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Using Model-Based Systems Engineering To Provide Artifacts for NASA Project Life-Cycle and Technical Reviews

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Abstract

The ability of systems engineers to use model-based systems engineering (MBSE) to generate self-consistent, up-to-date systems engineering products for project life-cycle and technical reviews is an important aspect for the continued and accelerated acceptance of MBSE. Currently, many review products are generated using labor-intensive, error-prone approaches based on documents, spreadsheets, and chart sets; a promised benefit of MBSE is that users will experience reductions in inconsistencies and errors. This work examines features of SysML that can be used to generate systems engineering products. Model elements, relationships, tables, and diagrams are identified for a large number of the typical systems engineering artifacts. A SysML system model can contain and generate most systems engineering products to a significant extent and this paper provides a guide on how to use MBSE to generate products for project life-cycle and technical reviews. The use of MBSE can reduce the schedule impact usually experienced for review preparation, as in many cases the review products can be auto-generated directly from the system model. These approaches are useful to systems engineers, project managers, review board members, and other key project stakeholders.

1.0 Introduction

The institutional requirements for how NASA performs systems engineering are in the NASA Procedural Requirements (NPR) 7123.1, "NASA Systems Engineering Processes and Requirements," (Ref. 1). The NPR defines a set of required systems engineering products for program and project life-cycle and technical reviews. It also describes the 17 common technical processes for space flight, research and technology, and institutional programs and projects. These processes, which are used throughout all life-cycle phases, form what is called the NASA "systems engineering engine". The NPR describes typical best practices, with inputs, activities, and outputs, for each process. The NPR also contains the roles and responsibilities for implementing the requirements and processes, guidance on tailoring and customization of requirements and processes, activities and requirements for contractor oversight, and life-cycle and technical review requirements. Supplementary information on all these topics is available in the "Expanded Guidance for NASA Systems Engineering, Volume 1and Volume 2," (Refs. 2 and 3). To date, NASA systems engineers have used primarily a document-centric approach to producing systems engineering artifacts and deliverables, although the NPR does not explicitly require this.

Currently, many systems engineers produce artifacts in the form of electronic records using office productivity software. The records are comprised of electronic documents, workbooks, diagrams, and chart sets. Since the contents of the electronic records are not related together in an organized fashion, several immediate and long-term problems can arise. Because each record is developed independently, the collection of records often contains inconsistencies in the detailed contents, despite intentional effort to find and correct errors. Identifying inconsistencies, determining all the affected electronic records, processing change requests to approve corrections, and making the updates are labor-intensive. System-level queries and analyses are also labor-intensive as manual effort is often needed to synthesize the information residing in a multitude of unrelated sources and dissimilar formats.

The systems engineering community is moving toward a model-based approach that offers many benefits, including eliminating inconsistencies. Models can be descriptive of the system or used to analyze its performance. This paper primarily discusses the descriptive modeling aspects. There are multiple tools, languages, and methods that can be employed to create models; this paper focuses on the application of SysML.

Over the past decade, NASA has investigated model-based systems engineering (MBSE) and the Systems Modeling Language (SysML) (Ref. 4) through exploratory usage, training, and working groups. Hundreds of systems engineers have been trained in the language and tools, and some projects are using MBSE; however there is not yet widespread use of MBSE. After receiving training, engineers are often unsure of how to apply it to their projects, and how MBSE fits within the NASA systems engineering processes. The NPR neither mentions nor prohibits the use of MBSE. The recently issued expanded guidance supplement to the NASA Systems Engineering Handbook, Volume 2 (Ref. 3) contains a section of introductory material about MBSE and efforts are underway as part of a MBSE Pathfinder to develop and evaluate how to use MBSE within the NASA systems engineering processes (Ref. 5).

A previous MBSE effort related to the NPR was the modeling performed by the Agency-level Systems Engineering Working Group, the NASA Langley Research Center, and the NASA Integrated Model-Centric Architecture teams. This effort modeled the 17 systems engineering processes themselves, with the internal inputs and outputs, to find inconsistencies within the NPR and have them corrected for a future revision.

This paper provides a guide and some examples of how to use MBSE, specifically with SysML, to produce the primary systems engineering products required for project life-cycle and technical reviews. These products are of value to key stakeholders on the project such as the Lead Systems Engineer, Project Chief Engineer, Project Manager, Customer, Review Board, and others. The user may need to discuss the format of the artifacts with the key stakeholders, as the format may be different from what has been previously provided. The guidance in this paper is useful to system modelers and to people who are unfamiliar with MBSE, in illustrating how MBSE can be used to implement systems engineering processes.

2.0 Approach

The NASA systems engineering engine in the NPR identifies the processes that systems engineers use for their work. Each process has outputs, some of which are products that are required products for reviews. The NPR contains a table that lists the required products and their maturity at each of the major reviews. A few additional products not listed as required, such as interface definitions and implementation plans, are considered primary products. Since a multitude of systems engineering products can be generated through the course of a project above and beyond those needed for major reviews, the scope of the effort presented in this paper is that of the required and primary systems engineering products for NASA project life-cycle and technical reviews. The required systems engineering products are listed below, by review:

1. *Mission Concept Review*: baselined stakeholder identification and expectations definitions; baselined concept definition; approved measures of effectiveness definition.
2. *System Requirements Review*: baselined systems engineering management plan for projects, single-project programs, and one-step Announcement of Opportunity programs; baselined requirements.
3. *Mission Definition Review/System Definition Review*: approved technical performance measure definitions; baselined architecture definition; baselined allocation of requirements to next lower level; initial trend of required leading indicators; baseline systems engineering management plan for uncoupled, loosely coupled, tightly coupled, and two-step Announcement of Opportunity programs.
4. *Preliminary Design Review*: preliminary design solution definition.
5. *Critical Design Review*: baseline detailed design.
6. *System Integration Review*: updated integration plan; preliminary verification and validation results.

7. *Operational Readiness Review*: updated operational plans; updated operational procedures; preliminary decommissioning plans.
8. *Flight Readiness Review*: baseline disposal plans; baseline verification and validation results; final certification for flight/use.
9. *Decommissioning Review*: baseline decommissioning plans.
10. *Disposal Readiness Review*: updated disposal plans.

Sections 3.0 to 16.0 contain information for each of the major systems engineering products listed above. Each of these sections contains subsections that identify artifacts necessary to produce the products and is displayed in the following format: artifacts, model elements and relationships, model validation, and additional details. The artifacts subsection lists products commonly generated for reviews and the SysML equivalent artifacts. The model elements and relationships subsection explains which SysML table, matrix, model element, diagram, relationships, or other elements would generate or contribute to this artifact. The model validation subsection has common questions that can be considered to evaluate completeness and accuracy of model artifacts relative to the model's intent using basic SysML modeling queries. There are many validation techniques not described here, such as scripting and visualizations, that can be used; the ones listed are suggestions.

Since many of the system model elements are used across the system life-cycle and in multiple artifacts, duplicative information is referenced and not repeated. Some of the model elements may be put into a system model earlier than necessary for a particular review and serve as placeholders for later use. The maturity of the model elements, diagrams, and information in a system model depends on where the project is in its lifecycle. In the beginning, the model incorporates high level information as the project is still being developed. During this phase, development of stakeholder identification and expectations definition, concept definition, measures of effectiveness, cost and schedule, system engineering management plan, and requirements are modeled. Many model elements will contain only key or placeholder information. As the project matures, more information is added to the model such as technical performance measures, architecture, lower level requirements, interfaces, and activity flows, to name a few. These all come together to support testing, verification and validation, flight certification, mission scenarios, and mission operations.

3.0 Stakeholder Identification and Expectations Definition

The stakeholders are identified within the model, linked to their needs, goals, and objectives (NGOs); wants; and constraints. This is useful during change impact assessments, as the systems engineer can determine which stakeholders will be affected if a NGO changes or cannot be satisfied.

3.1 Artifacts

The artifacts used to identify the stakeholders and their expectations, in general, are listed in Table 1.

TABLE 1.—STAKEHOLDER AND EXPECTATIONS ARTIFACTS

Stakeholder and Expectations artifacts	Model artifact
List that identifies customers and stakeholders	Table.
List of expectations (needs, wants, desires, capabilities, and constraints)	Table or matrix.
Traceability of stakeholder expectations to stakeholders	Table or matrix.
List of expectation allocated to stakeholders	Table or matrix.
Priority of the expectation	Table.
Other aspects of the expectations, such as how they are being satisfied	Table or matrix.

3.2 Model Elements and Relationships

This section discusses two possible ways to capture stakeholder information. The first is to use the SysML elements of an actor and a requirement block. The second is to use the SysML elements of a stakeholder actor and a concern. There are advantages and disadvantages to both approaches that are not discussed here as it is beyond the scope of this paper. The model elements and relationships for both approaches are listed in Table 2.

Figure 1 shows an example using requirement blocks to capture the NGO and then traced to the corresponding stakeholder that established the NGO. It also shows how the satisfy relationship indicates that a requirement is developed to satisfy a NGO.

Figure 2 shows an example of how the comments or concerns are displayed in a table. It also shows how the stakeholder NGOs are being satisfied as noted in the annotated element column and which stakeholder is interested. The Annotated Element column shows the model elements that are anchored to the concern and in turn satisfy it.

