# *Seamless tool integration in an automotive use case*

## *An experience report*

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***Abstract*—The development of today's complex systems requires the use of a variety of different tools. In order to efficiently and effectively handle the complexity of the development process, the tools have to collaborate in a seamless way. Interoperability and openness are getting more crucial than ever before. The project CRYSTAL (CRitical sYSTem engineering AcceLeration) has identified this need and aims for an Interoperability Specification (IOS) as an open European standard for the development of safety-critical embedded systems. The IOS comprises existing open specifications and provides extensions wherever necessary.**

**In this paper, we describe our experiences with the application of the Crystal IOS in an automotive use case. We will show the engineering activities which are supported by our tool chain and how we are trying to achieve a seamless integration of the involved tools. As a conclusion, we report some of our experiences in the implementation of this use case.**

***Keywords—seamless tool integration; open specifications; interoperability ;OSLC;***

## I. INTRODUCTION

The processes of developing, deploying, governing, operating and maintaining modern safety-critical embedded systems is highly complex and requires specialized tools supporting different activities throughout the entire product life cycle. Therefore, OEMs and suppliers are typically operating a large set of tools from different vendors often complemented by custom in-house solutions. The overall process can be effective and efficient only, if it supports collaboration among all stakeholders and consequently interoperability between the tools they are using. Considering the ongoing outsourcing and globalization activities, interoperability and openness is getting even more crucial. In addition, the demand for supporting a large number of product variants further increases the complexity to be handled.

Today, tool integration is often done in an ad-hoc manner by creating proprietary bridges between each pair of tools. Such an approach does not scale, since the number of required bridges grows exponentially with the number of employed tools. Moreover, the resulting tool chain becomes extremely vulnerable to common changes like version upgrades from tool vendors, and the efforts for maintaining a large set of bridges is sooner or later no more acceptable. The main technical challenge in addressing this problem is the provision of open and common interoperability technologies supported by the different tools that generate and provide access to data covering the entire product lifecycle.

The project CRYSTAL (CRitical sYSTem engineering AcceLeration) has identified this need and takes up the challenge to establish and push forward an Interoperability Specification (IOS) as an open European standard for the development of safety-critical embedded systems in the automotive, aerospace, rail and health care domain. This standard will allow loosely coupled tools to share and interlink their data based on standardized and open technologies that enable common interoperability among various life cycle domains. This reduces the complexity of the entire integration process significantly. CRYSTAL is strongly industry-oriented and will provide ready-to-use integrated tool chains having a mature technology-readiness-level (up to TRL 7). In order to reach this goal, CRYSTAL is driven by real-world industrial use cases from the automotive, aerospace, rail and health sector and builds on the results of successful predecessor projects like CESAR, SAFE, iFEST, MBAT on European and national level.

Creating and establishing a new standard on a large scale in an already consolidated market cannot be achieved by small individual organizations. With a budget of more than 82 million Euro and 68 partners from 10 different European countries, CRYSTAL has the critical mass to accomplish this endeavor. The project consortium is made up of participants from all relevant stakeholders, including OEMs, suppliers, tool vendors and academia.

Here, we will describe one of the industrial use cases from the automotive domain which is driven by AVL. AVL aims for an open integration of its own tools with tools from other vendors to enable seamless interoperability throughout the development process for their customers. In the remainder of this paper, we will focus on the different engineering activities that are supported by our tool chain and how we are using open standards to foster interoperability. This paper is structured as follows: Sec II. introduces the used specifications and provides some references to related work. Sec III. describes the engineering activities that should be supported by the actual tool chain. The tools and interoperability specifications that build up the tool chain are highlighted in Sec IV. Sec V finally concludes the paper with some lessons learned.

## II. Background and Related Work

This section introduces the most relevant specifications of the Crystal IOS[1].

### A. OSLC

Open Services for Lifecycle Collaboration (OSLC) [2] is an open community that creates specifications for integrating tools based on standardized and well-known web technologies such as Hypertext Transfer Protocol (HTTP), the Resource Description Framework[1] (RDF), and the Uniform Resource Identifier (URI).
It makes use of the linked data principles defined by Tim Berners-Lee[2]:

- Use URIs as names for things
- Use HTTP URIs so that people can look up those names
- When someone looks up a URI, provide useful information, using the standards (RDF*, SPARQL)
- Include links to other URIs, so that they can discover more things.

