ESEM: Automated Systems Analysis using Executable SysML Modeling Patterns

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Abstract. SysML is a modeling language used for systems analysis and design. While some domain-specific analyses (e.g., finite element analysis) can only be specified in SysML when combined with other vocabulary, many common analyses can be modeled purely in SysML using its parametric and behavioral semantics. In this paper, we focus on one kind of analysis, which is requirements verification, and propose a new Executable System Engineering Method (ESEM) that automates it using executable SysML modeling patterns that involve structural, behavioral and parametric diagrams. The resulting analysis model becomes executable using a general purpose SysML execution engine. We present our method and demonstrate it on a running example derived from an industrial case study where we have verified the power requirements of a telescope system. It involves dynamic power roll-ups in different operational scenarios and shows the automation capabilities of this method.

Introduction

Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification, validation and documentation activities, beginning in the conceptual design phase and continuing throughout later life cycle phases. A system model is an abstraction of selected aspects of the structure and behavior of a system that is expressed using a modeling language. SysML [6] is a standard, visual, and general-purpose system modeling language developed by the Object Management Group (OMG) [13] and often used in the context of MBSE. SysML is defined in terms of its syntax, semantics and notation. It is also organized into a collection of interrelated viewpoints that describe a system from different perspectives including: requirements, structure, behavior and parametrics. Many of SysML viewpoints are graphical (e.g., block definition diagram, parametric diagram, activity diagram, etc.), while some take other forms (e.g., requirements table). SysML enjoys strong tool support (e.g., MagicDraw [11] and Rhapsody [18]) and is actively used in

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various domains like aerospace, defense and automotive. For users in those domains, MBSE with SysML is becoming part of their day-to-day systems engineering practice.

Among the many activities of modeling with SysML, we focus in this paper on system analysis, which is about decomposing the system into its components for the purpose of studying how well those components work together and interact to meet some objectives or satisfy some constraints. Furthermore, we focus on one common kind of system analyses, which is requirement verification. In this analysis, the objective is to assess whether a system design meets the objectives and satisfies the constraints that are implied by the system requirements. Other kinds of analyses exist; such as trade study analysis, where the objective is to rank alternative designs in terms of their effectiveness vs. their cost, but they are out of scope of this paper.

Many approaches in the literature describe how to perform model-based system analysis by simply describing what each SysML viewpoint is for. However, there is no integrated story or method, which describes how to use SysML for system analysis. Also, many approaches augment the SysML syntax (with other UML profiles) and/or semantics and develop custom tools to analyze the models, where the SysML syntax and semantics are sufficient.

In this paper, we present an approach to model-based systems analysis with SysML that is both rigorous and automated. The approach supports the kind of system analysis we mentioned earlier, i.e., requirements verification. The approach’s rigor is established with a modeling method that is an extension of INCOSE’s [12] Object Oriented Systems Engineering Method (OOSEM) [1]. The extension, dubbed Executable System Engineering Method (ESEM), proposes a set of analysis design patterns that are specified with various SysML structural, behavioral and parametric diagrams. The purpose of the patterns spans the formalization of requirements, traceability between requirements and design artifacts, expression of complex parametric equations, and specification of operational scenarios for testing requirements including design configurations and scenario drivers. Furthermore, the approach is automated in the sense that the analysis models can be executed. The execution of the parametric diagrams is done with a parametric solver, where the execution of the behavioral diagrams is done with a simulation engine based on standard execution semantics.

Furthermore, we introduce our system analysis method and demonstrate it on a running example derived from an industrial case study where we have applied the method to analyze one of the subsystems of the Thirty Meter Telescope (TMT) [9] system that is currently being developed by the TMT Observatory Corporation. The main objective for the TMT related analysis is to provide state-dependent power roll-ups for different operational scenarios and demonstrate that requirements are satisfied by the design.

The SysML modeling tool we used is MagicDraw [11] and the parametric solver and simulation engine we used are part of its Cameo Simulation Toolkit (CST) [16].