TABLE 2.—STAKEHOLDER AND EXPECTATIONS MODEL ELEMENTS AND RELATIONSHIPS

Approaches	Stakeholder and Expectations elements	Model element and Relationship
Using actor and requirement block model elements	Customer and Stakeholder	Actor or Actor with the “stakeholder” stereotype.
	Expectations	Requirement block.
	Traceability between stakeholders and expectations	Trace relationship from the requirement block to the actor.
	Satisfaction of stakeholder expectations	Satisfy relationship from another model element such as a diagram, activity, or block to the requirement block.
	Expectation Priority	Attribute of a requirement block.
Using stakeholder actor and concern model elements	Customer and Stakeholder	Actor with the “stakeholder” stereotype.
	Expectations	Comment (note that a comment becomes a concern when the relationship between the comment and stakeholder is applied).
	Traceability between stakeholders and expectations	Anchor relationship from the concern to the stakeholder.
	Satisfaction of stakeholder concerns	Concern is anchored to a model element. This can be shown in a table as an “Annotated Element”.
	Expectation Priority	Attribute of a comment block.

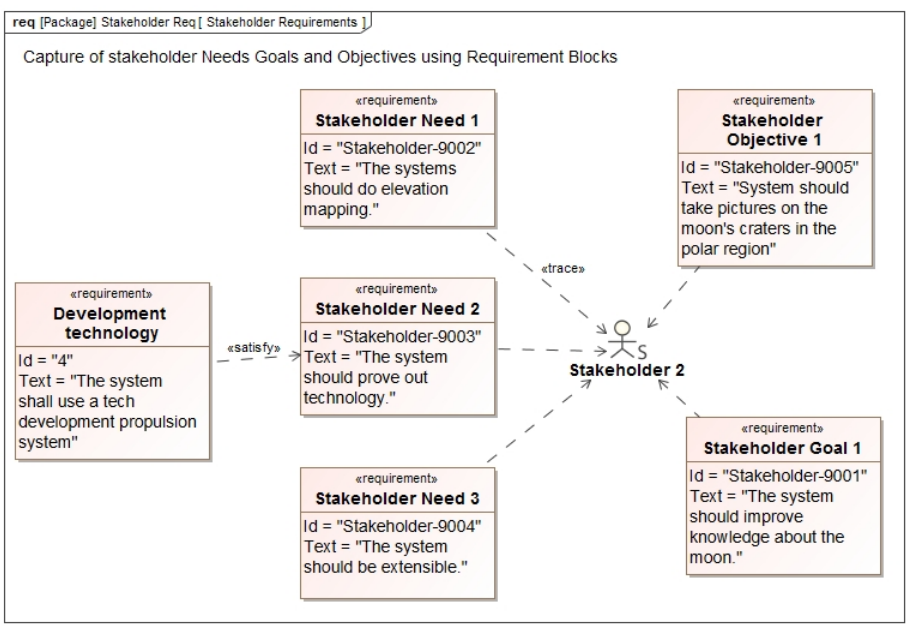


Figure 1.—Stakeholder requirements captured using requirement blocks.

Criteria

Element Type: Comment ... Scope (optional): Concerns ... Filter:

#	Body	Annotated Element	Stakeholder
1	Need 1 - The United States needs higher fidelity knowledge about the moon.		Stakeholder 1 Stakeholder 2
2	Need 2 - The United States needs to demonstrate new technologies for lunar exploration.	4 Development technology 4.1 propulsion system	Stakeholder 2
3	Need 3 - The system needs to be extensible to future space missions.		Stakeholder 3 Stakeholder 2
4	Goal 1 - The mission will obtain accurate elevation maps in the polar regions of the moon.		Stakeholder 3 Stakeholder 1 Stakeholder 2
5	Objective 1 - The mission will image craters in the polar region of the moon		Stakeholder 1 Stakeholder 2
6	Objective 2 - The mission launch date is no later than the end of the year 2025.	1 Launch By bbd	Stakeholder 3

Figure 2.—Stakeholder requirements captured using comments.

TABLE 3.—STAKEHOLDER IDENTIFICATION AND EXPECTATIONS DEFINITION VALIDATION

Validation question	Validation method
Does every expectation have at least one associated stakeholder?	Use an allocation matrix that contains stakeholders, expectations, and the allocation relationships to evaluate whether each expectation is allocated to a stakeholder.
For later in the life cycle, have all the expectations been satisfied?	This can be shown two ways: (1) a satisfy matrix that contains expectations and the satisfy relationships to model elements; or (2) a table that lists all the expectations and model elements that satisfy the expectations.

3.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 3. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

3.4 More Detail

Expectations can be major and minor concerns. Minor expectations can be smaller tasks or analyses that need to be completed later in the project life-cycle, and if useful to the systems engineering planning effort, may be captured within the model.

4.0 Concept Definition

In starting any project a concept of operations (ConOps) for the mission or system is needed to detail the mission lifecycle and objectives. It is necessary to have an understanding of the whole mission and project timeline to design the system. The ConOps also helps define the high-level architectural structure, requirements, activities, and functions the system must address or perform and establishes trade space boundaries. To begin a project, an overview of the project scenario is created at a very high level. This overview could include events or activities, such as launch, payload separation, travel to locations, perform science, etc. These events are decomposed into smaller activities or functions. For example, the launch event might be decomposed into smaller activities such as install payload, load propellant, and trickle charge batteries. The ConOps is updated with greater fidelity as the project progresses and as more details of the mission, objectives, and functions are defined.

For clarity, for this document, an activity can be decomposed into multiple functions, where a function is at its lowest level of decomposition for either the function or modeling level. For simplicity, the term function is used, in this section, to represent both activities and functions and not to get it confused with activity diagrams.

4.1 Artifacts

The artifacts for concept definition, in general, are listed in Table 4.

4.2 Model Elements and Relationships

The model elements and relationships commonly utilized in the development of concept definition are listed in Table 5. The table is broken into four groups: mission scenarios, top-level architecture and defining functions; functional flow using activity diagrams; functional decomposition; and common element and relationship.

TABLE 4.—CONCEPT DEFINITION ARTIFACTS

Concept definition artifacts	Model artifact
Mission scenario and functions	Use case diagram.
Top-level system architecture concept	Block definition diagram.
System functions	Use case diagram and activity diagram.
System functional flows (data and activity)	Activity diagram.
Functional decomposition	Block definition diagram or activity tree diagram.

TABLE 5.—CONCEPT DEFINITION MODEL ELEMENTS AND RELATIONSHIPS

Concept definition	Elements	Model element and relationship
Mission scenarios, top-level architecture and defining functions	Stakeholder	Actor that interacts with the system.
	Top level architectural elements of system-of-interest	Blocks.
	External system or subsystem	Blocks. These are systems, subsystems, or environments that are outside and interface with the system-of-interest.
	Design boundary or boundary of technical effort	System boundary. The system boundary signifies the functional boundary of the system-of-interest.
	System capabilities	Use case. The use case shows describes the capabilities the system needs to perform, from the stakeholder point of view.
	Stakeholder interaction with system capabilities	Use case diagram, association relationship between the actors and the capabilities they use or perform within the system-of-interest.
	Decomposition of functions and activities	Refine or satisfy relationship to provide more details of the use case.
Functional flow (using activity diagrams)	Multiple uses of the same functions	Action or call behavior action. A call behavior action is an instance of a function or activity that is used multiple times or calls other activity flows. The action is used at the lowest level of decomposition. The lowest level that is modeled is determined by the level of detail required by the project.
	Allocation of functions to system or subsystem interactions	Swim lanes. Swim lanes capture which block performs which activities when allocated. At the high level, it may be the system. As the activities are decomposed, the swim lanes may become subsystems or components.
	Data interfaces	Activity parameter nodes and pins on the action. This is useful to capture what input a function needs before it can execute or what outputs a function creates that other functions need.

TABLE 5.—Concluded.

Concept definition	Elements	Model element and relationship
	Sequencing of functions	Activity diagrams show the functions and the order or sequence of the functions. As the project matures, the functions are decomposed. Activity diagrams may contain many functions. Control indicated the order in which system functions must occur.
	Data passed between functions	Object flows. These can represent signals, power, data, fluids, etc.
Functional decomposition	Functions	Activities. These can also be depicted in an activity tree in a Block Definition Diagram to help maintain appropriate and consistent level of decomposition throughout.
	Decomposition of functions	Direct composition relationship. The relationship should also have the AdjunctProperty stereotype so the usage of the function in functional flows becomes a part property of the parent function.
Common	Associating functions to requirements	Satisfy relationship. This allows the project to know if a specific function or activity is needed and can show compliance to requirements.

TABLE 6.—CONCEPT DEFINITION VALIDATION

Validation question	Validation method
Does each function have a corresponding requirement identified?	A matrix showing all the activities related to requirements via a satisfy relationship can be used to validate the completeness of identified requirements relative to identified functions.
Have the function been allocated to an owning system or subsystem?	This is done using a matrix or table listing the functions assigned to a system or subsystem via the allocate relationship.
Have all the identified functions (as part of the decomposition) been utilized somewhere in a functional flow?	A matrix showing the usages of the functions.

4.3 Model Validation Information

The main ways to show compliance are described in Table 6. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

4.4 More Detail

Top-level capabilities of the system-of-interest are modeled as use cases. Use cases refine stakeholder expectations (requirements). Relationships among use cases, actors, the system-of-interest, boundaries, constraints, and environments are modeled in use case diagrams or in a block definition diagram as a system context. System behaviors, are modeled as actions. Actions can be allocated to other model elements and defined as activities. Relationships among functions, e.g., the order in which they should occur or functional interfaces, are shown on activity diagrams.