OSLC consists of a core specification [3] and a set of domain specifications. The core specification defines essential properties, behavior, and services that expand the W3C Linked Data concept[3] and enables the integration of tools. Additionally, domain specifications are created and maintained by specific working groups in order to support a common vocabulary. These specifications include requirements management, change management, architecture management, quality (test) management, and asset management. The base for these specifications are concrete use case scenarios. The scenario-based approach ensures that the specifications only contain a minimal set of domain properties, because OSLC promotes the idea of a stable standard which specifies just enough for realistic integration scenarios.

Data integration with OSLC mainly consists of two parts: a provider, which is responsible for managing and providing data via a web service, and a consumer, which is able to request and manipulate (Create, Update, Delete) data. In order to be able to communicate, provider and consumer have to comply with the same specification. There is no need to change the data model or the tool behavior. Consumers can create links between OSLC resources by embedding the URL of the related OSLC resource as a property of the resource itself. OSLC providers can store the link information in a tool independent format which enables traceability beyond different tools.

Experiences of the application of OSLC in different application scenarios have been reported by several authors [4, 5, 6]. Biehl et. al [7] furthermore describe an approach for the automatic generation of OSLC adapters in order to overcome the cumbersome and recurring implementation work for the common parts of an adapter. We have not used a generation approach for our implementation, instead we are relying on the existing frameworks Eclipse Lyo[4] for Java and OSLC4net[5] for C#.

### B. Functional Mockup Interface (FMI)

The FMI standard currently evolves itself to be the standard for co-simulation (so far there has been none). FMI standard version 1.0 (see [8]) was published in 2010 as one result of the ITEA2 project MODELISAR. FMI 2.0 followed in July 2014. The FMI 2.0 standard [9] consists of two main parts: (1) FMI for Model Exchange with the intention to provide generated C-Code of a dynamic system model in the form of an input/output block that can be utilized by other modeling and simulation environments. Models (without solvers) are described by differential, algebraic and discrete equations with time-, state- and step-events. (2) FMI for Co-Simulation with the intention to couple two or more models with solvers in a co-simulation environment. The subsystems are solved independently from each other by their individual solver - data exchange between subsystems is restricted to discrete communication points. Data exchange and the synchronization of the slave simulation solvers is controlled by master algorithms between subsystems and. FMI allows standard, as well as advanced master algorithms, e.g., the usage of variable communication step sizes, higher order signal extrapolation, and error control.

A component implementing the FMI standard is called Functional Mockup Unit (FMU). A FMU is a zip-file with extension ".fmu" which contains all necessary components to utilize the FMU (for co-simulation): (a) An XML-file containing the definition of all exposed variables of the FMU, as well as other model information. It further includes a slave-specific XML-file with relevant information for the communication, e.g. flag indicating the ability of the slave to support advanced master algorithms (e.g. the usage of variable communication step sizes, higher order signal extrapolation, or others). (b) A small set of easy to use C-functions to initiate the communication with a simulation tool, to compute a communication time step, and to perform the data exchange at the communication points are provided in source and/or binary form. (c) Further data can be included in the FMU zip-file (e.g. a model icon (bitmap file), documentation files, maps and tables needed by the model, and/or all object libraries or DLLs that are utilized). Several publications show the application of FMI [10,11].

### C. ASAM ODS

ASAM (Association for Standardization of Automation and Measuring Systems) is an association that coordinates the development of technical standards especially in the field of measurement, calibration and test automation. It supports the vision that tools can be freely interconnected to allow a seamless exchange of data throughout the development process. The standards define protocols, data models, file formats and application programming interfaces (APIs) for the use in the development and testing of automotive electronic control units. ODS (Open Data Services) [12] is one of these standards and focuses on the persistent storage and retrieval of

[1] http://www.w3.org/RDF/
[2] https://www.w3.org/DesignIssues/LinkedData.html
[3] http://www.w3.org/standards/semanticweb/data
[4] http://www.eclipse.org/lyo/
[5] https://oslc4net.codeplex.com

testing data. The standard is primarily used to set up a test data management system on top of test systems that produce measured or calculated data from testing activities. A typical scenario for ODS in the automotive industry is the use of a central ODS server, which handles all testing data produced by vehicle test beds. The major strength of ODS as compared to non-standardized data storage solutions is that data access is independent of the IT architecture and that the data model of the database is highly adaptable yet still well-defined for different application scenarios.