The remainder of this paper is organized as follows: Section 2 provides some background on relevant technologies we refer to; an introduction to our running example is given in Section 3; Section 4 discusses our ESEM method and demonstrate it on the running example; a discussion of related work is given in Section 5; and finally, Section 6 provides conclusions and outlines future work.
Background

Executable Models
System modeling tools (e.g., MagicDraw, Papyrus [17], Rhapsody [18], Enterprise Architect [21]) are becoming more popular thanks to the standard modeling languages they use (e.g., SysML) and their graphical notations. However, those tools are still mostly used as drawing tools, where the graphical notation rather than the abstract syntax and semantics matters. For example, one may use a SysML tool to author a block definition diagram (BDD) to represent an organization chart, where blocks represent employees and generalization relationships represent their reporting chains. Obviously in this case, the semantics of generalizations is not consistent with that of a reporting relationship. This situation is partially due to one or more of the following reasons: users’ lack of understanding of the language semantics, the imprecise semantics of the language, and the permissiveness of tool itself (relaxing the language rules).

One way to alleviate this problem is to go beyond models as pretty pictures and make them executable. This approach lifts modeling to a whole new level, the model becomes “alive”, and helps create a different experience for the modeler using those tools. The execution semantics are typically defined on a subset of the modeling language. Limiting the modeling to that subset, the tool can limit the vast options available to modelers to model the same thing in the complete language. Moreover, for execution to work, semantics have to be precisely defined, which also helps validate models for correctness. The executability of models also enables debugging them to see if it the behavior captured by the modeler is what the modeler actually expects. When unexpected behavior occurs, the problem typically falls in one of the following categories: a) user error in the model, b) misunderstanding of the semantics by the user, c) ambiguity or lack of formal semantics by the language specification, d) bug in the implementation of the tool, or e) a potential behavior of the system that had not been anticipated.

One obvious challenge with this approach is agreeing on and defining the execution semantics precisely, and not leaving it up to proprietary tool implementations. This is usually the role of standards. ESEM applies standards from different standards bodies (e.g., OMG [11] and W3C [14]). However, it’s important for a tool to remain semantically consistent across the complete tool chain that may apply different standards.

UML [5] was introduced in 1997, while SysML, defined as a profile of UML, was introduced in 2007. However, the lack of precise execution semantics was limiting the ability to use UML/SysML to analyze, specify, verify, and validate system requirements and design, for example provide executable activity diagrams and associated timelines, even though this was considered an important requirement for behavior diagrams in the UML for Systems Engineering RFP. Executable UML (xUML) aims at augmenting UML with a behavioral specifications that are precise enough to be effectively executed. A subset of xUML, called Foundational UML (fUML) [7], has been standardized by OMG to fill the gap in the standards. Since SysML is a profile of UML, it inherits these execution semantics.

Model Execution Engine
Executable models are executed with the help of an execution or simulation engine. The purpose of a simulation is to gain system understanding, explore and validate desirable or undesirable behaviors of a system without manipulating the real system, which may not have yet been defined or available, or
because it cannot be exercised directly due to cost, time, resources or risk constraints. Simulation is typically performed on a model of the system, by visualizing and identifying system defects in early development stages when changes are cheaper.

The modeling diagrams in this paper were modeled with MagicDraw, a popular SysML modeling tool. The execution of the models were performed using the Cameo Simulation Toolkit (CST), which is a plugin to MagicDraw enabling model execution for early system behavior simulation. The toolkit comes with a built-in parametric solver and integrations with popular analysis tools (e.g., MATLAB/Simulink, Maple, and Mathematica).

CST is a simulation platform based on OMG fUML standard, which defines precise model execution semantics and a virtual machine for UML, enabling compliant models to be transformed into various executable forms for verification. It supports instantiation and integration of structural and behavioral semantics of systems, mainly based on UML activity diagrams (inherited by SysML).

CST uses fUML as a foundation to plug additional standard engines, such as W3C SCXML [8] (State Chart XML) engine for state machines, JSR223 for scripting-action languages, and a parametric solver based on PSCS (Precise Semantics of UML Composite Structures) [19]. SCXML provides a generic state machine–based execution environment based on Harel state charts [20] and is able to describe complex state-machines, including sub-states, concurrency, history, and time. In this paper we make particular use of the parametric solver, and the behavior (fUML and SCXML) execution engines of CST.

