizing the evolution of the AUTOSAR meta-model related to different design roles in the automotive development process. The results of five of these measures (*Number of elements*, *Number of attributes*, *Number of changes*, *Number of changed elements* and *Number of changed attributes*) including the definition of design roles are already presented in the similar scope in Papers C, D, E and F. The remaining two measures (*Complexity* and *Average depth of inheritance*) are not considered relevant for answering the main research question of this thesis presented above.

3. "**Quantifying Long-Term Evolution of Industrial Meta-Models - A Case Study**" written by *D. Durisic, M. Staron, M. Tichy, J. Hansson* and published in the *Proceedings of the International Conference on Software Process and Product Measurement (MENSURA), pp. 104-113, 2014.*

   The paper presents the study which analyzes which of the five properties of the AUTOSAR meta-model, namely size, length, complexity, coupling and cohesion, are mostly affected by the AUTOSAR meta-model evolution. The analysis is done by calculating ten software measures between available historical releases of the AUTOSAR meta-model. The results of the measures and general conclusions of the paper are not considered relevant for answering the main research question of this thesis.

The PhD candidate was the main contributor in planning and execution of all three studies, and writing of all three publications.

1.4 Research methodology

The research methodology used in this thesis mainly consists of a series of case studies which aim to increase understanding of meta-models, models and system requirements, and validate our methods used for monitoring the evolution of certain properties of these three artifacts. Using only one research method, however, does not usually suffice for the combined work of practitioners and researchers for solving industrial problems [29]. Therefore,

our methods are developed following the methodology of constructive research which relies on the results of our case studies.

As all of our methods are based on the use of software measurement, we used the methodology of the GQM approach described in Section 1.2.1 as part of the constructive studies for developing the actual measures. In particular, we first defined the general goal for the measurement and the questions the measurement results need to answer about the analyzed entities for achieving this goal. We then developed the measures using conceptual models of these entities and their properties, e.g., domain-specific models and meta-models.

In this section, we first summarize the theory of case study and constructive research in Sections 1.4.1 and 1.4.2, respectively. We emphasize in bold the important terms used in Section 1.4.3 in which we demonstrate how we used the two research methods in our studies. Finally, we discuss threats to validity of our results in Section 1.4.4.

1.4.1   Case study theory

Case study is classified as an empirical research method [17] and it focuses on the examination of a real-world situation, which makes it suitable for industrial evaluations. Yin [43] defines a case study as an iterative process consisting of five phases, as shown in Figure Figure 1.5:
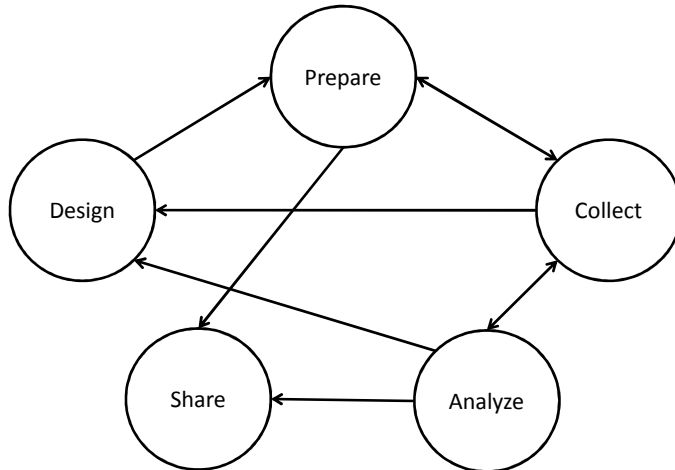
Figure 1.5: The five phases of a case study [43]

In this section, we focus on the design, collect and analyze phases. The design phase consists of the following five components [43]: (i) Research questions, (ii) Study propositions, (iii) Unit of analysis, (iv) Linking data to prepositions and (v) Criteria for interpreting the findings.

