The Spacecraft Simulator Reference Architecture

Walsh, A[1]; Wijnands, Q[3]; Lindman, N[3]; Ellsiepen, P[1]; Segneri, D[1]; Eisenmann, H[2]; Steinle, T[2]

[1] *VEGA Deutschland GmbH*
Europaplatz 5, 64293 Darmstadt, Germany
Email:
Anthony.Walsh@vega.de, Peter.Ellsiepen@vega.de, Daniele.Segneri@vega.de

[2] EADS *Astrium GmbH*
Claude-Dornier-Straße, 88090 Immenstaad, Germany
Email:
Harald.Eisenmann@astrium.eads.net, Tobias.Steinle@astrium.eads.net

[3] *ESA/ESTEC*
Postbus 299, 2200 AG Noordwijk, The Netherlands
Email:
Niklas.Lindman@esa.int, Quirien.Wijnands@esa.int

ABSTRACT

This paper presents an overview of the Spacecraft Simulator Reference Architecture (SSRA) study, which is being performed by VEGA Deutschland and Astrium Satellites within ESA's Technology Research Programme (TRP).

Simulation has become more and more a crucial activity in the support of a wide range of engineering and operational activities during the lifecycle of a space programme. Considerable effort is currently invested by programmes in the development of simulation and test facilities. Although it is widely recognised that simulation now forms a crucial part of the system engineering process, there has been a tendency until recently to treat simulation as a supporting activity. The application of simulation by the different disciplines and across project phases is often uncoordinated with facility specific solutions being developed to address particular needs.

It is nowadays recognised that a more coordinated and consistent approach to the development of simulation products across project phases would bring substantial benefits. This would promote the most effective use of simulation within the system engineering process to minimise the overall space programme risk and cost. The industrial experience has shown that a number of simulation and test facilities are procured which are common across all space programmes. Experience has also shown that there is much commonality between the infrastructure and models developed for each of these facilities. This experience has been captured in the ECSS E-TM-10-21 "System Modelling and Simulation" Technical Memorandum which provides guidance to system engineers on how to use system simulation to support their system engineering tasks. This Technical Memorandum identifies the typical facilities that can be procured and their associated high level requirements. It also identifies possible model reuse across simulation facilities. However, it does not specify which enabling simulation technology should be used to achieve this.

The objective of the Spacecraft Simulator Reference Architecture study is to define and validate a reference architecture which is aligned with the E-TM-10-21 that promotes model reuse and maximises the benefits of modelling and simulation in support of the Systems Engineering function. It is based on the use of the Simulation Modelling Platform (SMP) specification as the simulation technology to enable the reuse of model implementations across simulation facilities. The reference architecture can be considered to serve as a template which can be applied and extended for simulator developments in space programmes. The reference architecture captures the semantics of the space system simulation problem domain. For example, the language of the reference architecture includes as first order concepts such items as Equipment Models or System Level Interfaces (e.g. power lines, bus lines, etc) using a terminology which is natural to a system engineer. This language is independent of the underlying simulation technology. This domain specific language is then mapped to the SMP platform by a set of mapping rules which describe how model elements in this language are represented by SMP models and interfaces. The separation of the domain semantics from the target platform allows the underlying simulation technology to evolve without having major impacts on the reference architecture. For example, future evolutions of SMP would have a minimal impact on the reference architecture. As the scope of the reference architecture is to support simulation model reuse across the full project life-cycle, there are a number of important constraints which have been considered in its design, in particular:

- the efficient evolution of models across the project life-cycle

- support for hardware-in-the-loop and hard real-time
- the configuration of simulation benches from engineering databases

Tooling is required in order to support the application of the reference architecture on a project. A modelling approach based on the use of UML profiles has been applied in the study in order to take advantage of existing UML tools. This approach was adopted in order to minimise the effort spent in the study on tooling development. However the use of UML is not mandated by the reference architecture and an approach using a domain specific language modelling environment can also be considered.

The Preliminary Design Review of the reference architecture has recently been completed and the verification phase of the project is currently on-going. However the definition of a reference architecture which is widely accepted within the spacecraft simulator community is a long process and the results of this study are just a first step in achieving this ultimate goal.

CONTEXT

Simulation is a key activity that supports the specification, design, verification and operations of space systems. System Modelling and Simulation (M&S) can potentially support a number of use cases across the spacecraft development life-cycle, including activities such as system design validation, software verification & validation, spacecraft unit and sub-system test activities, etc.