5.0 Measures of Effectiveness (MOE), Measures of Performance (MOP), and Technical Performance Measures (TPM)

MOE, MOP, and TPM are all captured the same in the modeling world. The only difference is in the calculations performed with them and the relationships among the model elements. MOE are the operational measures of success and are intended to focus on how well the mission operational objectives are can be achieved from the mission success criteria and are derived from the stakeholder's expectations. MOP are measures that characterize physical or functional attributes relating to the system and are typically derived from MOE. TPM are derived from the MOE and MOP. They are critical or key for mission success. TPM are measures such as mass, availability, mobility, user or operator comfort, CPU capacity, and parameters associated with critical events during operations.

5.1 Artifacts

The artifacts used for MOE, MOP and TPM, in general, are listed in Table 7.

5.2 Model Elements and Relationships

Creating MOE, MOP and TPM using parametrics may be difficult to set up. Once accomplished, it is easier to collect, manage, and see trends. Many of the model elements and relationships in this section are setting up parametrics. It is beneficial to reference the MBSE tool-of-choice user guide. Start off small and then increase the parametric detail as needed, rather than starting off too large with too many variables to troubleshoot initially. The model elements and relationships for MOE, MOP, and TPM are listed in Table 8.

TABLE 7.—MOE, MOP, AND TPM ARTIFACTS

Measures of Effectiveness (MOE), Measures of Performance (MOP) and Technical Performance Measures (TPM) artifacts	Model artifact
Metric (MOE, MOP, or TPM)	Instance.
Metric (MOE, MOP, or TPM) to NGO(s) traceability	Table.
Metric (MOE, MOP, or TPM) to requirements traceability	Table.
MOE, MOP and TPM decomposition	Matrix.
Tracking trends	See Section 10.0, Required Leading Indicator Trends.

TABLE 8.—MOE, MOP, AND TPM MODEL ELEMENTS AND RELATIONSHIPS

Measures of Effectiveness (MOE), Measures of Performance (MOP) and Technical Performance Measures (TPM)	Model element and Relationship
Metric value associated with MOE, MOP, and TPM	Parameter owned by a constraint block. The constraint block holds the value that is used to identify a pass fail when compared to the calculation results.
System and subsystem	Block. This block is used as the owning system of the constraint block.
Value used in calculating parameter(s) to compare with metrics	Value attribute within the system/subsystem/component block it represents.
Equation to calculate parameter(s) to compare with metrics	Constraint block. The constraint block holds the constraint equation the MOE/MOP are assessed against, and the parameters necessary to populate the equation. The parametric diagram assigns the values for which the equation need to execute. Note that the equation could be a series of equations.
Results from calculations	Instances. When performing parametric calculations, instances are used for generating them. Performing these calculations at key decision points and saving the data elsewhere, would allow the model to show the changes of the TPMs over the life of the project.
Associating metric to a system/subsystem/component	Direct composition.
Associating a metric to an NGO	A satisfy relationship to NGO or concern is anchored to the metric.
Associating a metric to requirement	A contains relationship is used the requirement and the related constraint block, or block definition diagrams with the constraint blocks and their related elements.

5.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 9. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

5.4 More Detail

Quantitative TPM can be used in parametric diagrams. Figure 3 shows an example of a block definition diagram that would be used to perform a system mass roll-up. The system blocks have value properties of mass and total mass. The mass value is the mass for the block that is contained only within that block and not in lower-level blocks. Total mass for a block is the mass of the block added to the rolled-up mass from lower-level system blocks. For example, the total mass for System 3 is the rolled-up mass value from lower-level blocks Subsystems 3a and 3b, and the mass of System 3 that is not within Subsystems 3a and 3b. The Mass_rollup_pattern has a generalization relationship to all model elements associated within the calculation which is not shown.

TABLE 9.—MOE, MOP AND TPM VALIDATION

Validation question	Validation method
Which MOE, MOP or TPM satisfy a concern?	Table showing the MOP and TPM with their related model elements via the satisfy relationship.
Which MOP and TPM are related to a requirement, system or subsystem?	Table showing the MOP and TPM with their related model elements. The relationship used is dependent on the project.
Have the constraint equations been implemented correctly in the model?	Run a known configuration to show that the model configuration produces the expected results.

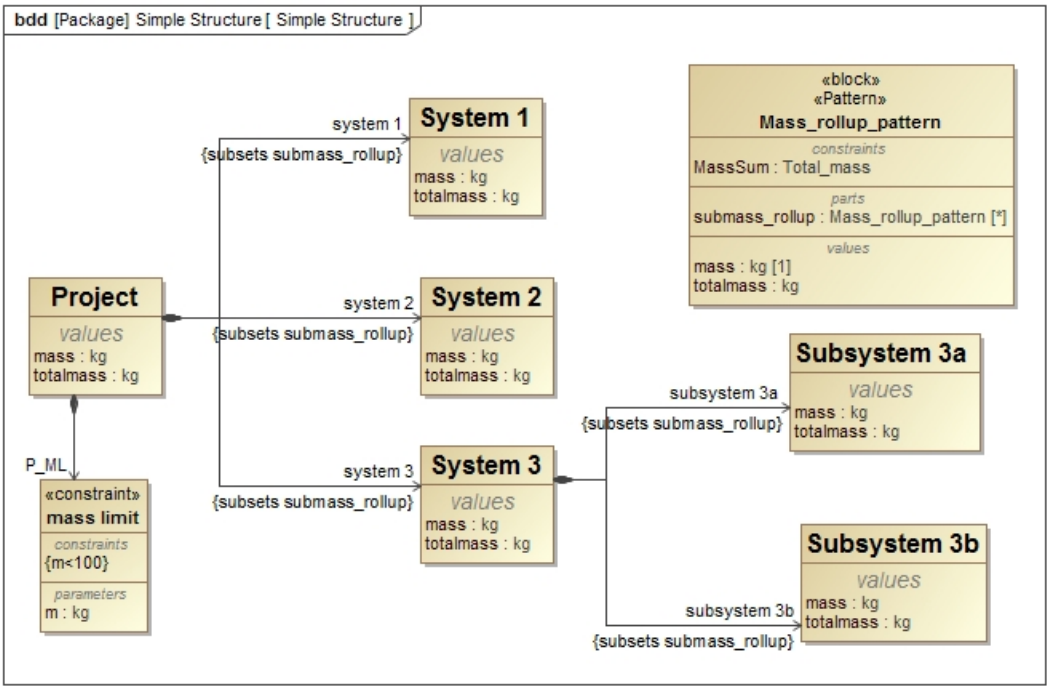


Figure 3.—System block diagram set up for TPM.

Figure 4 shows the parametrics based on the Mass_rollup_pattern. The parametric diagram is where the value properties are assigned to parameters on the constraint. The model has a constraint block for the mass roll-up equation.

Based on Figure 3 and Figure 4, calculations on instances are performed. Table 10 shows the mass roll-up instances over the course of 10 days of work. An additional constraint block, not shown, performs trending and validates that the mass margins are met. For this example, the mass limit is 100 kg. The table allows the project personnel to see trends and know when there is a failure to meet a metric.

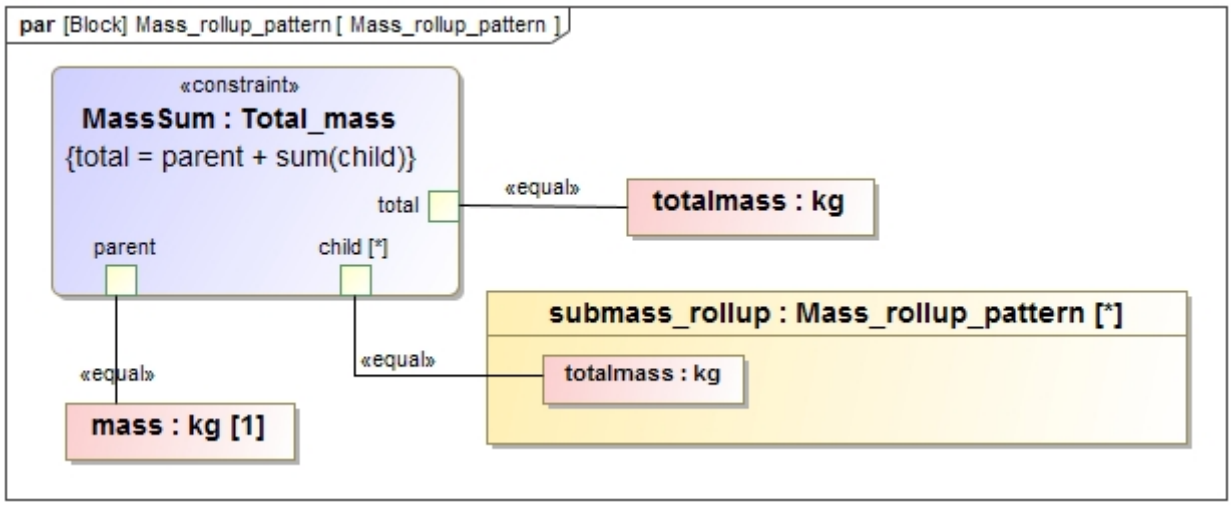


Figure 4.—Parametric diagram for a mass roll-up.