The design of each study begins with a clear definition of **research questions**. Providing answers to these questions is the main goal of the case study. In order to understand how to achieve this goal, however, the scope of the study is defined together with the identification of elements which are to be examined (the study propositions). Next, the **unit of analysis** (i.e., the "case"), the elements of which are to be examined, is defined. The data obtained from this

examination are then linked to the propositions in order to answer the defined research questions using, e.g.,, statistical analysis. Finally, the criteria for data interpretation are defined in order to indicate when the obtained results can be considered valid, e.g., by defining the statistical significance.

The **data collection phase** can include both qualitative and quantitative data collection methods [17]. Qualitative data can be obtained by analyzing documentation, performing observations, conducting interviews, etc. Interviews are especially common in analyzing industrial cases because they provide quick answers to question from experts. They can be formal with a precisely-defined set of questions, informal relying on a casual discussion with experts [35] or semi-formal where questions are pre-defined, but can be deviated from during the interview [7]. Quantitative research represents the analysis of numerical data in order to explain a certain phenomenon [1]. Quantitative data is usually obtained by measurement.

In the **data analysis phase**, the data can be analyzed using different methods, e.g., pattern matching (comparing the empirical pattern with one or several predicted patterns) and explanation building (e.g., using theoretically proven concepts) [43]. Quantitative data can be analyzed using a number of statistical methods, including correlation and time-series analysis.

1.4.2 Constructive research theory

"The aim of constructive research is to solve practical problems while producing an academically appreciated theoretical contribution" [25]. Constructive studies consist of the following six main phases [21]:

1. Understanding the industrial context and selecting a problem (case study)

2. Understanding the study area (literature review)

3. Designing one or more solutions (creation of a novel construct)

4. Demonstrating the solution's feasibility (case study)

5. Validating the results (case study)

6. Generalizing the results (possible further case studies)

Understanding the industrial context and selecting a problem usually involves a case study which aims to increase the understanding of the industrial context and identify relevant problems for further studies, e.g., by conducting interviews and documentation reviews. **Understanding the study area** aims to increase the understanding of the scientific problem and the surrounding theory, usually by conducting literature reviews. **Designing one or more solutions** aims to solve the identified industrial and scientific problem by creating a novel construct, e.g., a method, tool, technique or process [27], and it is based on the knowledge obtained in the first two phases.

The phases of **demonstrating the solution's feasibility** and **validating the results** usually require additional case studies, in which the novel construct is evaluated and empirically validated on the chosen units of analysis. Finally, the phase of **generalizing the results** involves a detailed discussion

on the practical use of the novel construct in other industrial contexts that
face similar problems, and may therefore involve further case studies.

As we can see from this description, all phases of constructive research,
except from the second phase, usually require conducting a case study. This
is why constructive research and case study methods should be combined for
solving practical problems and delivering academically rigorous contribution.
The benefit of this combined approach is that solutions for the relevant prac-
tical problems are produced quickly and their feasibility is directly tested in
the real industrial contexts. The use of constructive research with case studies
has some drawbacks as well. One drawback is that multiple case studies are
usually needed for generalizing the results. Another drawback that the pro-
duced solutions may not always be the best and/or optimal solutions, which
could have been identified by, e.g., conducting longer experiments with differ-
ent parameters and testing them in multiple scenarios.

1.4.3   Research methods used in our papers

In order to address our research questions, we conducted eight studies, each
described in one of the Papers A-H. Three studies were conducted using the
case study method, four studies were conducted using constructive research
which included additional case studies in the way described in the previous
section, and one study was a tool presentation. The description of the research
methodology we used in each study/paper is described below.

1. **Paper A**

   The study presented in Paper A was conducted following the construc-
   tive research method. In order to understand the industrial context and
   select a problem for the study, we first conducted a case study using
   architectural models from Volvo Cars as units of analysis. We analyzed
   the organization of these architectural models. As the outcome, we for-
   mulated our study problem in *RQ1*. In order to understand the study
   area, we performed a literature review of the complexity measures that
   can be used for monitoring the evolution of architectural models.

   We used the outcomes of the case study and the literature review to
   design a solution to the problem defined in *RQ1*. The solution repre-
   sents a new method based on two software measures developed following
   the GQM approach. The goal of the measurement was to monitor the
   complexity increase of the automotive architectural models when new
   functionality is introduced into the system. In order to achieve this goal,
   we searched for the answer to the questions of what is the complexity and
   coupling change between two version of one architectural model resulting
   in the definition of the complexity and the coupling measures. We also
   developed the *QTool* which is able to calculate the two measures for the
   two evolving architectural models at different time points.