The parametric solver uses the fUML standard to create objects (instance specifications) of blocks (UML classes stereotyped with SysML Block) and set their attribute (property) values. Also, as SysML’s parametric diagram is based on UML’s composite structure diagram, ports (properties at the boundary of classes) and connectors (between properties) are part of the execution model. One notable kind of connector is a binding connector which makes the values of properties at both ends of the connector equal. If one value changes, the change propagates to the opposite end. These semantics allow the “given” values (of pre-bound attributes) to immediately propagate after fUML Object instantiation and update any “target” values (of unbound attributes) after constraints evaluate. Initially, at instantiation of objects and attributes, CST analyzes the causality of attributes, i.e., determines which attributes are given and which are target in the parametric equation. Initial solving provides the given values and derives the target values.

Whenever the value of an attribute that is bound to constraint parameter changes, the constraint is re-evaluated and updates all related variables, creating a cascade effect, which may trigger more and more related constraints evaluations. If that happens during behaviors execution (state machine or activity), CST re-evaluates the parametrics and considers an entire cascade as part of the run-to-completion step (an atomic action which happens at the same instant of time). We rely on this feature of CST to do dynamic (behavior based) roll-ups using parametrics, as will be seen next.

**Object Oriented System Engineering Method (OOSEM)**

The Object Oriented Systems Engineering Method [1] integrates top-down system and functional decomposition with a model-based approach that uses SysML to support the specification, analysis, design, and verification of systems. OOSEM is intended to ease integration with object-oriented software development, hardware development, and test. It encourages use of object oriented models to capture system and component behavioral, performance, and physical
characteristics that provide the basis for integrating other specialty engineering models. The adoption of OOSEM concepts provides a more systematic approach to properly use SysML, capture the required information, and organize the model. The application of appropriate MBSE methods for the problem domain (like OOSEM) is valuable in defining common concepts and procedures, and keeping the resulting artifacts consistent in a shared project model. A key benefit results from the proper management and evolution of multiple generations of functional and physical implementations. OOSEM defines the “black-box specification” as the system’s externally observable behavior and physical characteristics. The system design defines how the system achieves the externally observable behavior. OOSEM distinguishes logical (aka conceptual) and physical (aka realization) system design. The logical design decomposes the system into components that are abstractions of the physical components without imposing implementation constraints.

Running Example

In order to help the reader follow our proposed method for model-based system analysis, we introduce a running example that we will be referring to in the next section. The example is extracted from a large industrial case study that involves the modeling and analysis of the Alignment and Phasing System (APS) within the Thirty Meter Telescope (TMT) [9], under development by the TMT International Observatory (TIO). The full case study is not presented here for brevity.

The core of the system is a wide-field, alt-az Ritchey-Chretien telescope (Figure 2) with a 492 segment, 30 meter diameter primary mirror, a fully active secondary mirror and an articulated tertiary mirror. The Alignment and Phasing System (Figure 3) is a Shack-Hartmann (SH) wavefront sensor responsible for the overall pre-adaptive Optics wavefront quality of the TMT.

The Jet Propulsion Lab (JPL), where the first and third authors work, participates in several subsystems of the TMT and delivers the complete APS. The TIO is the customer, which provides the APS requirements to JPL, and JPL delivers an operational system to the TIO. The APS team pursues an MBSE approach to analyze the requirements, come up with an architecture design and eventually an implementation. The APS team uses several modeling patterns to capture information such as the requirements, the operational scenarios (use cases), involved subsystems and their interaction points,
the information exchanged, the estimated or required time durations, and the mass and power consumption.

The focus for this example is on defining executable SysML models to simulate scenarios based on fUML and SCXML semantics and to produce static mass and dynamic (state dependent) power roll-ups, and duration analysis. The goal is to use standard languages and tools as much as possible and to minimize custom software development.

Based on the customer supplied requirements and derived use cases, the goals are to a) identify participating subsystems, b) identify interfaces and interactions among subsystems, and c) analyze operation scenarios to ensure that power requirements are always met.