TABLE 10.—MASS ROLL-UP INSTANCE FOR MASS TRENDS

#	Name	P_ML: mass limit	totalMass: kg	system 1.totalMass: kg	system 2.totalMass: kg	system 3.totalMass: kg	system 3.subsystem 3a.totalMass: kg	system 3.subsystem 3b.totalMass: kg
1	Project 06-01-2016	pass	75.0	10.0	15.0	50.0	25.0	25.0
2	Project 09-01-2016	pass	95.0	10.0	25.0	60.0	25.0	35.0
3	Project 06-05-2017	pass	93.0	10.0	25.0	58.0	21.0	37.0
4	Project 06-06-2017	pass	97.0	14.0	25.0	58.0	21.0	37.0
5	Project 06-10-2017	fail	105.0	17.0	28.0	60.0	21.0	39.0

6.0 Cost and Schedule for Technical Implementation

Cost and schedule currently are usually kept in an external tool because of the amount of detail. However, some information can be kept within the model. The data can be exported to be combined with external data. This section will describe how the data can be stored within the MBSE tool and how the data can be shown. It does not go into how the information can be imported or exported from the model. This section does not show the full extent of all the cost and schedule artifacts, but gives an overall idea of how to capture the data. Section 7.0, System Engineering Management Plan, has some additional information on this topic.

6.1 Artifacts

The artifacts used for cost and schedule artifacts, in general, are listed in Table 11.

6.2 Model Elements and Relationships

The model elements that would be used are listed in Table 12. Some of the elements listed below are attributes. Depending on how the model is structured, these attributes could be part of a stereotype, generalization from another block, or block specific. How the attribute is defined is not discussed.

6.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 13. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

TABLE 11.—COST AND SCHEDULE ARTIFACTS

Cost and Schedule artifacts	Model artifact
Key events	Table to show event dates or Activity diagram to show event flows.
Cost projections	Table with the system, subsystem, and component attributes and the resultant from the parametric output.
Variance from one date to another	Instance table.
Completion or delays of activities	Table.
Work Breakdown Structure (WBS) elements structure	Block diagram.

TABLE 12.—COST AND SCHEDULE MODEL ELEMENTS AND RELATIONSHIPS

Cost and Schedule	Model element and Relationship
WBS element	Value property or attribute within a block. The value properties can be typed to capture WBS properties so that budgets, work authorizations, schedules and such can be correlated together. These blocks can be then related to architecture or requirement blocks.
Cost values	Value property or attribute of a block defined as a real variable so it can be used in a parametric calculation.
Schedule dates, key events dates, etc.	Value property or attribute of a block defined as a date variable.
Equation to do Cost or Schedule study	Constraint block. See section 5.0, MOE, MOP and TPM, for an example of performing calculations.

TABLE 13.—COST AND SCHEDULE VALIDATION

Validation question	Validation method
Is the cost information being calculated correctly?	Can be validated by having a table with the information and manually doing a check or comparing the results in an external tool.
Are all the events captured within the model?	Can be verified by creating a table listing all the events and the events have all the necessary data the project requires.
Are all the events in the model scheduled and costed?	Can be validated by creating a table listing all the events with schedule and cost data. Empty or missing cells indicate potentially missing data.

6.4 More Detail

When doing cost and schedule, it is important to make sure that the data is changed in only a single location, and that all calculations pull the information the same way. If updates are done in multiple locations, then data can become obsolete, knowing which is correct can be difficult, and finding the source of any errors can be difficult.

Using the model to capture cost or schedule information, each update can be captured and documented as an instance in the model. These instances can be shown in an instance table to can be used to perform trending analysis and for status.

7.0 System Engineering Management Plan (SEMP)

The SEMP is a living document that the project generates to define the technical integration methodologies and activities. The SEMP captures the processes the project uses and identifies the responsible party. The model may not contain all the information in its entirety that is in the SEMP. However, the system model can be used to generate sections of the document. Below are suggestions on how certain information is kept within the model.

7.1 Artifacts

The artifacts used for the SEMP, in general, are listed in Table 14.

7.2 Model Elements and Relationships

The model elements and relationships that are used in creating the SEMP artifacts are listed in Table 15.

7.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 16. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

TABLE 14.—SYSTEM ENGINEERING MANAGEMENT PLAN ARTIFACTS

SEMP artifacts	Model artifact
SEMP Document	Output from the model using information from within the model, in addition to information that supplements model-generated content.
System Decomposition	Block definition diagram.
WBS Layout	Block definition diagram.
Technical Summary of SEMP sections	Artifact.
Responsibility and organizational structure	Block definition diagram and allocation matrix.
External or NASA Standard	Block that contains attributes such as report name and report owner, with external hyperlink.
Project processes such as Engineering Review Board and Project Control Board	Activity diagrams.
Various processes such as configuration management, SE processes, waiver process, etc.	Activity diagram or sequence diagram to lay out the process.

TABLE 15.—SYSTEM ENGINEERING MANAGEMENT PLAN MODEL ELEMENTS AND RELATIONSHIPS

SEMP	Model element and Relationship
SEMP	Package or content diagram. These diagrams contains folders or package information that can be found elsewhere in the model in a single diagram.
Textual content	Artifact or comment. In the document world, it is the text part of the document that describes a section. When sections are repeated in other sections, it is better to capture the information in an artifact for easy reference. Comments and text boxes can be used when information is used for a single diagram. The textual content can be used to generate an external document if necessary.
Personnel and organizations associated with the project	Actors. These actors use an allocation relationship to the WBS structure.
System component	Block. See Section 9.0, Architecture Definition, for more information.
WBS structure	Block. The structure is very similar to defining the system components, but instead of system and part, the blocks represent work packages. The direct composite relationship is used to show the breakdown of the work to system components. The black diamond is on the higher level and points to the next level down.
Project process activities	Action block or call behavior action block. A control flow relationship is used to between action blocks, to show the process flow.
Organizational task allocation	Swim lanes. Swim lanes capture which organization, such as project level or team, performs the process function.
Data interactions	Activity parameter nodes and pins on the action block. This is useful when showing what input is needed before the process activity can proceed such as a change package and the outcome of that activity such as a scheduled review date, for the process to continue.

TABLE 16.—SYSTEM ENGINEERING MANAGEMENT PLAN VALIDATION

Validation question	Validation method
Does the model have all the processes that are required in a SEMP?	Package diagram or content diagram and verify that all required sections contain the pertinent information.
Do the WBS elements have allocations to an organization or role?	Matrix with all the WBS allocated to an organization or role?
Do the process elements have owners (personnel or system) associated with them?	Matrix.

7.4 More Detail

There are two ways of capturing the information necessary for creating a SEMP; a package diagram method as shown in Figure 5 or a content diagram shown in Figure 6. The SEMP outline used in Figure 5 and Figure 6 is based on the guidance in Appendix D of NPR 7123.1B (Ref. 1). As shown, it displays that a WBS structure diagram is created and associated with Section 3.2 of the SEMP and the WBS allocation matrix diagram associated with Section 4.0 of the SEMP. The difference between the two options is how the artifacts that satisfy the SEMP section are kept. In a package diagram, the SEMP information can be stored two ways: (1) an artifact is created inside the package and then the artifact is hyperlinked to the artifact within the model as shown in package 3.2 System Structure or (2) the artifact is stored within the package as shown in package 4.0 Technical Effort Integration. The artifact will not appear unless it is kept within the package location.

In a content diagram the artifact is dragged and dropped onto associated package which creates a hyperlink to the artifact within the model. Either way is acceptable and is a project decision on which to use.

The WBS structure diagram shown in Figure 7 is an example WBS structure that based on a space-flight project from Work Breakdown Structure (WBS) Handbook, Appendix C, (Ref. 6). Details associated with the WBS elements can be added using generalization or stereotype to add attributes that are required by the project. Figure 8 shows the allocation of work to the organizations. Figure 7 and Figure 8 are the artifacts that are shown in Figure 5 and Figure 6.

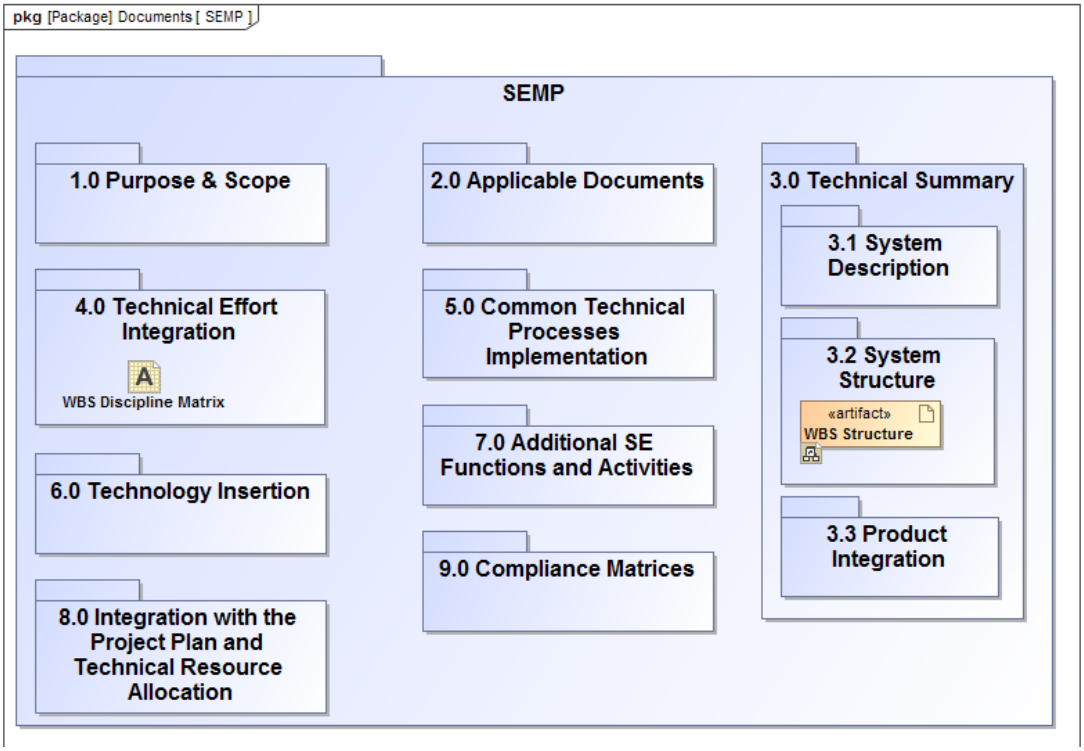


Figure 5.—Package diagram for SEMP.