   In order to demonstrate the solution's feasibility and validate the results
   empirically, we conducted another case study in which we evaluated our
   method and the *QTool* using two architectural models from Volvo Cars
   as units of analysis. The results are empirically validated by comparing

the measurement results with the expectations from the experts from Volvo Cars on the complexity increase of the two analyzed models.

2. **Paper B**

   The study presented in Paper B was conducted following the case study method using AUTOSAR meta-model as a unit of analysis. The study aimed to increase the understanding of the industrial context and select a relevant problem for the constructive research presented in Paper C. In the design phase, we defined *RQ2 - RQ4*. In the data analysis phase, we studied the organization of the AUTOSAR meta-model and created examples using four meta-modeling approaches in order to address *RQ2* and *RQ3*. In order to address *RQ4*, we identified that the evolution of domain-specific meta-models related to different architectural features and its impact on the development projects is one of the biggest challenges for the meta-modeling practitioners. We used this finding to formulate our research problem in Paper C.

3. **Paper C**

   The study presented in Paper C was conducted following the constructive research method. In Paper B, we already identified that the evolution of domain-specific meta-models related to different architectural features and its impact on the development projects is one of the biggest practical meta-modeling problems. We used this finding to formulate our general study problem in *RQ5*, and divided it into more concrete study problems formulated in *RQ6 - RQ8*. In order to understand the industrial context, we extended the knowledge obtained in Paper B related to the organization of the AUTOSAR meta-model by conducting an interview with one of the AUTOSAR's change managers. This helped us to to understand how changes related to different AUTOSAR features are implemented in the AUTOSAR meta-model. In order to understand our study area, we performed a literature review of the meta-model differentiation techniques and applicable measures.

   We used the outcomes from Paper B, the interview and the literature review to design a solution to the problems defined in *RQ6* and *RQ7*. The solution represent two constructs: (i) a data model that is able to capture relevant changes between different AUTOSAR meta-model versions (*RQ6*), and (ii) a measure of meta-model change (*NoC*) which is developed following the GQM approach based on this data-model. The goal of the measurement was to monitor changes between different meta-model versions. In order to achieve this goal, we searched for the answer to the question of how many atomic changed occurred between two meta-model versions resulting in the definition of the *NoC* measure. We also developed the *ARCA* tool that is able to calculate *NoC* between two AUTOSAR meta-model releases, related to a set of chosen AUTOSAR features, and targeting a set of chosen AUTOSAR modeling tools.

   In order to demonstrate the solution's feasibility and validate the results empirically, we conducted a case study in which we evaluated and validated the data model and the *NoC* measure using AUTOSAR features and AUTOSAR modeling tools as unit of analysis. We asked the experts

from different tooling vendors to provide us with the estimated efforts needed to support different AUTOSAR features in their modeling tools. We used this collected data in the data analysis phase to perform correlation analysis between the results of *NoC* and the estimated efforts in order to address *RQ8*. The generalization of our findings from this study is described in Paper D.

4. **Paper D**

   The study presented in Paper D was conducted following the case study method using Modelica and UML meta-models as units of analysis. The study aimed to generalize our findings described in Paper C, i.e., to assess the applicability of our data model and the *NoC* measure on additional meta-models. In the design phase, we defined *RQ9*. In the data analysis phase, we performed a study of the organization of Modelica and UML meta-models. We calculated *NoC* between different releases of these two meta-models, respectively, in order to address *RQ9*.

5. **Paper E**

   The study presented in Paper E was conducted following the constructive research method. The study aimed to extend the results presented in Paper C so that they can be used for identifying the optimal set of architectural features to be used in the development projects. Therefore, we formulated our study problems in *RQ10* and *RQ11*. In order to understand the study area, we performed a literature review of the existing optimization methods.