Approach: Executable System Engineering Method (ESEM)

In this section, we present our approach to system analysis, called the Executable System Engineering Method (ESEM), which is guided by and extends OOSEM. We will use the running example, introduced in the previous section, to explain and demonstrate the steps of the method. The overall objective is to show how requirements are traced to design artifacts, how analysis is defined with a set of SysML patterns, and how this analysis explains that the design satisfies the requirements. We will refer to relevant aspects of OOSEM in the description.

Step 1: Formalize Requirements

The first step is to formalize the customer requirements that are often provided in textual form. For example, one requirement in our running example is that the power consumption of the APS within the dome of the telescope has to be under 8.5 kW, as shown in Figure 4. The requirements are captured in a pattern at two levels: customer and supplier. This is because suppliers may impose more rigid requirements on the design. The separation allows for testing both sets of requirements.

On the customer level, the requirement is first captured using a Requirement (named Peak Dome Load). Then, a design’s black-box Block (named APS Blackbox Customer) is specified. Recall that OOSEM requires systems to be designed first as a black box exposing only an interface and hiding all realization details. The customer can then choose to refine the requirement, using a <<refine>> relationship, by constructs such as a Constraint Block (which they do not do in this example) or attribute values on the black-box block (e.g., the pwrPeakLimit attribute of APS Blackbox Customer has a value of 8.5 kW).

On the supplier level, the Requirement is further refined by a Constraint Block (named Peak Power Load Constraint) if one is not provided by the customer. The constraint block provides a boolean expression that is a formalization (in some formal language) of the textual requirement (p<requiredPeakLimitLoad). Notice that the constraint may expose parameters (e.g., requiredPeakLimitLoad) that could be bound to information (e.g., pwrPeakLimit) from the black box block. We will see this binding in an upcoming step. The supplier may also specify its own black-box Block (named APS Blackbox Supplier) inheriting from the customer’s black-box and redefine some of its attributes (e.g., pwrPeakLimit is redefined to have a value of 8.1 kW, i.e., the supplier intends to support a lower peak power than requested by the customer).
Step 2: Specify Design

The next step is to design the system decomposition according to OOSEM by inheriting the black-box block by two white-box blocks: a conceptual system and a physical system (the latter realizes the former).
However, in our example, we do not show the conceptual system design for brevity and focus only on the physical system decomposition. In this case, the APS Physical Node (Figure 5) consists of several opto-mechanical components, which have to be controlled with motors using several local and remote computers. The node is installed in two locations, the Dome and the Summit Facilities Building. The relevant parts are specified in the decomposition tree representing the installation (Figure 6).

![Figure 6 APS product breakdown](image)

**Step 3: Characterize Components**

Once the design is specified, the next step is to augment it with analysis patterns. Recall that the requirement in the running example specifies the power consumption peak for the Dome Installation. The analysis needs to explain (by simulation) that the power consumption according to the design always satisfies this requirement for every defined operational scenarios (more on this later on). In other words, the constraint block we defined in the first step needs to be satisfied in every scenario.

When inspecting the constraint, we find that the interesting value is the power of the APS node. This value represents the aggregate (roll-up) of the power values of all the subcomponents of the node. The question that arises is how to model this roll-up (a common requirement in system analysis). For this, we propose a reusable roll-up modeling pattern that is able to capture this roll-up efficiently. The
pattern can recursively propagate the particular value up a hierarchy of components characterized by this value. When the values being propagated are static (e.g., mass), we call this a static roll-up. However, when the values are dynamically changing based on the behavior of the system, we call this a dynamic roll-up. In our example, since power (unlike mass) varies depending on the state of every component, we are dealing with a dynamic roll-up requirement. However, for simplicity, we first describe how the pattern supports static roll-up, then describe how it can be modified to support dynamic roll-up.

The pattern (e.g., PowerRollupPattern) is modeled (Figure 7) with a Block that is extended by all the components participating in the roll-up. The block adds several properties to each component: a) a value property (e.g., lPower) representing the local value to be propagated, b) a part property (e.g., subPower) typed by the pattern and representing all the subcomponents of this component, and c) a value property (e.g., totalPower) representing the total value for the subcomponents. Notice that the subcomponent property is defined as a “derived union”, meaning that its value is computed as the union of the values of all properties that subset it (i.e., defined as its subset). In this case, all components participating in the roll-up (e.g., Dome Installation Physical, from Figure 6) need to have their subcomponent properties (e.g., bench_1 and instrument rack_1) subset this property. While configuring this pattern may seem daunting to do, the analysis tool can automate this process.