As the use of modelling and simulation has grown, it has been recognised that a more coordinated and consistent approach to the development of simulation products across project phases could bring substantial benefits. This would promote the most effective use of simulation within the system engineering process to minimise the overall space programme schedule, risk and cost. The industrial experience has shown that a number of simulation and test facilities are procured which are common across all space programmes. Experience has also shown that there is much commonality between the infrastructure and models developed for each of these facilities. This experience has been captured in the E-TM-10-21 "System Modelling and Simulation" Technical Memorandum [2] which provides guidance to system engineers on how to use system simulation to support their system engineering tasks with the following objectives:

- Maximise the benefits of using M&S in support to the Systems Engineering function
- Reduce effort in developing and maintaining simulators
- Preserve investment in modelling a system, independently of the tools
- Improve collaboration between involved teams / communities by addressing distribution and interoperability aspects
- Facilitate reuse from phase to phase, project to project

To achieve these objectives, the E-TM-10-21 identifies the concept of the Virtual System Model (VSM), which provides the core of the simulation facilities that support the system engineering tasks. The E-TM-10-21 identifies a number of simulation facilities which are typically used to support the system engineering tasks. These facilities provide the basis upon which a consistent and harmonised approach to the development of simulation products across project phases can be considered. The different simulation facilities are required during different phases of the project, depending on the system engineering tasks being performed. This is summarised in Figure 1, which shows when during the project life-cycle each of the facilities identified by the E-TM-10-21 are required.

In-order to facilitate the reuse of models from the VSM across facilities, a Reference Architecture (RA) is required which captures the interfaces and models which are common across the different facilities, both in the same project and across projects. The RA serves as a template which can be applied and extended for simulator developments in future space programmes. The specification developed within the SSRA study activity defines the VSM RA which fulfils the objectives outlined in E-TM-10-21.

The RA specification covers the definition of the RA for the space segment and the ground-to-space models. Although the simulation infrastructure implementation is outside of the SSRA, it is important that interfaces and models defined by SSRA are portable between infrastructures such that model implementations can be reused. The RA specification therefore uses the SMP specification as the simulation technology to enable the reuse of model implementations across simulation facilities. The SMP specification is being standardised within ECSS as part of the E-40 software engineering standards (i.e. E-TM-40-07). The SSRA specification is based on SMP2 version 1.2 [3].

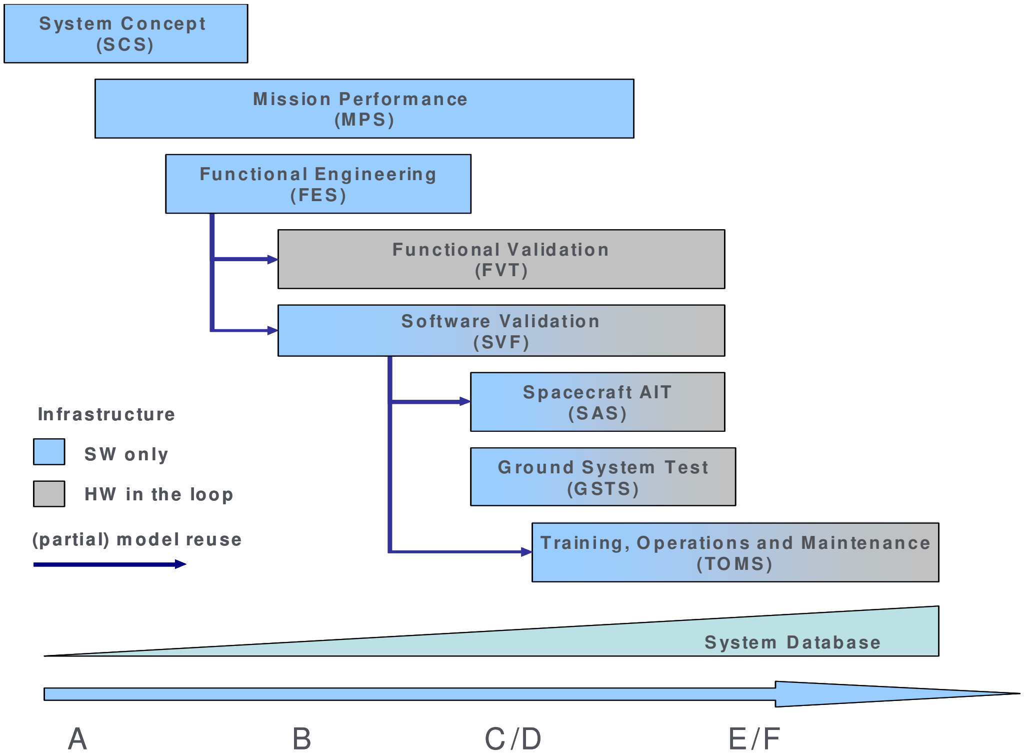

Figure 1 – Simulation Facilities required during the Project Life-cycle

APPROACH

The Reference Architecture captures the semantics of the models and interfaces of the Virtual System Model and how the models can be configured to fulfil the needs of the individual simulation facilities identified within E-TM-10-21.