   We used the *NoC* measure presented in Paper C and the literature review to design a solution to the problems defined in *RQ10* and *RQ11*. The solution involved constructing a method (*MeFiA*) that is able to calculate the *NoC* measure in the domain-specific meta-models related to different architectural features (*RQ10*). The method is also able to identify the optimal set of features to be adapted in the development projects based on their meta-model impact (*RQ11*). We also extended the *ARCA* tool to be able to identify this optimal set in car development projects.

   In order to demonstrate the solution's feasibility, we conducted a case study in which we evaluated the *MeFIA* method using AUTOSAR meta-model as a unit of analysis.

6. **Paper F**

   The study presented in Paper H describes the *ARCA* tool which is developed in the constructive studies described in Papers C and E. The study also shows the industrial use of *ARCA* in order to address *RQ12*. The presented data is obtained from the two case studies described in Papers C and E, which were used to demonstrate the feasibility of the solutions developed in the constructive studies of these two papers, respectively.

7. **Paper G**

   The study presented in Paper G was conducted following the constructive research method. In order to understand the industrial context and select a problem for the study, we first conducted a case study using using the

AUTOSAR standardized requirements as units of analysis. We analyzed the organization of the AUTOSAR requirement specifications and the structure of the requirements itself. As the outcome, we formulated our study problem in *RQ13*. In order to understand the study area, we performed a literature review of the requirements engineering field focusing on how to cope with the evolution of system requirements.

We used the outcomes of the case study and the literature review to design a solution to the problem defined in *RQ13*. The solution involved constructing a method that is able to (i) analyze the evolution of requirements related to different specifications and (ii) calculate a number of measures related to different specification. The measures are developed following the GQM approach. The goal of the measurement was to monitor changes in the specifications between their different releases. In order to achieve this goal, we searched for the answer to the questions of (i) how many requirements are semantically changed between the two versions of one specification and (ii) how mature is the new version. This resulted in the definition of a set of measures for counting added, deleted and modified requirements (inspired by the similar measures for added, deleted and modified meta-model elements), and the *RMI* measure. We also developed the *SREA* tool that is able to calculate the measures used by our method related to these specifications/requirements.

In order to demonstrate the solution's feasibility, we conducted another case study in which we evaluated our method and the *SREA* tool using a set of AUTOSAR specifications and their requirements.

8. **Paper H**

   The study presented in Paper H was conducted following the case study method using the AUTOSAR meta-modeling environment as a unit of analysis. In the design phase, we defined *RQ14*. In the data collection phase, we calculated the *NoC* (defined in Paper C) in the AUTOSAR meta-model (syntax) related to a set of chosen AUTOSAR features using the *ARCA* tool (presented in Paper F). We also calculated the *Number of changed requirements* (defined in Paper G) in the AUTOSAR specifications (semantics) related to these features using the *SREA* tool. In the data analysis phase, we calculated correlation between the results of the *ARCA* tool and *SREA* tools in order to address *RQ14*.

1.4.4 Research validity

According to Cook and Campbell [13], four types of validity threats to empirical studies conducted in the area of software engineering shall be considered. We explain below how we addressed each of them in our studies.

1. **Internal validity**

   Internal validity is concerned with the results of the analysis not being casual, i.e., the relationship between the measured properties and the outcome should not be random. The most severe threat to the internal validity in our studies was related to the measurement process which was performed by developing software tools, e.g., *QTool*, *ARCA* and *SREA*,

for calculating different measures, e.g., *NoC* and *RMI*. In order to ensure internal validity, we performed detailed testing of the tools using smaller examples before employing them for the measurements in the studies.

2. **External validity**

   External validity is concerned with the generalization of results. In our studies, this is related to the applicability of our results to models, meta-models and system requirements used by other companies facing similar problems. There are two particular threats to the external validity of our studies. The first threat is that the proposed methods and tools would apply only to the automotive software development process at Volvo Cars and not to other automotive companies. In order to minimize this threat, we included other automotive companies (OEMs and software/tool suppliers from the AUTOSAR consortium) in the process of defining and evaluating our methods and tools.