A static roll-up pattern needs to define a parametric diagram, that describes how the total value property equals the sum of all the subcomponent value properties. Since all component blocks inherit from the Pattern block, they also inherit its parametric diagram. Solving this system of parametrics with a solver makes the total value calculation roll up the component hierarchy, culminating in the calculation of the total value at the top level component (APS Physical Node).

A dynamic roll-up pattern adds a behavior diagram (e.g., a state machine diagram) to specify how the local value changes based on behavior. This typically involves the behavior diagram changing the local value at certain points. For example, in our running example, the local power value of a component is a function of its operational mode. Therefore, we added a state machine diagram in the pattern (called PRBehavior in Figure 7) with states (On, Off, Standby) that represent the modes. Each state changes the local value (lPower) in its entry action. This allows the roll-up algorithm to aggregate different values for each component depending on its state. If an event caused a component to transition to a different state that changes its local value, this would trigger the roll-up of the total value again to the top.

The pattern also allows for some variability by each component in the design. By representing some values as as value properties on the Pattern block, each component inheriting the pattern can change those values by redefining the corresponding properties. In our running example, the pattern defines two constant power values: operatingPower and standbyPower, representing the power values in the On and Standby states, respectively (the power has a value of zero in the Off state). The entry actions of the corresponding states simply assign those values to the local value.
This works fine for simple variability. However, some components may have more complex behavior (than the one inherited from the pattern) affecting their local values. In this case, those components need to redefine the inherited behavior diagram. For example, component SH CCD redefines its state machine (Figure 8) to have states with entry actions that call activity diagrams (Figure 8). Those activity diagrams change the local values consistently with the inherited pattern. However, they also change the value of a constraint property (pwrC typed by Power Constrained block), defined on the pattern, by another value (an instance of subtype block SH CCD - ON or SH CCD - STANDBY), resulting in dynamic constraint checking. Other changes in the state machine could be other states and/or transitions.

Alternatively, a specialized roll-up could be created (where the specific behavior is owned) which is inherited by the component instead of modifying the component itself and make it own the specific behavior.
Step 4: Specify Analysis Context

The next step after adding the analysis patterns is to specify the analysis context. In this case, we use the analysis pattern from [1] to model that context (Figure 10). Specifically, we define a block representing the analysis context (Dome Peak Power Limit Margin Analysis) that composes both the black-box block (ABS Blackbox Supplier) and the design block that should satisfy the requirement (Dome Installation Physical). Note, that the analysis is done using the supplier black box specification. The compliance with the original customer requirement is analyzed in a separate step. The analysis uses the constraint block which refines the textual requirement (Figure 4) and adds other constraints to compute also the margin (with respect to the internally specified peak power limit) and store the maximum power during a simulation. The corresponding parametric model is shown in Figure 11.
The analysis context is actually defined with an abstract block and is used only to specify a parametric model. However, concrete analysis blocks corresponding to operational scenarios (use cases) need to be defined as well. Each concrete analysis block specializes the abstract analysis block, inheriting its parametric model, and defining a behavioral diagram (we use sequence diagrams) that acts as a scenario driver. Figure 12 shows a simplified scenario for a subset of components in the running example.
Step 5: Specify Operational Scenarios

Once the analysis details are added, the next step would be to define a set of operational scenarios corresponding to the use cases specified by the customer (we skipped this step since it does not differ from the usual definition of use cases in OOSEM). Each scenario becomes a use case that can be analyzed using a simulation engine. In the running example, those operational scenarios represent different power consumptions configurations.