The RA defines a conceptual meta-model for engineering of functional system simulators of space applications. The meta-model used to define the RA therefore includes as first order concepts such items as Equipment Models or System Level Interfaces (e.g. power lines, bus lines, etc) using a terminology which is natural to a Systems Engineer. These domain concepts are missing from a generic simulation domain language, such as SMP. For this reason, SSRA takes an approach where the reference architecture is formulated in a language (i.e. domain specific language) which is independent of the target simulation platform (i.e. SMP) and can be easily understood by both system and simulation engineers. Such an approach of separating the domain semantics from the target platform also allows the underlying simulation technology to evolve without having major impacts on the reference architecture. For example, future evolutions of SMP would have a minimum of impact on the RA.

This approach is already promoted by OMG's Model Driven Architecture (MDA) which identifies the concept of Platform Independent Model (PIM) and Platform Specific Model (PSM). The SSRA PIM level model is called the Space System Simulation Model (S^3M). The SSRA PSM is the SMP platform. The RA specification therefore defines both the S^3M and its mapping to the SMP platform.

SPACE SYSTEM SIMULATION MODEL

The SSRA defines a conceptual model of space system simulation, called the Space System Simulation Model (S^3M). An S^3M meta-model has been specified in UML and defines the semantics for data items for all kinds of models and networks that are used in SSRA. In order to enable modelling within the study, the S^3M conceptual model has been mapped to an SSRA UML profile. The SSRA does not, however, mandate the use of the SSRA UML profile and a project applying the RA is free to define an equivalent Domain Specific Language (DSL) and associated tooling derived from the SSRA conceptual model. The choice of using a UML profile or DSL for modelling of the S^3M is a project specific decision and will depend on the simulator development process and the experiences of the simulation development team. In the case of the study, the choice of UML profile was taken to reduce the effort required to develop tooling within the study as existing UML tools could be used. It should be noted, however, that the ultimate goal of promoting the reuse of simulation models and artefacts between projects and across project phases will in practice be largely dependent on the existence and reuse of a standard tool chain that implements the RA.

The following Figure 2 shows the core design elements that comprise the S^{3}M.

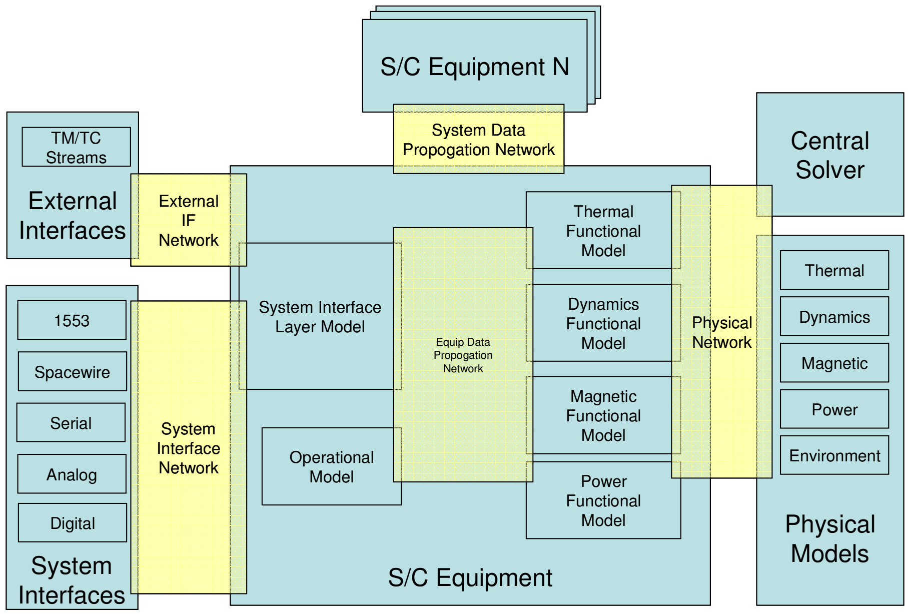

Figure 2 – S^{3}M High Level Architecture

The core design elements comprise the following simulation model categories:

- Spacecraft equipment model, which is a template for models that simulate real spacecraft equipments.
- Physical models which model the different physical aspects of the spacecraft (e.g. thermal network, spacecraft dynamics, etc).
- Central solver model which provides the functionality to centrally solve systems of coupled Ordinary Differential Equations (ODE) by applying an appropriate numerical solving method.
- System interface models which simulate the spacecraft electrical harnesses between equipments.
- External interfaces models which simulate the links with external systems (e.g. ground stations, data relay spacecraft, etc).

The simulation model instances are connected using a number of network types, which represent the model connectivity from different viewpoints. The following networks are identified:

- System interface network, which connects equipment model instances and reflects the spacecraft topology of the equipments and electrical harnesses.
- Physical networks, which connect equipment model instances to according physical models (e.g. Dynamics, Thermal, etc) for the propagation of physical data. It also includes the connection of equipments and physical models to the central solver where these models contribute to a numerical solving process of a set of ODEs.
- System data propagation network, which connects equipment model instances that are not connected via the system interface models.
- External interface network, which connects equipment model instances to external systems, such as ground stations for the propagation of data

A spacecraft equipment model, whether simulating an On-Board Computer (OBC), AOCS equipment (e.g. OCDU, etc) or Payload has a common decomposition and common interfaces. This has been driven by the following requirements:

- Support the evolution of the equipment model as it is used across the different test benches. This is achieved through the separation of equipment concerns, where each concern is encapsulated in an equipment sub-component.

- Allow the easy replacement of a simulated equipment model by the real equipment hardware within a test bench.

- Focus on a common core of model interfaces which are reused across all equipment types.

The RA specification only identifies the concept of a generic spacecraft equipment model. Specific equipment types can be defined within the framework of the SSRA, but to achieve the widest applicability of the SSRA across organisations, the definition of these types was outside of the SSRA scope.

Figure 3 illustrates a simulation test bench example UML model that has been modelled using the SSRA UML profile that implements the S^3M concepts in UML.