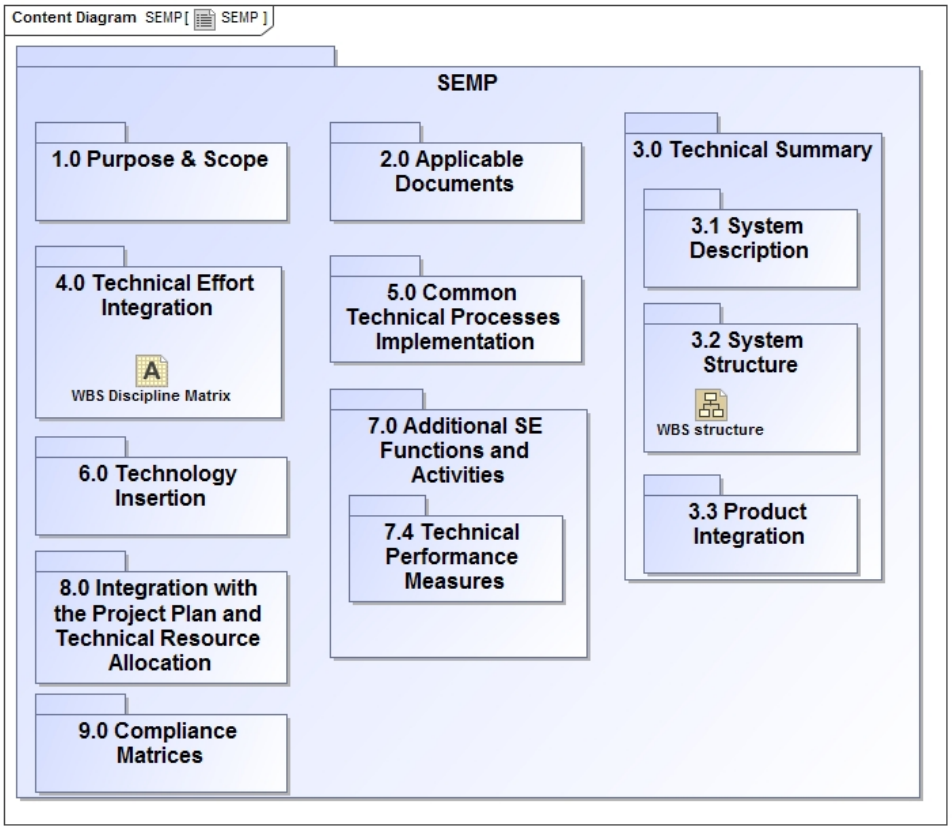


Figure 6.—Content diagram for SEMP.

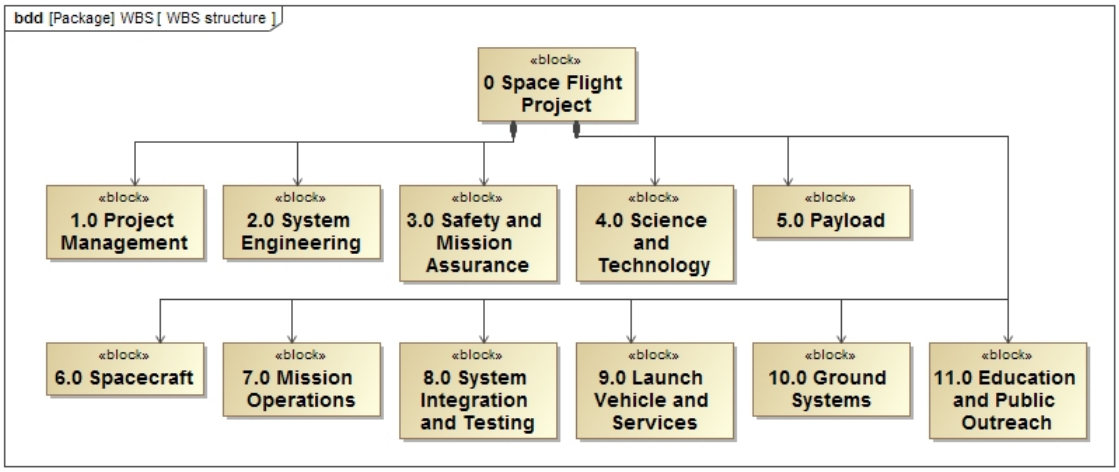
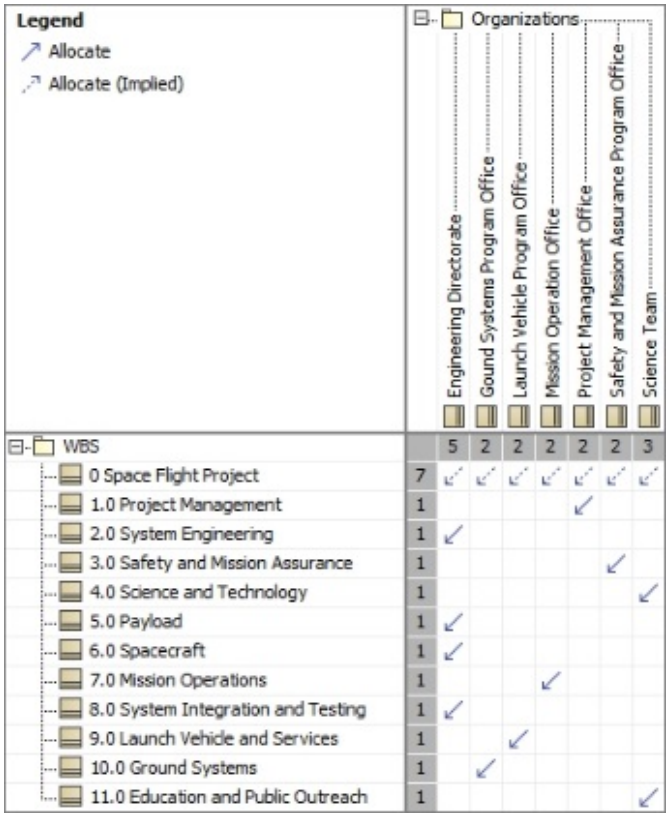


Figure 7.—WBS package diagram.



Legend
Allocate
Allocate (Implied)

WBS		Engineering Directorate	Gound Systems Program Office	Launch Vehicle Program Office	Mission Operation Office	Project Management Office	Safety and Mission Assurance Program Office	Science Team
		5	2	2	2	2	2	3
0 Space Flight Project	7	↙	↙	↙	↙	↙	↙	↙
1.0 Project Management	1					↙		
2.0 System Engineering	1	↙						
3.0 Safety and Mission Assurance	1						↙	
4.0 Science and Technology	1							↙
5.0 Payload	1	↙						
6.0 Spacecraft	1	↙						
7.0 Mission Operations	1				↙			
8.0 System Integration and Testing	1	↙						
9.0 Launch Vehicle and Services	1			↙				
10.0 Ground Systems	1		↙					
11.0 Education and Public Outreach	1							↙

Figure 8.—WBS discipline allocation matrix.

8.0 Requirements and Allocation of Requirements to Next Lower Level

Requirements are a way to state the physical and functional capabilities that a particular design, product or process must be able to perform. The requirement work starts at the very beginning during mission concept followed by decomposition. Requirement decomposition ends when the project is ready to make, buy or build. Requirements not only include the high level project and mission requirements, but also include technical, performance, interface, environmental, operational, reliability, safety, specialty and human factors. The requirements become more specific as they are further decomposed. The approach here is for text-based requirements.

8.1 Artifacts

The artifacts used to state, trace, and allocate requirements, in general, are listed in Table 17.

8.2 Model Elements and Relationships

The model elements and relationships that capture requirements artifacts are listed in Table 18.

8.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 19. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

TABLE 17.—REQUIREMENTS ARTIFACT

Requirement artifact	Model artifact
Requirements at various levels	Requirement diagrams.
Requirement traceability	Requirement diagram or matrix.
Requirement allocation to systems, events, functions and other relationships	Matrix.