## III. Supported Engineering Activities

The considered use case consists of 5 engineering activities. An engineering activity can be seen as a typical activity of an engineer, which should be supported by a tool chain.

### *A. Formalize Requirements*

The major purpose of this engineering activity is to derive (semi-)formal, machine-processible requirements from natural language requirements. The term semi-formal here refers to the fact that the notion not necessarily has strictly defined semantics. Currently, tools such as HP Quality Center, PTC Integrity or Excel are typically used to manage natural language requirements.. In our use case we are evaluating three methods to semi-formalize them: SysML requirement profiles, sequence chart-based techniques, and boilerplate techniques based on domain-specific languages.

As a precondition, we assume that natural language requirements are available and stored in a requirement management tool (e.g. HP QualityCenter). We consider vehicle requirements, testing requirements, as well as legal requirements (modeling of selected parts of the WLTP emission legislation). The engineering activities are then comprised of the following steps:

- Reading natural language requirements from a requirement management tool into a requirement formalization tool.
- The requirements engineer derives semi-formal requirements by means of the formalization tool. One natural language requirement can be represented by n semi-formal requirements.
- The semi-formal requirements are stored in the requirements management tool.
- Each semi-formal requirement is linked to its corresponding natural language requirement.

Consequently, the post-condition of these steps is that the semi-formal requirements are stored and interlinked accordingly.

### *B. Heterogeneous Simulation*

Heterogeneous simulation (also called co-simulation) describes the ability to couple two or more simulation models executed in different tools at run-time. This is quite important since the simulation tool landscape is usually very heterogeneous and a typical development process involves several domain-specific modeling and simulation tools. However, it is important to enable a holistic system simulation already at an early stage of development. Development frontloading ensures that system integration can already be tested in the simulation phase.

A simple example of a co-simulation consists of and engine model and a functional model that describes the control algorithms of the engine's ECU. Both models are created using dedicated modeling and simulation tools. Here, it is helpful to have the possibility to couple the two models in order to get feedback about their interactions.

The engineering activity assumes that the simulation models have already been created. It consists of the following steps:

- Appropriate simulation models are selected based on the requirements.
- The simulation models are coupled (connecting input and output signals).
- The co-simulation is configured (step-size, simulation time, and so on).
- The co-simulation is executed.
- The simulation results are stored in a dedicated database.

### *C. Heterogeneous Real-Time Simulation*

Heterogeneous real-time simulation is quite similar to the previous engineering activity, but with the additional requirement of real-time capabilities. At a certain point in the development process, simulation models are replaced by physical components. Taking the example from above, we would now like to couple the functional model with a real engine on an engine test bed. These means that the models as well as the interfaces (data exchange) need to be real-time capable.

The engineering steps for this activity can be described as follows.

- The co-simulation configuration of the heterogeneous simulation (in office) can be reused.
- The simulation model which is available as physical component now can be replaced by a placeholder for this component.
- Non-real-time simulation models have to be exchanged by real-time capable versions.
- The models, model parameters, and the coupling information should be exported.
- This information will then be used for the configuration of the test bed.
- The simulation models can be executed together with the physical component on the test bed.

- The measurement results are stored in a dedicated data base.

### D. Validate Design against Requirements

The purpose of this engineering activity is the validation of a system design with respect to requirements based on simulation (or testing on a testbed).

The pre-condition for this activity is that the requirement formalization activity has been finished and the semi-formalized requirements are stored and accessible. Furthermore, test cases have been defined (in a test management tool), linked to requirements, and executed. A test case here basically describes a simulation run. The test results (i.e. simulation results) are stored and accessible.

The engineering activity is comprised of the following steps:

- Select a test case in the validation tool.
- Read all requirements which are linked to the selected test case from the requirements management tool into the validation tool.
- The validation tool analyses the simulation or measurement results and compares them to the formalized requirement limits.
- Validation results (i.e. passed or failed for all checked requirements) are generated – optionally with some addition information (such as failure reason, detected deviation from limits, etc.).
- The validation results are stored as annotations in the requirement management tool.