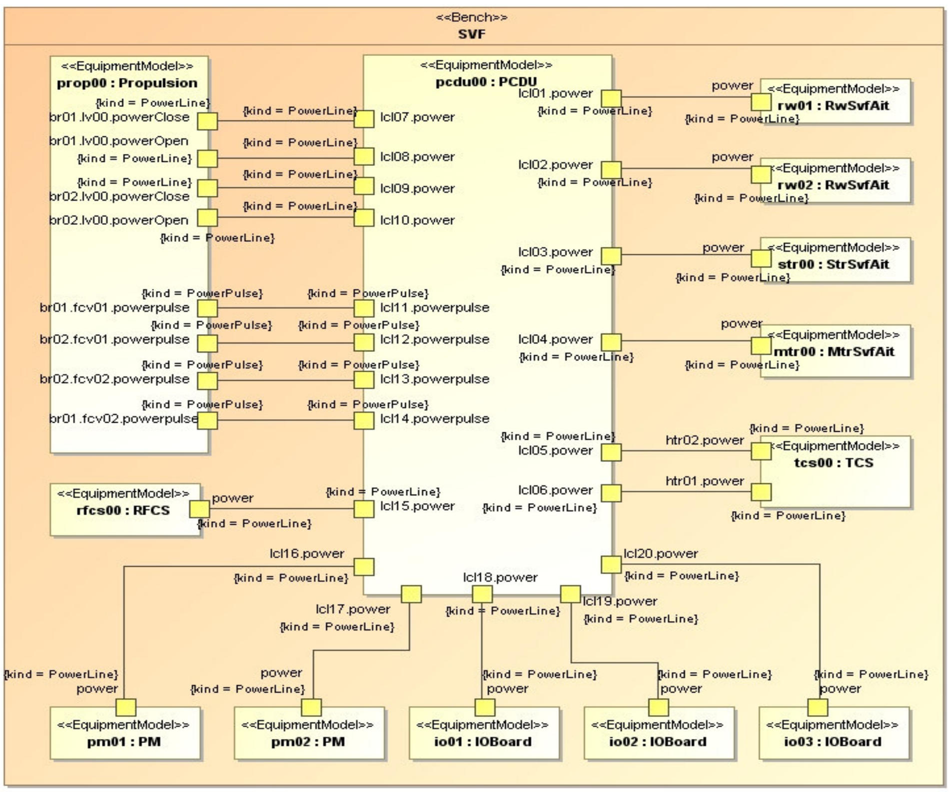

Figure 3 – S^3M Simulation Facility Example

S^3M-SMP MAPPING

The mapping of an S^3M model to the SMP simulation platform is defined by a set of patterns and mappings which specifies how each model element in the S^3M is mapped to SMP. Each S^3M pattern is represented via a UML collaboration diagram showing S^3M model instances that represent the roles taking part in the pattern. The S^3M models are specified with respect to the SSRA UML profile and represent the S^3M context for this pattern. Figure 4 illustrates an example mapping that has been defined for a synchronous binary interface which is part of the spacecraft system interfaces.

As part of the study, extensions were made to the current SMP data flow mechanism in-order to support the modelling of S^3M Standard Simulation Ports. These updates have been included in the implementation of the SMP environment used for testing of the RA interfaces. These extensions are not part of the current SMP specification, but have been documented in detail and could be considered by the ECSS E-40-07 working group for inclusion in the E-40-07 SMP specification.

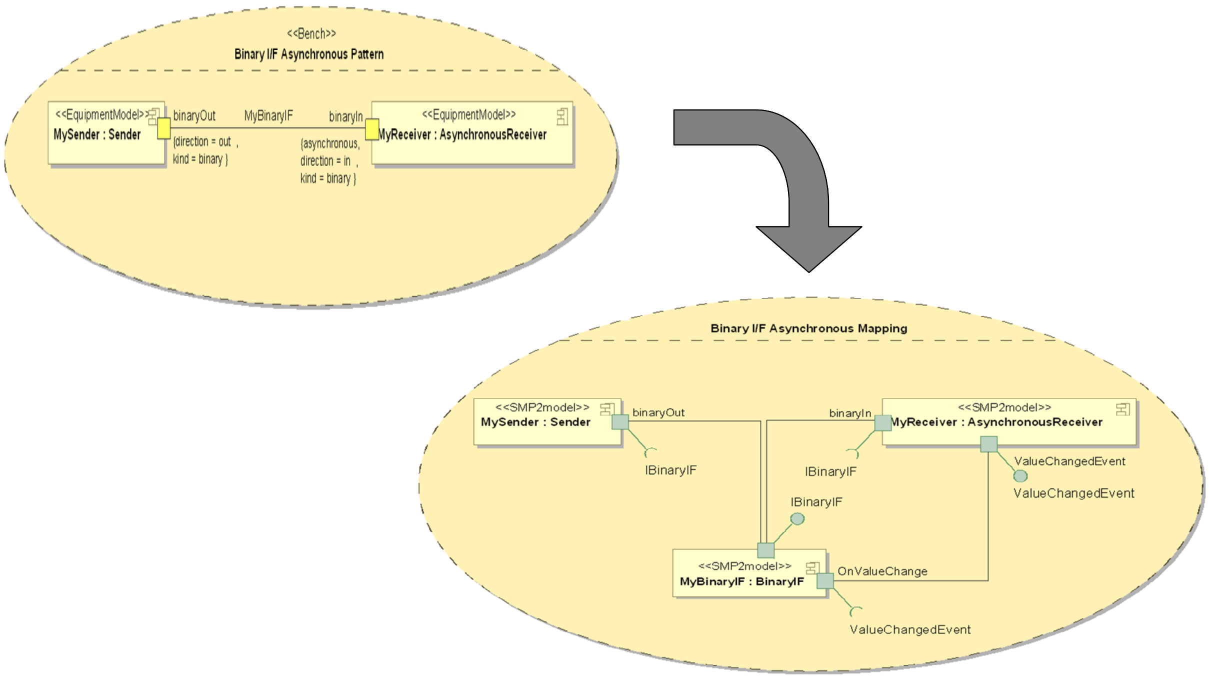

Figure 4 – SSRA S^{3}M-SMP Mapping

PROJECT APPLICATION

The successful application of the SSRA on a project requires a certain level of tool support. The SSRA avoids being overly prescriptive about how it should be applied in-order that it can be easily integrated into the chosen simulation development process. This freedom in the application of the SSRA however means that some tooling support can only be discussed in general terms, as it depends heavily on the chosen development process. Figure 5 illustrates the tooling that may be expected for a project using the SSRA.