Figure 12 Simplified Analysis Scenario

The sequence diagram changes the states of the different components, by sending them signals, causing the rolling-up to occur automatically when the state changes. It can also specifies duration constraints to time the injection of signals and therefore specify how long a component shall remain in a certain state. Moreover, using state constraints (on components) also allows verification during execution if a component is actually in some state (e.g. “On”) in its state machine, or if a value property satisfies some constraint (e.g. “totalPower<190”). In addition, a special Analysis Driver component injects the signals to bring the system component into the right state expected for the scenario.
Step 6: Specify Configurations

We propose to capture those power consumptions configuration using different instance specifications trees, shown in a table in Figure 9. The rows correspond to the elements of the decomposition tree and the columns correspond to the power, which is consumed in a particular state (Operating, Standby). Such table facilitates the configuration data entry.

This instance specification approach suffers from two problems: a) keeping the block decomposition tree and the instance specification tree in sync may be tedious (however, tool support may mitigate that), and b) instance specifications cannot be displayed on internal block diagrams (a SysML limitation), as often desired. Both problems, however, can be avoided by creating a full specialization hierarchy of the design blocks, essentially treating every block in this tree as a singleton (instance specification).

![Data configuration table](image)

*Figure 9 Data configuration table*
Also, as shown in Figure 13, each concrete analysis instance specification needs to reference (with an <<analyzes>> relationship) a specific instance specification from the analysis configuration (step 4) as its initial condition. In addition, it needs to reference (with an <<explains>> relationship) another instance specification from the analysis configuration to hold the final result of the execution. We define the new stereotypes, <<analyzes>> and <<explains>>, on a Dependency relationship to capture this pattern.

**Step 7: Run Analysis**

In this step, we run the configured analysis using a simulation engine, such as CST. This provides several outputs such as: a) timeline of the states of the individual components (Figure 14), which shows state changes of individual components during the simulation, b) rolled up masses and power and margin (Figure 15), and c) value profiles (Figure 16), which show the total value over time of the rolled up value (total power of dome installation part of the APS). These products represent different views that can be used by the engineer to analyse the results.

**Figure 13 Instance specifications for specific analysis configuration**

**Figure 15 Rolled up power and margin**
Step 8: Evaluate Requirement Satisfaction

As soon as the results of the different scenarios are available, the satisfaction of the original customer requirement has to be demonstrated. This is done with a separate analysis context (Satisfy Peak Load Constraint Analysis), this time using the customer’s (rather than the supplier’s) black box, as shown in Figure 17.
The analysis has to show that the design (of the dome installation) satisfies the requirement for the results of all specified scenarios. The instance specification of this analysis (Satisfy Peak Load Constraint Analysis) references all available results (e.g. aps.dome installation_14) and verifies that all supplier results also satisfy the customer requirement (max(supplier) <= customer). The result of this analysis explains the satisfy relationship between the design and the requirement. The parametric diagram of such analysis in the running example is shown in Figure 18.
The results of the analysis show that for two runs the load constraint of the supplier is satisfied (i.e. pass) and the customer requirement is satisfied as well because the results of all analyses are below the required peak power limit.

Discussion

Different rollups can be applied to different characteristics of a system like mass and power. They basically follow all the same pattern. Originally the mass and power roll-up for the APS was maintained and calculated in an Excel spreadsheet for different (simplified) scenarios and updated whenever a requirement or the system design changed. However it, was completely disconnected from the SysML system model which captures the different operational scenarios, the system design, and the requirements. Integrating the roll-ups simplified the maintenance and consistency of the data and the documents, which are subsequently generated from the model.

Related work

The area of model-based system analysis has previously been investigated in the literature.

One notable work in this area is by Zwemer [3], where he discusses how to model static rollups in SysML using four different strategies with increasing complexity and versatility: a) quantity-specific constraints (each part has its own rollup constraint), b) complex aggregates (same as in a but the rollup constraint is defined on a supertype of the parts and used in every part), c) complex aggregates and recursion (same as in b but the constraint is rather used in the supertype and recurses down the hierarchy of parts), and d) multiple-inheritance (same as in c but supports different rollups on different kinds of parts by having different supertypes for them). Our approach to static rollup described in this paper is similar to strategy d, with one difference. In his approach, Zwemer describes how the subpart properties on the subtypes are only related to their counterpart in the supertype at the instance model, by assigning the slot values of the subtype properties also to the supertype property. However, in our approach, the supertype property is specified as a derived union of all its subsetting subtype properties. This avoids the duplicate slot assignment and makes the creation of the instance model much easier. Moreover, unlike our approach, Zwemer’s does not describe how to perform a dynamic rollup.