### E. Linking Calibration and Measurement Data

For this engineering activity, we assume that a customer requests the calibration of an engine according to a specific norm (e.g. Euro5[6]). This can be seen as the calibration goal. As a result of this engineering activity, calibration and corresponding measurement data are linked in order to reproduce the measurement results for each calibration data set. This enables the evidence for certification (proof that emission norm is fulfilled).

As a prerequisite we assume that the initial data (A2L and HEX file) has been imported in the calibration data management tool.

The engineering activity consists of the following basic steps:

- Project manager assigns calibration tasks (represented in a .dcm file) to calibration engineers. The calibration is usually not done by one person, because it involves thousands of calibration parameters. These parameters are packaged in several .dcm files, each containing a logically related set of calibration parameters.
- Calibration engineers perform calibration tasks and test the setting in a test run. The measurement results of this test run are stored in a record file.
- Record files are stored in a dedicated ASAM ODS database.
- Link calibration data (DCM file) to measurement results (record file).

## IV. TECHNICAL REALIZATION

This section describes the realization of the tool chain based on open standards wherever possible and meaningful. Figure 1 illustrates the considered tool chain.

### A. Formalize Requirements

As mentioned before, we are evaluating different approaches for requirement formalization. Here we are focusing on the realization using the boilerplate approach. More information about the sequence chart-based techniques can be found in [13]. The tools involved in this integration scenario are HP Quality Center (HPQC) for requirements management and Refine – a prototype implementation of the boilerplate-based approach. Refine is an Eclipse-based prototype built upon the Xtext[7] framework. Xtext supports the creation of textual domain-specific languages. In the Crystal project, VIF has defined a requirements specification grammar. The resulting domain-specific requirements language supports the requirements engineer in writing "good" requirements. More detailed information about the tool and the language can be found in [14].

Xtext has not only the advantage that the editor and many useful features are generated automatically, it furthermore provides advanced parsing capabilities. We use these capabilities to extracts min/max values from the requirements. This information is then used in the follow-up engineering activity.

In this engineering activity, interoperability is supported by OSLC. AVL has implemented a prototype OSLC RM Provider for HPQC. This provider supports CRUD (create, retrieve, update and delete) services for Requirements. Refine implements a consumer interface that supports the import of natural language requirements, the export of semi-formal requirements, and the update of natural language requirements with the respective link information. The OSLC interface has been implemented to support consistency checks.

[6] https://www.theaa.com/motoring_advice/fuels-and-environment/euro-emissions-standards.html