TABLE 18.—REQUIREMENT MODEL ELEMENTS AND RELATIONSHIPS

Requirement	Model element and Relationship
Technical and programmatic requirement	Requirement block.
Parent to child relationship	Derive, trace, or containment relationship.
Requirement to other model elements	Satisfy or refine relationship.
Allocation of requirements to the next level down system or subsystem	Allocate relationship. The allocation relationship allows the next level down to know which requirements are assigned to them and which are not.
Requirements verified by a verification event	Verify relationship. A verification event can verify multiple requirements.
Additional attributes of a requirement block	Requirement block stereotype. This stereotype is commonly used when extra attributes are required for all requirements. Types of attributes that could be added are: requirement status (draft, preliminary, baselined); verification status (open, closed), and rationale to name a few.
Measuring value in a requirement	Value attribute within a block or requirement (if set as an attribute). This value can be in a requirement field and then placed or referenced in a constraint block for performing a mathematical relationship.
Associating requirements to NGO	See Section 3.0, Stakeholder Identification and Expectations Definition.
Associating functions to requirements	Satisfy relationship.

TABLE 19.—REQUIREMENT VALIDATION

Validation question	Validation method
Does every requirement have a parent or a child depending on the requirement level?	Matrix.
Have the requirements been allocated to the physical structure elements?	Allocation Matrix.
Do the requirements have the necessary information for the level of maturity?	Validation Scripts within the model, tables.

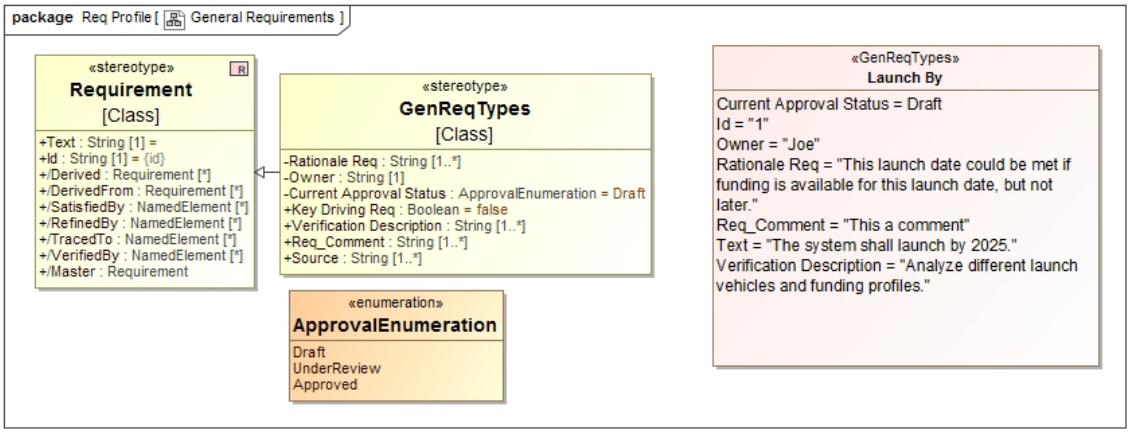


Figure 9.—General requirements stereotype profile.

8.4 More Detail

Requirement blocks are usually related to the following model elements: concerns, activity, functions, verification events, and blocks. These model elements are described in other sections within this paper. Relationships between the requirements and other model elements are created as the requirements are reviewed and baselined, and as more detail is added within the model.

Figure 9 shows an example of how attributes can be added to requirements and what they look like in the SysML requirement element after the stereotype is applied. The GenReqTypes stereotype is applied to a requirement block by a generalization relationship. When the “Launch By” requirement has the stereotype <<GenReqTypes>>, the attributes of the GenReqTypes are applied. Figure 9 shows selected attributes but more are available.

9.0 Architecture Definition

Architecture definition is the system physical and logical structure and interconnections. This is not the WBS structure, but uses a similar construct. The architecture definition defines and breaks down the system into subsystems, and subsystems into assemblies or components, and so on until it is decomposed to the level the project needs. Depending on the project, the architecture may use three levels or less, or may have more levels if necessary. How the system and subsystems interface among each other is described in Section 11.3, Interface Definition. Having the architecture defined can make it easier to identify functions prior to allocating them to subsystems.

9.1 Artifacts

The artifact used for architecture definition, in general, are listed Table 20.

9.2 Model Elements and Relationships

The model elements and relationships that are used in architecture definition artifacts are listed in Table 21.

TABLE 20.—ARCHITECTURE DEFINITION ARTIFACTS

Architecture definition artifacts	Model artifact
System structure	Package diagram, block definition diagram or architecture block definition diagram

TABLE 21.—ARCHITECTURE DEFINITION MODEL ELEMENTS AND RELATIONSHIPS

Architecture definition	Model element and Relationship
System, subsystem, and components	Block. This can be physical or logical structure elements.
Relationships among the system, subsystem and components	Composition relationship.
Part of a system	Part property (solid diamond).
Part that contributes to the system architecture but exists independently	Reference property (open diamond).
Specific use of a part	Instantiation of block. This can be for specific choices, such as a model number or part option.

TABLE 22.—ARCHITECTURE DEFINITION VALIDATION

Validation question	Validation method
Does the physical and logical structure decomposition go down to the correct level?	Block definition diagram.
Does the physical and logical structure have the right components at the right level?	Block definition diagram.
Does every architectural element perform a function?	Matrix.

9.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 22. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

9.4 More Detail

This structure is used in the allocation of requirements. It is also used in the allocation of functions to architectural elements via activity swim lanes. See Section 4.0, Concept Definition, and Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.

10.0 Required Leading Indicator Trends

The required leading indicator trends are items such as mass margin, power margin, and the number of actions from reviews. For the trends that can be calculated within the model, go to Section 5.0, MOE, MOP and TPM, for more information on performing parametrics (calculation) within the model. This section will only address value properties.

10.1 Artifacts

The artifacts used for required leading indicator trends, in general, are listed in Table 23.

10.2 Model Elements and Relationships

The model elements and relationships that are used in creating required leading indicator trend artifacts are listed in Table 24.

TABLE 23.—REQUIRED LEADING INDICATOR ARTIFACTS

Required leading indicator artifacts	Model artifact
Product leading indicator trends	Simulation results. See Section 5.0, MOE, MOP, and TPM.

TABLE 24.—REQUIRED LEADING INDICATOR MODEL ELEMENTS AND RELATIONSHIPS

Required leading indicator	Model element and Relationship
Project Metrics	Value property within a block. To show trends, an instance is created at every milestone. These are placed in an instance table to show trends.

TABLE 25.—REQUIRED LEADING INDICATOR VALIDATION

Validation question	Validation method
Are the trends current and up-to-date?	Check the latest instance date that was created and simulated.

10.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 25. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

10.4 More Detail

Another way to get information that is not currently in the model is to use scripts to pull the information and then populate the model from an authoritative source of truth. A set of leading indicators that might exist within a model include: mass, power profile, power margin, number of requirements, number of requirement changes, number of tbd/tbr in requirements, requirements compliance, milestone review artifacts (model related), and verification burndown status. These are leading indicators that could be populated within the model using parametrics (see Section 5.0, MOE, MOP, and TPM) or by simple scripting techniques. Other, such as review actions status, drawing percent released, number of defects, and schedule slippage would need scripting or manual entry of the information.

Table 10 shows how the mass roll-up instances can be used for trending. It is easy to follow how the mass of a system changes over time so one can predict whether there would be a risk of failing a metric.

11.0 Design Solution Definition

The design solution definition process is used to generate and evaluate alternative solutions, and select one or more for further work. This process is also known as doing trade studies. Many facets may need to be considered for a comprehensive solution. The alternative solutions artifacts are captured as options in the model, and then the base model is updated based on the decisions. A wide variety of alternative solutions are possible for mission to system to subsystem, etc., so not all of the artifacts are described. Below are just a few to give a feel for what is possible.

11.1 Artifacts

The artifacts used for design solution definition, in general, are listed in Table 26.

11.2 Model Elements and Relationships

The model elements and relationships are covered in the sections identified in Table 26.

TABLE 26.—DESIGN SOLUTION DEFINITION ARTIFACTS

Design solution definition artifacts	Model artifact
Scenarios of alternative solutions	Use cases, activity flows. See Section 4.0, Concept Definition, as alternative solutions are different ways to accomplish a task or mission.
Effects of alternative solutions	Instances, parametrics. These are used to collect information for an alternative solution, such a mass, fuel, or temperature deltas. See Section 5.0, MOP, MOE, and TPM.
Make-buy-reuse specification requirements	See Section 13.0, Technical Plans.

11.3 Model Validation Information

Model validation information is covered in the sections identified in Table 26.

11.4 More Detail

Each of the sections referred to in Table 26 describes the artifacts, model elements and relationships and model validation in more detail.

12.0 Interface Definition

Interface definition describes the interfaces items at each level of the architecture, for example external interfaces at the system level, subsystems to subsystem interfaces at the next level, and continues down to the desired level. This includes both logical and physical interfaces with the associated detail.

12.1 Artifacts

The artifacts used for interface definition, in general, are listed in Table 27.

12.2 Model Elements and Relationships

The model elements and relationships that are used in creating interface definition artifacts are listed in Table 28.

12.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 29.

These questions are only a starting point and they can be performed using model-generated tables and diagrams.

12.4 More Detail

The way interfaces are represented is rapidly changing due to modeling tools having more capability to handle the information associated with them. It is important to look at vendor software and identify its capabilities for identifying and validating interfaces.