   The second threat is related to the AUTOSAR meta-modeling environment (AUTOSAR meta-model and AUTOSAR requirements) that was the unit of analysis in Papers A - C and E - H . The proposed methods and tools we applied to the AUTOSAR meta-modeling environment should also be applicable to other domain-specific meta-models. Therefore, we mapped the layers of the AUTOSAR modeling environment to the layers of MOF which is a commonly accepted modeling hierarchy. In addition to this, we discussed in the included papers the steps that need to be taken in order to apply the proposed methods to meta-models of other domains, e.g., avionics and telecommunications.

   Finally, the goal of Paper D was to minimize the external validity threat of the *NoC* measure, which is used in Papers C, E, F and H. Therefore, we calculated the measure to two additional meta-models of Modelica and UML. As opposed to the AUTOSAR meta-model which is an architectural meta-model, UML is a general-purpose meta-model and Modelica is a behavioral meta-model. Therefore, we analyzed three different types of meta-models which significantly reduces the threat that *NoC* is only applicable for measuring the evolution of the AUTOSAR meta-model.

3. **Construct validity**

   Construct validity is concerned with the mismatch between theory and observations. In our studies, this was related to the ability of the measures to capture the desired properties of the analyzed system. In order to define our measures in a rigorous way, all measures were defined according to the GQM approach based on the data model that enabled us to have open discussions about the ability of the measures to capture the desired properties of the measured entities. Additionally, we performed theoretical and empirical validation of the complexity and coupling measures presented in Paper A. We also performed empirical validation of the *NoC* measure used in Papers C, E, F and H. Finally, we showed that it is possible to calculate the measures of requirements evolution used in Papers F and H on a case of AUTOSAR requirement specifications.

4. **Conclusion validity**

Conclusion validity is concerned with the degree to which the conclusions of the studies are reasonable. In Papers C and H, this was related to the significance of the results from the statistical analysis, which was high. In Papers A, D, E, F and G, the conclusions were derived based on studying and applying our methods to industrial scenarios. The conclusion was that the results could capture the desired properties, thus validating our hypothesis that simple measures can be used as preliminary indicators. Finally, Paper B presents our opinion based on our experience in working with domain-specific meta-models, and shall be taken as a position paper.

1.5 Conclusions and future work

The main contribution of this thesis are three methods (and software tools) that can be used for automated impact assessment of using new architectural features, that require updates of the modeling language, on the development projects. We showed that using these methods and combining their results in the development process is able to accelerate the work of system designers responsible for planning architectural updates in the development of automotive software systems. This, in turn, enables faster and cheaper innovation cycles in the car development projects.

The first method and the tool ($QTool$) are based on two structural measures of complexity and coupling in the architectural models. The method is able to identify parts of the system which became overly complex after the implementation of new architectural features. We showed that this information can be used by the automotive system designers to identify and prioritize testing areas in the system and/or rework the system's architecture in order to reduce the number of potential faults. This, in turn, contributes to the increased speed of automotive software development and higher quality of software.

The second method ($MeFIA$) and the tool ($ARCA$) are based on the measure of change in the architectural meta-models (NoC). The method is able to estimate the impact of using new architectural features on the used modeling tools. We showed that this information can be used by the automotive system designers to decide which architectural features shall be used in the system, and to plan updates of the modeling tool-chain.

Additionally, we showed that with the help of the $ARCA$ tool, it is possible to identify the actual AUTOSAR meta-model changes caused by a particular feature and relevant to a specific modeling tool used by one design role. This, in turn, has a potential to significantly reduce the number of inspected AUTOSAR meta-model changes in the detailed impact assessment for different modeling tools, e.g., from more than 35000 changes to less than a hundred for the majority of AUTOSAR features and tools.

The third method and the tool ($SREA$) are based on the measure of change in the system design requirements. The method is able to identify the subset of design requirements which are affected by the use of new architectural features. We showed that this information can be used by the automotive system designers to more quickly understand how to use the new features in the architectural models, and to identify unstable requirement specification which

are candidates for inspection. This, in turn, has a potential to significantly reduce the number of analyzed design requirements, e.g., from more than 20000 requirements to less than a hundred for the majority of AUTOSAR features.