[7] https://eclipse.org/Xtext/

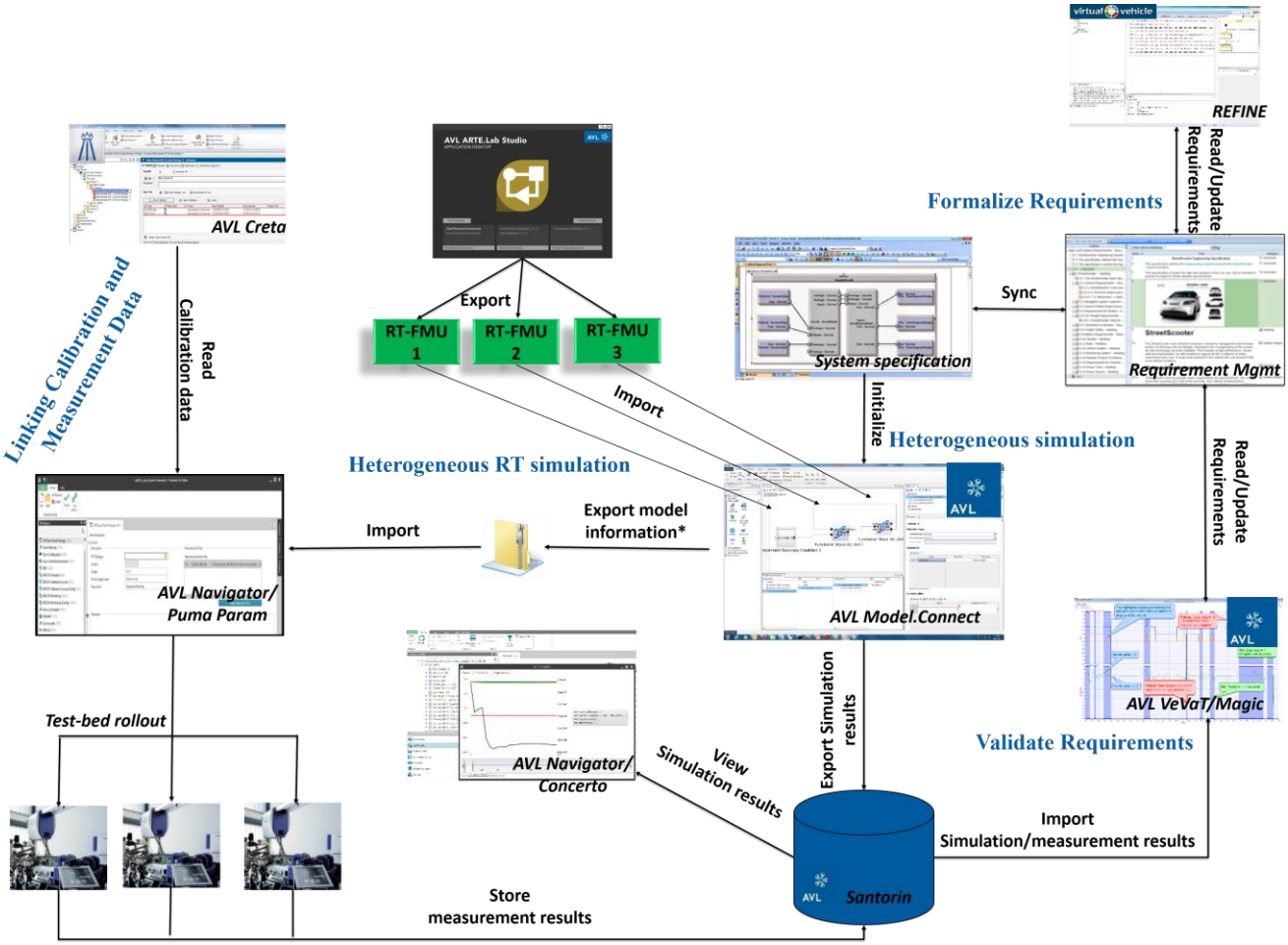


**Figure 1: Overview of the toolchain**

### *B. Heterogeneous Simulation*

For heterogeneous simulation, we are using the AVL product Model.CONNECT. Some of the tool features (e.g. FMI execution) have been developed in the context of Crystal-Model.CONNECT is a platform to set up and execute system simulation models, which are composed of subsystem and component models from multiple model authoring environments. Models can be integrated based on standardized interfaces (FMI) as well as based on specific interfaces to a wide range of well-known simulation tools. Model.CONNECT supports the user in organizing system model variants. These variants may describe different configurations of the system under investigation as well as different testing scenarios and testing environments.

Model.CONNECT can be used as follows: The first step in the setup of a simulation is to add model templates into a system (i.e. model interfaces and input elements such as signal table). As a next step, the concrete models and configurations are added to the templates. After inserting the data into the model elements and defining the port units, the elements need to be connected so that they can communicate with each other. One input can be connected to only one output, while one output can be connected to one or more inputs. In order to use this setup to perform the actual simulation, several additional steps are needed, i.e. defining the simulation time, setting the simulation properties, configuring the monitoring view, etc.

The results of a simulation can be exported into AVL Santorin. AVL Santorin is a tool for measurement result management and adheres to the ASAM ODS standard.

### *C. Heterogeneous real-time Simulation*

For this engineering activity we want to reuse as much information as possible from the previous heterogeneous simulation step. With this, consistency in the vehicle development process is ensured by reusing simulation models and model configurations from the office at the testbed.

AVL ARTE.Lab™ can be used to create real-time FMU's. These real-time FMUs can be used in Model.CONNECT by simply replacing the non-real-time FMU. The interconnection information (configuration), the simulation models and the

model parameters are stored in a zip-file which then is used for the preparation of the test bed. Using the central access point for parameterization of the testbed, the AVL Navigator, the zip-file is stored in the AVL SANTORIN database and can then be rolled out in the test field. The installation and deployment of the models, the parameters and the model configuration is done automatically. The traceability and reproducibility is ensured by using the same workflow and storage location as for other testbed parameters. The AVL Navigator framework with AVL Santorin enables the versioning of the stored parameters and model configurations.