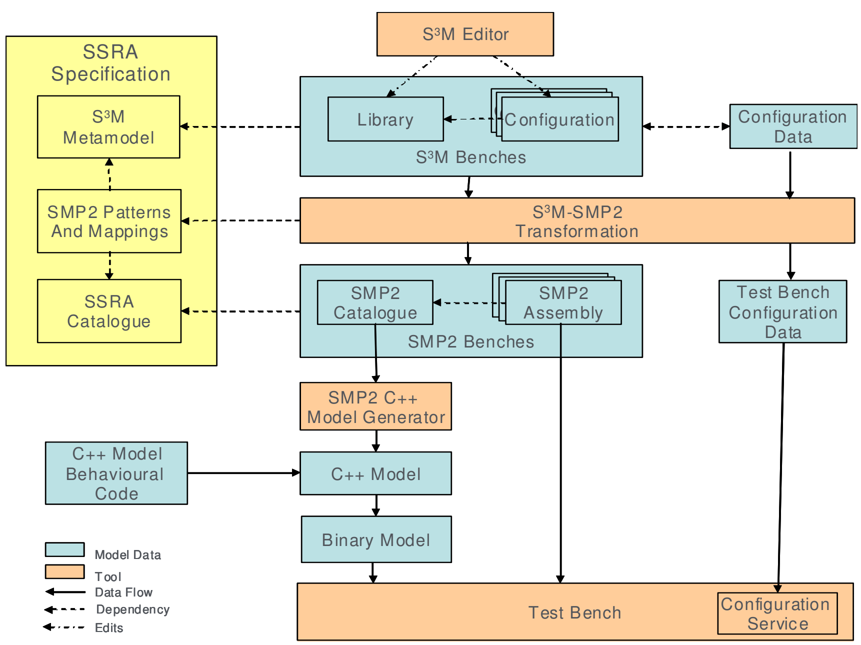

Figure 5 – SSRA Tools

The S^3M benches model consists of the library of equipment models used across the benches and a number of configurations for the different simulation facilities and variations of each single facility. The S^3M editor shall therefore provide a modelling environment which is natural for both a system and simulation engineer to model a spacecraft system simulation.

The S^3M benches library models are transformed into a set of SMP catalogues according to the rules of SSRA patterns. Each S^3M bench configuration is transformed as either an SMP assembly, a set of test bench configuration data or a combination of both which are used to configure the test bench simulation. SSRA defines a set of standard SMP catalogues, shown as "SSRA Catalogue" in the Figure 5, which contain the definition of standard SSRA SMP models and interfaces included in the SSRA patterns and mappings. The bench and standard SMP catalogues are transformed into SMP C++ models skeleton models using a standard SMP code generator. These can then be complied with C++ behavioural code to generate a set of SMP binary models which can be loaded by the test bench simulation environment. A test bench simulation environment supporting the SMP specification is therefore required. It is expected that standard implementations for the models defined by the SSRA catalogue will be provided as input into a project.

The content and format of the test bench configuration data is not defined by SSRA. The test bench configuration service is specific to the test bench configuration data and is therefore not standardised. In-order that a test facility model configuration can be ported from one simulation environment to another; it is recommended that the configuration service be implemented as an SMP simulation service. This allows the configuration service itself, which is required to configure the simulation models, to be ported to different simulation environments.

CONCLUSION

The Reference Architecture has been based on the objectives and principles of the E-TM-10-21 "System Modelling and Simulation" Technical Memorandum [2], which recognises that modeling and simulation are integral parts of the system engineering function.

SSRA defines a conceptual meta-model for engineering for functional system simulators of space applications. This model identifies and defines the concepts which are used along the engineering process in a formal model. This conceptual model has been mapped to a UML profile and defines how this can be transformed to an SMP based simulation platform, which supports the portability of simulation models across simulation environments.

The definition of a Reference Architecture which is widely accepted within the space simulation community is a long and difficult process and the results of this study are just a first step in achieving this ultimate goal. The adoption of Reference Architecture into a company's simulation development process also has to overcome the necessary evolution of existing tools and models so that they are aligned with the SSRA approach.

It is therefore important that confidence is gained in the application of the Reference Architecture and that suitable tooling, models and training is available to the simulation community. The next step in this process is therefore to gain experience of the application of SSRA in one or more pilot projects and to obtain feedback in its usage. This will drive the improvement of the Reference Architecture specification and better identify requirements on tooling and model implementations that are necessary for its adoption into an operational development process.

REFERENCES

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