TABLE 27.—INTERFACE DEFINITION ARTIFACTS

Interface definition artifacts	Model artifact
Interface diagrams	Interface block diagrams.
Interface control documents	Tables.

TABLE 28.—INTERFACE DEFINITION MODEL ELEMENTS AND RELATIONSHIPS

Interface definition	Model element and Relationship
System, subsystem, parts, component	Block. The use of blocks is defined in Section 9.0, Architecture Definition, and are re-used and elaborated for interface definition.
Internal system interconnections	Full ports and proxy ports.
External system interconnections	Full ports and proxy ports.
Type of matter, data information, or other entity flowing between interconnections	Item flows. The item flows can represent power, fluids, or something else such as mechanical load.
Units of what is flowing between interconnections	Value types such as kg, Watts, or bits per second.

TABLE 29.—INTERFACE DEFINITION VALIDATION

Validation question	Validation method
Are all the interfaces are identified?	The model can help by producing tables and matrixes showing the relationships between elements. The use of scripts with full ports having attributes for identifying the interface can be used to validate whether the system blocks have a least one interface identified. Additional work would be needed to validate that all the interfaces are correct and that all interfaces have been identified.
Are all the interfaces typed correctly?	Table showing the ports, with item flows typed.
Do the interfaces have the correct units?	Examine the value type for each type of port.

13.0 Technical Plans

System engineers develop many plans, including Implementation, Verification and Validation, Integration, Operational Plan and Procedure, Decommissioning and Disposal plans. Even though the plans have specific uses, the types of modeling elements utilized are mostly the same. The main differences among them are the content. For this reason, the discussion of these plans is combined in this section. Details associated with these plans, and their functions are captured in NPR 7123.1B (Ref. 1).

13.1 Artifacts

The artifacts used for technical plans, in general, are listed in Table 30.

13.2 Model Elements and Relationships

Most of the model elements and relationships can be shown in a generic table or matrix. The desired content is selected for display. A matrix often shows relationships among different model elements. The model elements and relationships that are used in creating technical plan artifacts are listed in Table 31.

13.3 Model Validation Information

Validation is captured in many ways and at various levels of maturity. The main ways to show compliance are described in Table 32. These questions are only a starting point. The validation method for the question can be performed using model-generated tables, matrices and diagrams; the details are not captured.

TABLE 30.—TECHNICAL PLAN ARTIFACTS

Plan	Artifacts	Model artifact
Common to all Technical plans	Plan	Output from the model using information from within the model, in addition to information that supplements model-generated content.
	List of detailed plans or procedures	Table or package diagram.
	List of Personnel, skill mix and training	Table or matrix.
	Requirements and interfaces for enabling systems	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level, and Section 11.3, Interface Definition.
Implementation plan	Implementation approach for end product	Table or matrix.
	Tools and equipment, raw materials, and specialized services list	Table or matrix.
	Vendor list	Table or matrix.
	Constraints from the strategy on the end product requirements, architecture, or design	Table with constraint blocks listed.
Verification and Validation plan	Verification approach for each requirement	Table or matrix.
	List of analyses, tests, inspections, and demonstrations during V&V	Table or verify matrix.
	List of requirements to be verified with approach	Table or verify matrix.
	List of stakeholder expectations to be validated with approach	Table or matrix.
	List of special equipment, conditions, or procedures	Table or matrix.
Integration plan	List of integration area or facility, and storage areas	Table or matrix.
	List of test equipment, tooling, and recording devices	Table or matrix.
	List of analyses, tests, inspections, and demonstrations during integration	Table or matrix.
Operational plan and Procedure	Operational approaches and scenarios for nominal operations	Activity diagrams, state machine diagrams.
	Operations approaches and scenarios for contingency, off-nominal, and degraded operations	Activity diagrams, state machine diagrams.
	List of operational states and modes	Table or matrix.
Decommissioning and Disposal plans	Approach for end product	Table or matrix.
	Tools and equipment, raw materials, and specialized services list	Table or matrix.
	Constraints from the strategy on the end product requirements, architecture, or design	Table.

TABLE 31.—TECHNICAL PLAN MODEL ELEMENTS AND RELATIONSHIPS

Plan	Elements	Model element and Relationship
Common to all plans	Plan	Package or content diagram. These diagrams contains folders or package information that can be found elsewhere in the model in a single diagram. See Section 7.0, Systems Engineering Management Plan, for more details about these diagrams.
	Textual content	Artifact or comment. In the document world, it is the text part of the document that describes a section. When sections are needed repeated for other sections, it is better to capture the information in an artifact for easy reference. Comments and text boxes can be used, when information is used for a single diagram. The textual content can be used to generate external document if necessary.
	Implementation approach for end product	Block from the design solution definition. Each block will have attributes that specify whether it is acquire new, build new, reuse without modification, or reuse with modification and any special considerations. The block multiplicity specifies how many of each are needed.
	Detailed procedure	Use case diagrams, activity diagrams and hyperlinked artifacts or block to an external procedure. The use case diagram depicts how an enabling system interacts with the actors to perform the procedure. The activity diagrams depicts how the procedure will flow. Many plans and procedures that are developed are kept in an outside repository and an artifact can be used as a means to hyperlink the document repository. Artifacts can have attributes associated with them such as procedural name, date, or author. However, it is easier to capture this information using a block.
	Spares, tools and equipment, raw material, or specialized service	Block. The details of these can be captured in value property attributes. The blocks can have allocation relationships with activities and end products.
	Vendor and Personnel	Actor and block. Each vendor or person can be depicted as an actor, which can be refined by a block.
	Skills and training	Block, but also be used as a part property for personnel block doing product implementation
	Requirement for enabling systems	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.
	Interface for enabling systems	See Section 12.0, Interface Definition.
	Constraints	Constraint blocks. These blocks are used to perform analysis such as validating that a requirement can still be met due to the implementation strategy on the end product requirements, architecture, or design. See Section 5.0, MOE, MOP and TPM.
	Integration area or facility, and storage areas	Block.
	Analyses, tests, inspections, and demonstrations during integration	TestCase activity.
	Operational states and modes	State machines and state machine diagrams.
Verification and Validation plan	Requirements to be verified	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level, and Section 12.0, Interface Definition. Each requirement has a relationship with one or more verification events. A Verify matrix shows the relationships between requirements and the verification events.
	Stakeholder expectations to be validated	See Section 3.0, Stakeholder Identification and Expectations Definition. Each expectation that is to be validated has a relationship with one or more validation events.
	Verification approach or method for each requirement	Value property of a requirement block named VerifyMethod. The property has an enumerated value type such as VerificationMethodKind. The allowed enumerated value types are user defined, and typically are analysis, test, demonstration, inspection, roll-up, synthesis, or combinations.
	Verification or validation event	Activity with the stereotype <<testcase>>. Each event can be represented as a <<test case>> that is related to the requirement block through a verify relationship. The different test cases can be depicted on a requirement diagram showing the details of the test cases within a particular test procedure.

TABLE 32.—TECHNICAL PLAN VALIDATION

Plan	Validation question
Common to all plans	Do all plans and procedures have an owner and status?
	Do all completed plans and procedures have a hyperlink to an external location or links to table and diagrams within the model?
	Does each end product have an approach, plan, procedure or sequence?
	Does each end product have a responsible organization?
	Are specialized skills, tools, and training identified?
Implementation Plan	Are requirements and interfaces to enabling systems identified?
Verification and Validation Plan	Do all requirements have a verification approach?
	Do all analyses, tests, inspections, and demonstrations have an owner?
	Are V&V areas, test equipment, tools, and training identified?
	Does each verification indicate when it is necessary to be completed, such as prior to system integration or product transition?
Integration Plan	Are integration areas, test equipment, tools, and training identified?
	Are analyses, tests, inspections, and demonstrations occurring during integration identified?
Operational Plan	Are contingency, off-nominal, and degraded operation scenarios addressed?
	Have the operational states and modes been identified?
Operational Procedure	Have contingency, off-nominal, and degraded operation scenarios been developed?
Decommission Plan	Have decommission of product being included into the design of the mission?
Disposal Plan	Are specialized skills, tools, and training identified?
	Are requirements and interfaces to enabling systems identified?

14.0 Verification and Validation (V&V) Results

The results from V&V include the outcomes of product verification and validation and reports providing the evidence of conformance with the requirements or expectations. V&V results also include work products such as records of procedural steps, failures or anomalies, corrective actions, and waivers.

14.1 Artifacts

The artifacts used for verification and validation results, in general, are listed in Table 33.

14.2 Model Elements and Relationships

The following model elements and relationships are often found in a verification report and can be represented by model elements and relationships as listed in Table 34.

14.3 Model Validation

Validation is captured in many ways and at various level of maturity. The main ways to show compliance are described in Table 35. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

14.4 More Detail

The Expanded Guidance Document Volume 1, Section 5.3 (Ref. 2) contains additional information on performing product verification and Section 5.4 for additional information on performing product validation.

Figure 10 shows a verification requirement (Id and Name) that is similar to requirements, but has specific attributes such as verification status. The figure also shows the requirement (Requirement Id and Name) that the verification requirement closes.