### *D. Validate Design against Requirements*

The tools used for this engineering activity are mainly HP Quality Center, AVL VeVaT /Magic, and AVL Santorin.

AVL VeVaT is a Verification & Validation Tool for various software products or software modules which generate voluminous numerical output – e.g. numerous single result values and/or huge sequences of numerical values (e.g. multi-channel time history data). It provides two approaches for checking the correctness of its numerical output data:

- Comparison of actual output data to already validated reference output data (mainly used for regression tests, where output data of a new product version get compared to validated data of a preceding software release)
- Detecting/deriving significant properties of output data (time history data) and compare them to numerical product requirements (e.g. deriving properties of a vehicle braking event from road measurement data and checking, whether e.g. braking time, braking distance, deceleration, ABS- influences etc. reside within required limits).

AVL VeVaT generates validation reports, which supply passed/doubtful/failed validation statements at several hierarchy levels, i.e. an overall statement and more detailed statements for subsections of analyzed data. It works on top of AVL Magic, which imports measurement or simulation values for the actual post-processing.

The integration for this scenario is twofold: First VeVaT reads and updates requirement and test case information using an OSLC interface. Simulation results are stored in ASAM ODS format and can be exported in the standardized ASAM-ODS ATF/X file format.

AVL VeVaT implements an OSLC consumer interface for Requirements and Test Cases. As a first step the user can select a test case. Test cases are defined in HPQC and can be retrieved using an OSLC QM interface. The OSLC QM provider for HPQC has been implemented by AVL for the Crystal project and does provide only the required functionality. Once the user has selected a test case, he can read all the requirements which are linked to this test case from HP Quality Center.

AVL VeVaT now has all the requirements for the selected test case together with the validation parameters (defined in the Formalize Requirements engineering activity). After the actual validation step, the requirements now have the validation results (passed/failed information) assigned to them. This information is written back to HPQC using OSLC.

### *E. Linking Calibration and Measurement Data*

In order to establish a link between the calibration and measurement data, a tool called AVL Navigator is used. This tool can basically be understood as a viewer on different databases. Therefore it is possible to browse measurement data and calibration data, but so far it was not possible to establish links and to navigate between the different types of data. The integration of calibration data in the AVL navigator has been realized using OSLC. The calibration management tool AVL Creta implements an OSLC provider interface for Assets. AVL navigator is implementing the corresponding consumer interface. It is now possible to link a selected DCM file to a test record.

## V. LESSONS LEARNED AND CONCLUSION

The described tool chain has been set up in a prototypical way. We have shown that the open specifications of the Crystal IOS cover a broad range of automotive engineering activities. Nevertheless, we also experienced that the practical application of FMI and ASAM ODS is much easier than the application of OSLC. This is mainly due to the fact that the OSLC specification is intentionally kept very open. This brings a lot of flexibility, but makes it hard to implement generally applicable interfaces. Furthermore, the work with OSLC requires a good understanding of web technologies. Especially because the OSLC specifications often simply refers to other specifications or relies on the knowledge of best practices for web development. One remaining open issue for the integration using OSLC is the question of security. The OSLC specification does not state much about security considerations, although this seems to be one of the most important topics. An important advantage of lifecycle integration is the possibility to query information over a variety of tools. This requires a comprehensive role and access management. A detailed investigation of security aspects is currently in work.

However, we have shown that OSLC does have advantages regarding the reuse of interfaces. For example, the HPQC Requirement provider has been used by the Refine tool and the VeVaT tool without any changes. On the other hand, we are also trying to investigate if we can simply replace the requirement management tool. This independence of a concrete tool is one of the main arguments for standardized interfaces. We have identified some weaknesses in the specification, which require the consumer to understand tool specifics. But these weaknesses could easily be fixed by adding some more details to the specification. Overall, we experienced no real show stoppers for this exchangeability of tools. Currently, the main problem is the lack of tools, which fully comply with the specification.

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