Another related work is by Paredes [15], where he discusses how to use SysML parametrics for requirement verification analysis. The work argues how analysis parametrics are better captured in their own context outside the system design itself. This allows a design to have multiple kinds of parametric analysis, and makes the analysis models themselves reusable across designs. The focuses on static parametric analysis (and rollup) but does not describe how to perform a dynamic one where the parametrics are behavior dependent.

Morkevicius [2] introduces an approach to automated requirements verification by analysis with SysML, which consists of formalization of text-based requirements, definition of analysis context and binding system properties to constrain parameters. Our approach extends it by adding customer/supplier relationship and formalizing the the satisfy relationship by analysis between design and requirement for a given number of scenarios.

System level simulation environments have been around since the late 1980s. Two prominent examples were Geode and ForeSight. Both provided many features also available in today’s tools but they were
not adhering to standard modeling languages nor well-defined execution semantics. Also, their software architecture was not open enough to be extended and customized.

Conclusions and future work

Requirement verification is an important kind of analysis that is often performed in the context of MBSE. In this paper, we described a new Executable System Engineering Method (ESEM) that can be used to automate requirements verification with a set of executable SysML modeling patterns. These patterns integrate parametrics with the execution semantics of behavioral diagrams. This enables one to specify scenarios for a requirement in the form of activities, sequence diagrams, and/or state machines, and execute analysis as part of those scenarios.

The proposed method integrates the standard pattern of an analysis context with the behavior execution pattern by specifying the scenario as the behavior of the analysis context. The instance of the analysis context contains the current state of the configuration, and the parametrics compute the values of selected properties as the scenario runs. Input data for the analysis context comes from a configuration involving instance specifications and their property values, and the output is another configuration that displays the computed values from the analysis.

We have also demonstrated our method on a running example, where we analyzed the power requirements of the Alignment and Phasing System (APS) of the Thirty Meter Telescope (TMT) system. We used the MagicDraw tool to create the analysis model, and the Cameo Simulation Toolkit to execute it. We showed that our method is able to tackle the various complex analysis needs of the APS.

In the future, we plan to improve some of the patterns in our current method. For example, we need to find a more formal way to tie value properties for each power mode (e.g. standby, on) to the state, instead of by naming convention in the state’s entry action. We also have to better capture interactions among system components at different levels of composition (e.g. motor controller and motor). This also involves the semantic distinction between (discrete and continuous) state variables and parameters of the system and those introduced for analysis only (e.g. constraint maximums or minimums). It is also desirable to improve the roll-up pattern that deals with state specific constraints, by avoiding hard coding constraint values in state invariant or other constraints. Furthermore, running simulations generates a large amount of results which are currently stored in instance specifications, which make the design model grow unnecessarily. Those results (sequence diagram recording, instance snapshots, simulation logs) should be stored outside of the system model in dedicated big data repository. Also, the usage of the Action language for Foundational UML (ALF) [4] shall be investigated as alternative to specify behaviors. The synchronization of instance specification trees to run the analysis with the design model is a challenge is the decomposition structure changes. Alternative approaches will be investigated.

We plan to tackle other kinds of model-based analysis activities, such as trade studies. This may require us to extend our method to handle those kinds of analyses.

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Biography

Robert Karban is a senior systems architect at the Jet Propulsion lab in the Systems Engineering and Formulation Division. Robert works in the domain of Model Based Systems Engineering (MBSE) as the task lead on providing a Model Based Engineering Environment (MBEE) for projects and applies modeling in the Thirty Meter Telescope project. Prior to that, he developed control and instrumentation systems for large telescopes at the European Southern Observatory applying model driven technology, and for particle accelerators at the European Organization for Nuclear Research (CERN). Robert is a Challenge team lead of INCOSE’s MBSE Initiative, an OMG certified SysML professional and an active member in OMG's revision task force for SysML. He started his career at Siemens Medical Devices developing System Software and received his M.S. in Computer Science from the Technical University of Vienna/Austria.

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