In order to achieve the full benefit of using these methods and tools in the development process, they should be used in combination. *ARCA* and *SREA* tools shall be used before one architectural feature is supported in the development process in two different ways: First, to indicate whether it is feasible to use the feature in the project time-frame considering its impact on the used modeling tools (*ARCA*) and requirements specifications (*SREA*). Second, to plan updates of the tools (*ARCA*) and analysis of the changes in the requirements specifications (*SREA*), in case it is considered feasible. The *QTool* shall be used after one feature is supported in the development process and used in the system models in order to indicate which parts of the system are mostly affected by the new feature. This information can be used to steer testing activities and possible restructuring of the system's architecture in case of significant complexity increase of its components.

As we can see, all three methods and tools are based on quantitative analysis of changes using one or more simple software measures. This validates our hypothesis that quantitative analysis of evolution of the three main MDE artifacts related to different architectural features can serve as a valuable early indicator of which features shall be used in the system, and what is their impact on the development projects.

The results presented in this theses provide opportunities for further research in the area of meta-model and system requirements evolution. Related to the evolution of meta-models, one direction could be to classify meta-model changes into categories according to their impact on different segments of the modeling tools (e.g., graphical user interface, tool importers or underlying data-base) and identify the ones that require most rework in the tools. The results of such a study can then be used to extend the *MeFIA* method and the *ARCA* tool to consider these categories in the measurement process e.g, by performing category based measurements or assigning different weights to different categories. This, in turn, can be used to steer the development of the tools where certain changes could probably be done automatically, e.g., changes affecting databases of the tools or simple textual editors of the meta-modeling elements and their properties.

Another direction could be to analyze the relation between different features based on their impact on the same parts of the meta-model. The results of such a study can be used to group similar features that should be used together in the development project, e.g., at the cost of tool-chain update that is much lower than the sum of costs of supporting each feature separately duo to the overlap of changes. This, in turn, can be used to complement the results of the *MeFIA* method in the analysis of which architectural features shall be used in the system.

Related to the evolution of system requirements, one direction could be to include natural language processing (NLP) techniques in the analysis performed by the *SREA* tool. This approach has a potential to additionally increase the speed of analyzing changes in the requirements specifications related to the use of new architectural features in the system, by filtering out syntactically changed requirements that have no semantic impact.

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Chapter 2

Case Study Background

Automotive Software Development based on AUTOSAR

D. Durisic

Based on Chapter 4 of the Automotive Software Architectures book, Springer, 2017

Chapter 3

Paper A

Measuring the Impact of Changes to the Complexity and Coupling Properties of Automotive Software Systems

D. Durisic, M. Nilsson, M. Staron and J. Hansson

Chapter 4

Paper B

Addressing the Need for Strict Meta-Modeling in Practice - A Case Study of AUTOSAR

D. Durisic, M. Staron, M. Tichy, J. Hansson

Proceedings of the 4th International Conference on Model-Driven Engineering and Software Development (MODELSWARD), 317-322, 2016

Chapter 5

Paper C

Assessing the Impact of Meta-Model Evolution - A Measure and Its Automotive Application

D. Durisic, M. Staron, M. Tichy, J. Hansson

Chapter 6

Paper D

Measuring the Evolution of Meta-Models - A Case Study of Modelica and UML Meta-Models

M. Jimenez, D. Durisic, M. Staron

Proceedings of the 5th International Conference on Model-Driven Engineering and Software Development (MODELSWARD), 2017

Chapter 7

Paper E

Identifying Optimal Sets of Standardized Architectural Features - A Method and its Automotive Application

D. Durisic, M. Staron, M. Tichy and J. Hansson

Chapter 8

Paper F

ARCA - Automated Analysis of AUTOSAR Meta-Model Changes

D. Durisic, M. Staron, M. Tichy and J. Hansson

Chapter 9

Paper G

Should We Adopt a New Version of a Standard? - A Method and its Evaluation on AUTOSAR

C. Motta, D. Durisic, M. Staron

Chapter 10

Paper H

Co-Evolution of Meta-Modeling Syntax and Semantics in Architectural Domain-Specific Modeling Environments - A Case Study of AUTOSAR

D. Durisic, C. Motta, M. Staron, M. Tichy