TABLE 33.—V&V ARTIFACTS

Verification and Validation artifacts	Model artifact
Verification report for each specified requirement	Table or requirement diagram.
Verification and validation event metrics (number complete, number remaining)	Parametric results.
Requirement metrics (number verified, number remaining)	Parametric results.
Expectation metrics (number validated, number remaining)	Parametric results.
List of results for each verification and validation event	Table or matrix.
List of external reports	Table or matrix with hyperlinks.
List of verification events and as-performed procedures	Table or matrix.
List of failures, anomalies, and corrective actions	Table or matrix of events that meet this criteria.
List of waivers	Table or matrix of requirements that meet this criteria.

TABLE 34.—V&V MODEL ELEMENTS AND RELATIONSHIPS

Verification and Validation	Model element and Relationship
Requirement	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.
Requirement traceability	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.
Verification method	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level, and Section 13.0, Technical Plans.
Special equipment, conditions, or procedures	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level, and Section 13.0, Technical Plans.
Result or status of each verification event	Output activity parameter for a Test Case, with user-defined name such as verdict. The parameter would have an enumerated value type with user-defined name such as VerdictKind that can have legal values such as Not Started, In Work, Pass, Fail, etc.
Existence of a variation, anomaly, or out-of-compliance result	Output activity parameter for a Test Case, with user-defined name such as variation, anomaly, or out-of-compliance. The parameter would have a value type of Boolean (false or true).
Variation, anomaly, or out-of-compliance result	Block that has the appropriate information. The block is a reference property of the requirement block and has a hyperlink to external information.
Corrective action and result of corrective action	Each action or result is represented as a block that contains attributes such as the owner. The block has a relationship to the test case and has a hyperlink to the external corrective action or result.
Verification or validation status	Attribute of a requirement block. A parametric diagram can be used to calculate metrics such as adding up the total number of requirements, the number of requirements verified, and the number remaining.
External Report	Block that contains attributes such as report name and report owner. The block has a relationship to the requirement block and has a hyperlink to external information.
Record of procedural steps	Block that contains attributes such as as-run procedure name and owner. The block has a relationship to the test case and has a hyperlink to the completed as-run procedure.
Waiver	Block that contains attributes such as the owner.

TABLE 35.—V&V VALIDATION

Validation question	Validation method
Does each TestCase have a status or result?	Table.
Does each requirement have a verification or validation status?	Table showing that the verification report has been approved.

Element Type: GenVerificationReq ... Scope (optional): Drag elements from the Mode

#	Id	Name	Verification_ Status	Requirement Id & Name
1	401	Launch By Verification	Closed	1 Launch By
2	402	Lifetime Verification	In_Process	
3	403	Environment Verification	Completed	3 Environment
4	404	Development technology Verification	Open	
5	405	Operate Verification	Open	
6	405.1	Orbit autonomously Verification	Open	
7	405.2	Orbit maintenance Verification	Open	

Figure 10.—Verification status information diagram.

15.0 Transportation Criteria and Instructions

The criteria for transportation can be stated as the requirements for transporting a product during manufacturing, assembly, integration, test and evaluation, or delivery to the customer. Requirements for packaging, special containers, handling equipment and fixtures, storage facilities, and transportation facilities fall in this category. Sensitive or hazardous products may have additional requirements to cover safety and environmental conditions during storage and transportation.

The aspects of transportation that cover the tracking of the configuration of the product, along with the data package, are not covered here. Those are typically handled by configuration and data management analysts.

Transportation instructions may be for procedures or other tasks associated with the handling and storage of a product.

15.1 Artifacts

The artifacts used for transportation criteria and instructions, in general, are listed in Table 36.

15.2 Model Elements and Relationships

The model elements and relationships that are used in creating transportation artifacts are listed in Table 37.

15.3 Model Validation Information

Validation is captured in many ways and at various level of maturity. The main ways to show compliance are described in Table 38. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

15.4 More Detail

See the Expanded Guidance Document Volume 1, Section 5.5, (Ref. 2) for additional information on performing transportation.

TABLE 36.—TRANSPORTATION ARTIFACTS

Transportation artifacts	Model artifact
List of transportation criteria	Table or matrix.
Transportation approach	Activity diagram.
List of transportation instructions	Table or matrix.

TABLE 37.—TRANSPORTATION MODEL ELEMENTS AND RELATIONSHIPS

Transportation	Model element and Relationship
Transportation requirement	See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.
Transportation Personnel	Actor and block. Each person can be depicted as an actor, which can be refined by a block. The actor may be used in use case or activity diagrams. Initially the actor and the block would be named by the role, such as crane operator, forklift operator, bonded storage custodian, etc. The block could contain part properties such as required skills and training. Later, the block would have value properties such as responsible organization, address, name or point of contact, or contact information. The block can have an allocation relationship with the end product(s), activities, test cases, or transportation instructions.
Skills and training list	Block. A skill or training can be depicted as a block, and used as a part property for personnel doing product transportation.
Special containers, handling equipment and fixtures, storage facilities, and transportation facilities	Block. A container, handling equipment or fixture, facility, or specialized service is represented as a block. The blocks can have value properties, such as type of fixture, or calibration or certification status. The blocks can have allocation relationships with activities and end products. These also can be modelled as a unique component subsystem or system themselves with their own requirements and verification depending on the complexity.
Transportation instructions	Use case diagram, activity diagram. The details of a particular instruction or procedure can be presented in a use case diagram, or an activity diagram or series of diagrams. The use case diagram depicts how an enabling system such as containers, fixtures, facilities, and services will be used by transportation personnel to transport the end products. The activities are the steps for that part of the transportation, and can have multiple levels of increasing detail. The activities can be allocated to actors or blocks.

TABLE 38.—TRANSPORTATION VALIDATION

Validation question	Validation method
Does each end product undergoing transportation have a responsible person allocated to perform transportation?	Table showing the responsible person.
If the end product is sensitive or hazardous, do requirements for safe handling during transportation exist?	Satisfy matrix showing that requirements were developed.
Are special skills, equipment, and facilities identified?	Table showing all the transportation attributes.

16.0 Certification (Flight/Use)

Certification for flight or use occurs with the submission of a data package that includes verification results, reports, and other evidence to indicate the design is certified. An example of the data package for flight is a Human Rating Certification Package. An example of the data package for use is a critical lift hardware certification package.

16.1 Artifacts

The artifacts used to identify certification, in general, are listed in Table 39.

16.2 Model Elements and Relationships

The model elements and relationships that are used in creating certification artifacts are listed in Table 40.

16.3 Model Validation Information

Validation is captured in many ways and at various level of maturity. The main ways to show compliance are described in Table 41. These questions are only a starting point and they can be performed using model-generated tables and diagrams.

TABLE 39.—CERTIFICATION ARTIFACTS

Certification artifacts	Model artifact
Certification criteria or deliverables	Table, matrix.
Certification data package	Package diagram.
Evidence of compliance to certification criteria	Matrix, requirements diagram.

TABLE 40.—CERTIFICATION MODEL ELEMENTS AND RELATIONSHIPS

Certification	Model element and Relationship
Certification criteria	Requirement. The criteria or deliverables are modeled as requirements. See Section 8.0, Requirements and Allocation of Requirements to Next Lower Level.
Verification result	See Section 14.0, Verification and Validation Results.
Report	See Section 14.0, Verification and Validation Results.
Waiver	See Section 14.0, Verification and Validation Results.

TABLE 41.—CERTIFICATION VALIDATION

Validation question	Validation method
Are all the certification criteria and deliverables in the model?	Table.
Do all the certification criteria and deliverables have a satisfy relationship with the correct evidence?	Matrices.

17.0 Conclusion

The gap between learning MBSE and the application of those skills within a project is often significant. The information and examples in this paper are intended to increase the use of MBSE by assisting those who are trained in tools and languages to use their knowledge more effectively. These approaches are useful to systems engineers and also to project managers, review board members, and other key project stakeholders.

Systems engineering is used throughout the project lifecycle and in many types of projects. A SysML system model can contain or generate most systems engineering products to a significant extent. Describing the use of MBSE for all the products and tasks encountered in a project is beyond what can be covered in this paper, so the work presented here is limited to the required and primary products for project life-cycle and technical reviews. The use of MBSE can reduce the schedule impact usually experienced for review preparation, as in many cases the review products can be auto-generated directly from the system model. Future work could provide more complete coverage of the topic.

References

1. National Aeronautics and Space Administration, 2015, NASA Procedural Requirements 7123.1B w/ Ch3, "NASA Systems Engineering Processes and Requirements," NASA Office of the Chief Engineer. Washington, DC (US).
2. National Aeronautics and Space Administration, 2016, "Expanded Guidance for NASA Systems Engineering. Volume 1: Systems Engineering Practices," NASA Office of the Chief Engineer. Washington, DC (US).
3. National Aeronautics and Space Administration, 2016, "Expanded Guidance for NASA Systems Engineering. Volume 2: Crosscutting Topics, Special topics, and Appendices," NASA Office of the Chief Engineer. Washington, DC (US).
4. Object Management Group, 2015, "OMG Systems Modeling Language (OMG SysML™) Version 1.4." Needham, MA (US).
5. Weiland, Karen J. and Holladay, Jon, 2017, "Model-Based Systems Engineering Pathfinder: Informing the Next Steps," 27th Annual INCOSE International Symposium (IS 2017). Adelaide, Australia, July 15–20, 2017.
6. National Aeronautics and Space Administration, 2010, NASA/SP—2010-3404, "Work Breakdown Structure (WBS) Handbook," NASA Office of the Chief Engineer. Washington, DC (US).